STUDYING ATMOSPHERIC DYNAMICS WITH LASERS IN REMOTE PLACES

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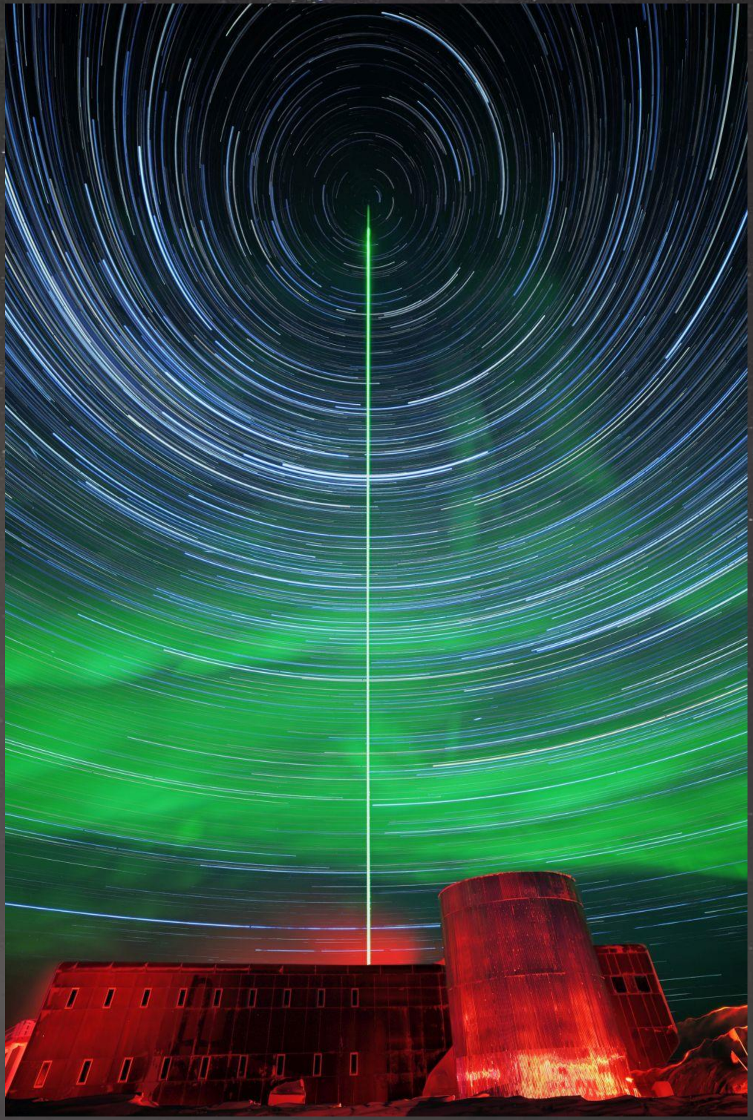


Photo: Marc Jacquart

Why do we study atmospheric dynamics?

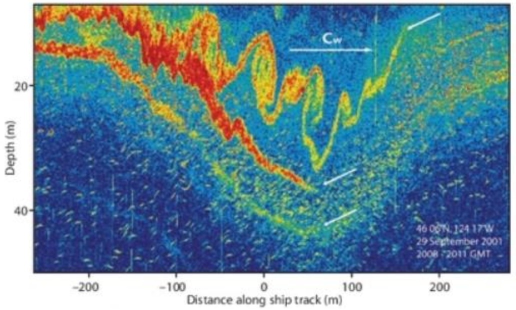
One example

Kelvin-Helmholtz instabilities

Instability in stratified shear flow of fluids and plasmas

They occur in:

in deep oceans,



Smyth and Moum, Oceanography, 2012

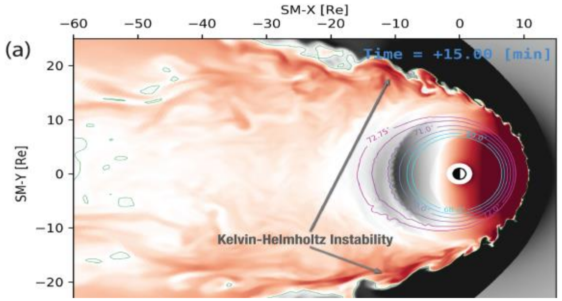
throughout the atmosphere,

Wikipedia

on other planets,

NASA/JPL-Caltech/SwRI/MSSS/Kevin M. Gill

in the magnetosphere

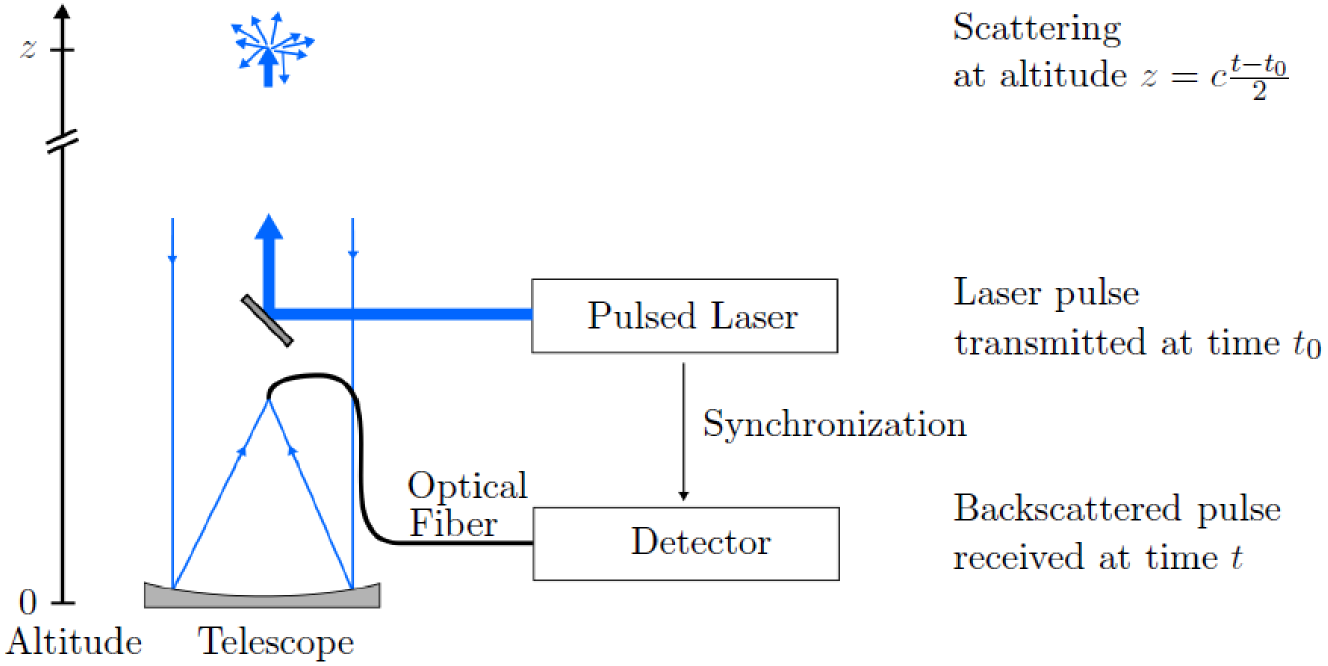


Sorathia et al., GRL, 2020

Outline

- How do atmospheric LiDARs work?
- What are atmospheric gravity waves and why are they important?
- What can we learn from LiDAR measurements of gravity waves in remote places?

The LiDAR Principle

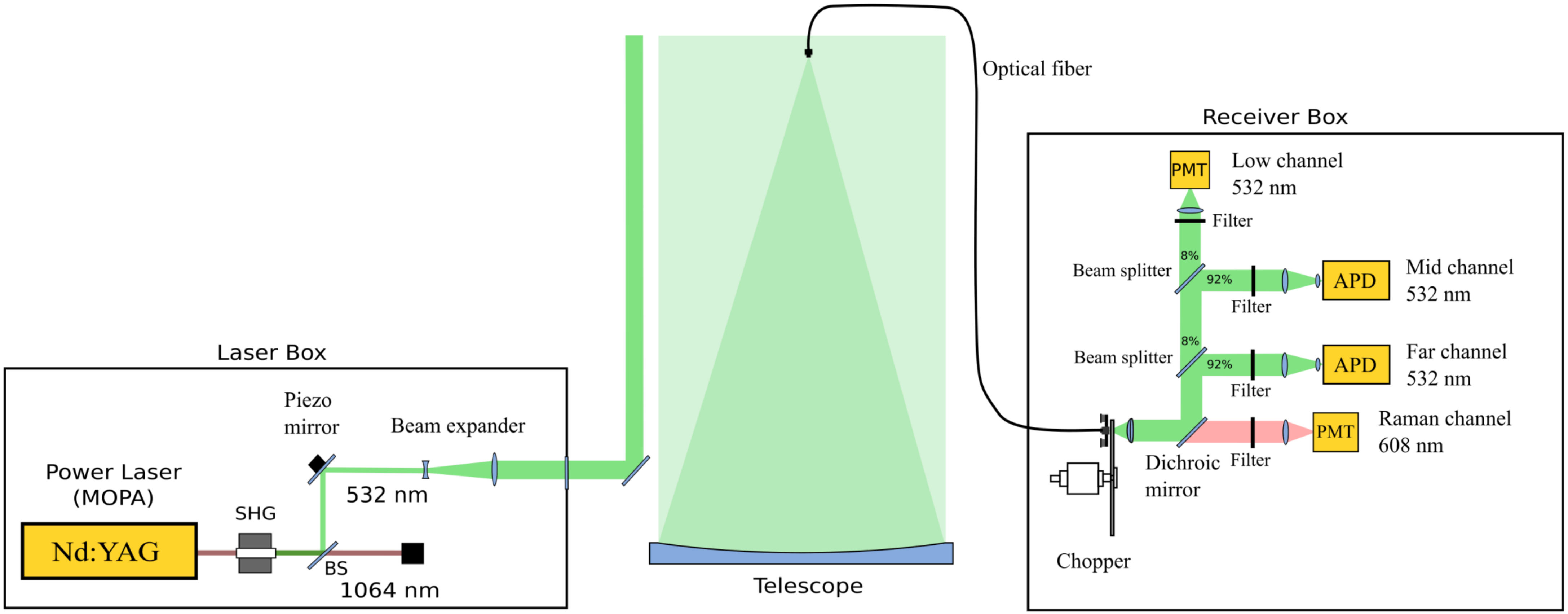


Received power:

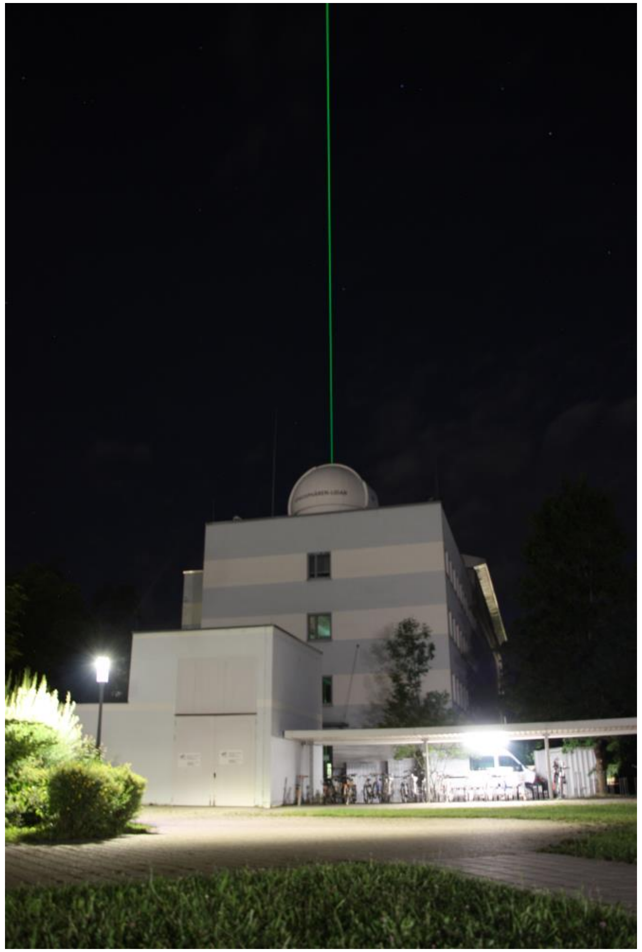
$$P(z,\lambda) = C\,\frac{1}{z^2}\,\beta(z,\lambda)\,T(z,\lambda)$$

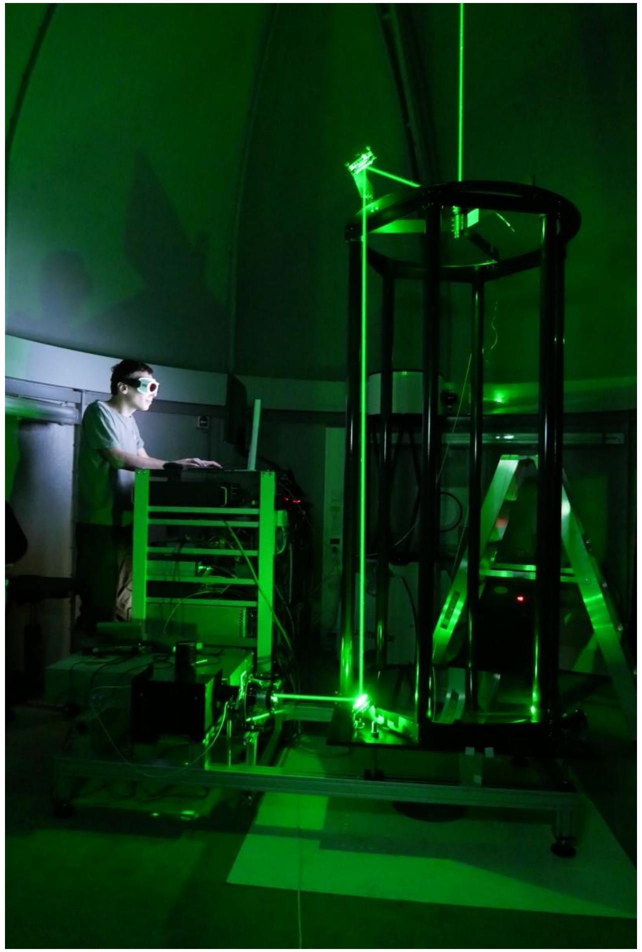
Volume backscatter coefficient
Proportional to air density

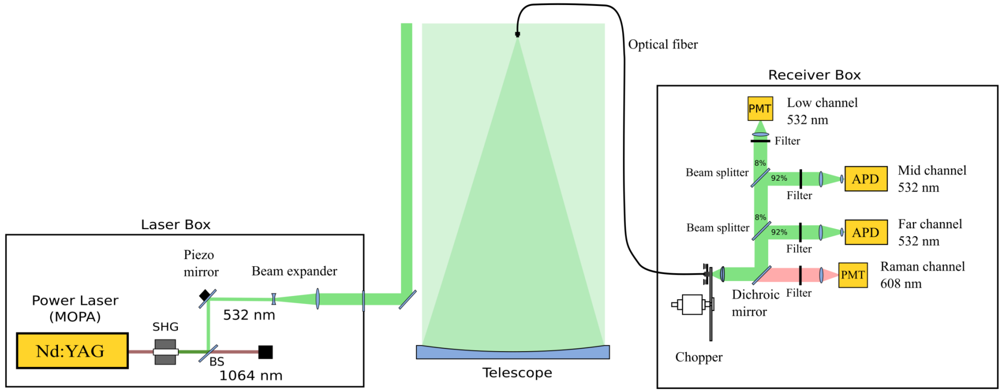
A Typical Rayleigh LiDAR Setup



A Typical Rayleigh LIDAR Setup



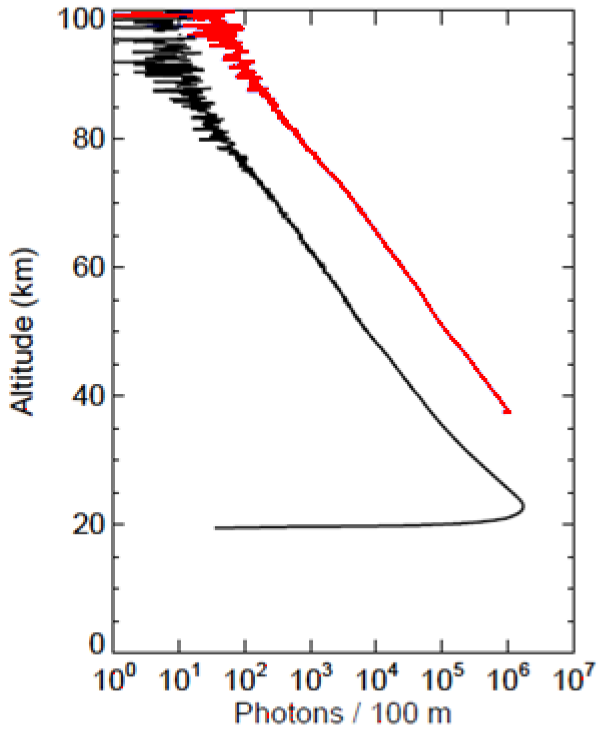




Retrieval of Atmospheric Temperature

Measurement

Photon counts



Data Processing

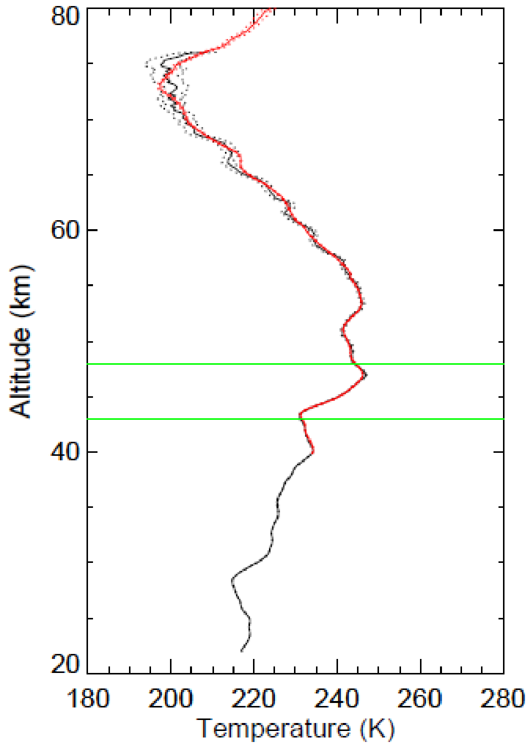
- Photon counts are proportional to density
- Atmosphere is in hydrostatic equilibrium
- Ideal gas law
- Temperature T_0 at top of profile is estimated

Integration of photon count profiles from top z_0 to bottom z:

$$T(z) = \frac{S(z_0)}{S(z)} T_0 + \frac{M}{k_B} \int_{z_0}^{z} \frac{S(z')}{S(z)} g(z')\, \mathrm{d}z$$

Data Product

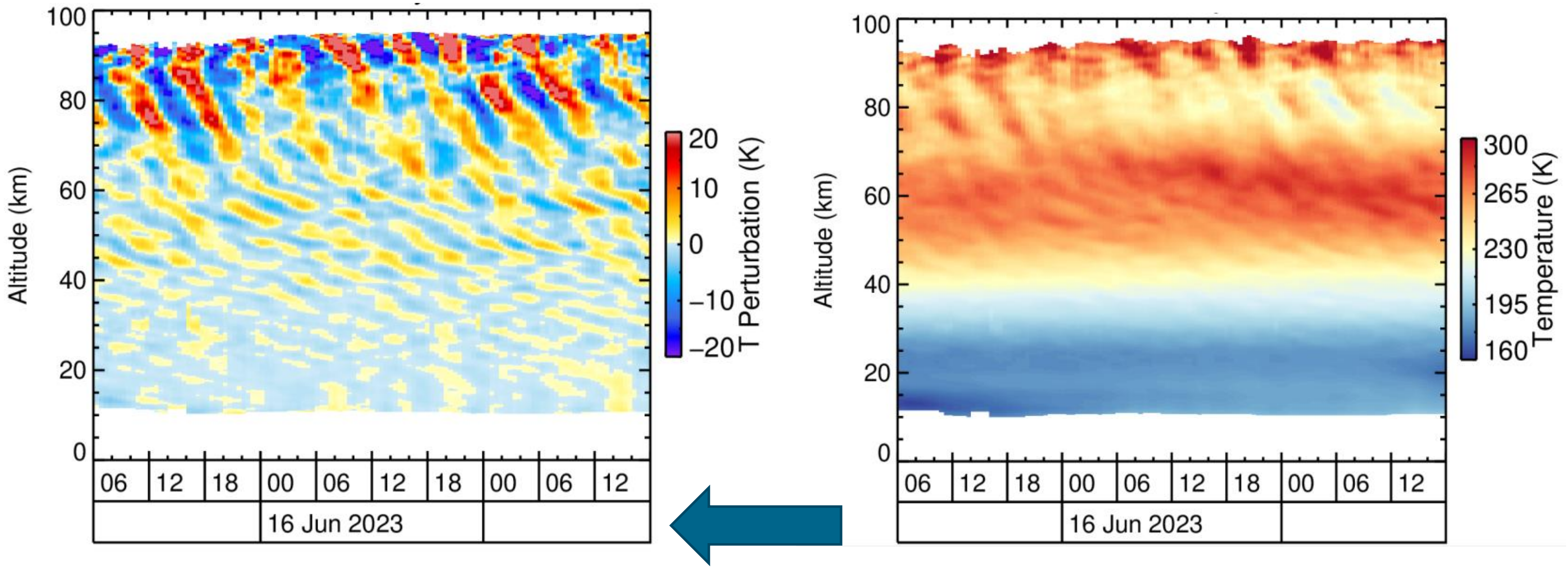
Temperature profiles



Example: Temperature Observations at South Pole

Temperature anomalies

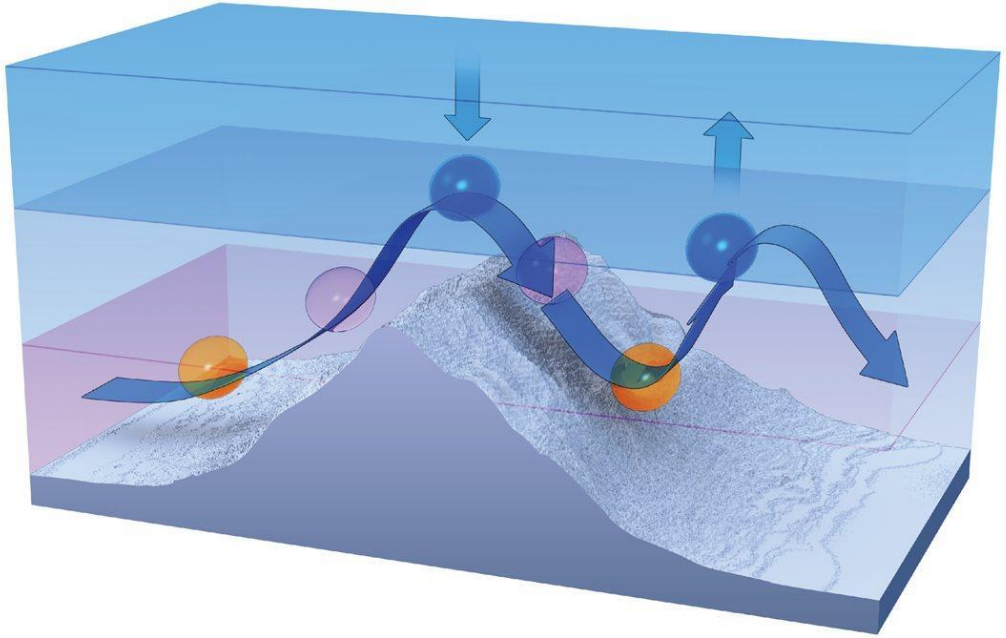
Temperature profiles



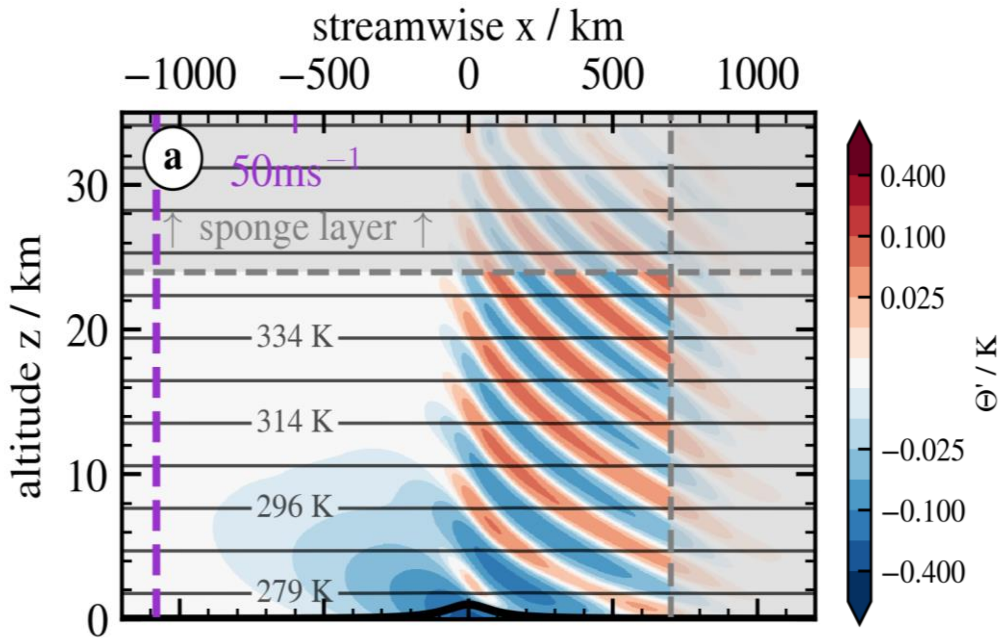
Spectral filtering

What are Atmospheric Gravity Waves?

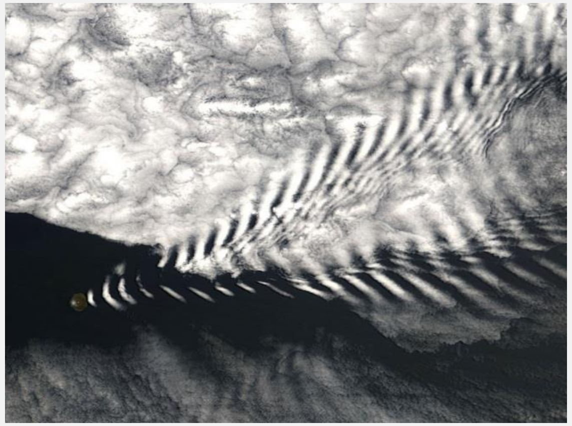
Wind



Source: weather.gov/Jack Williams



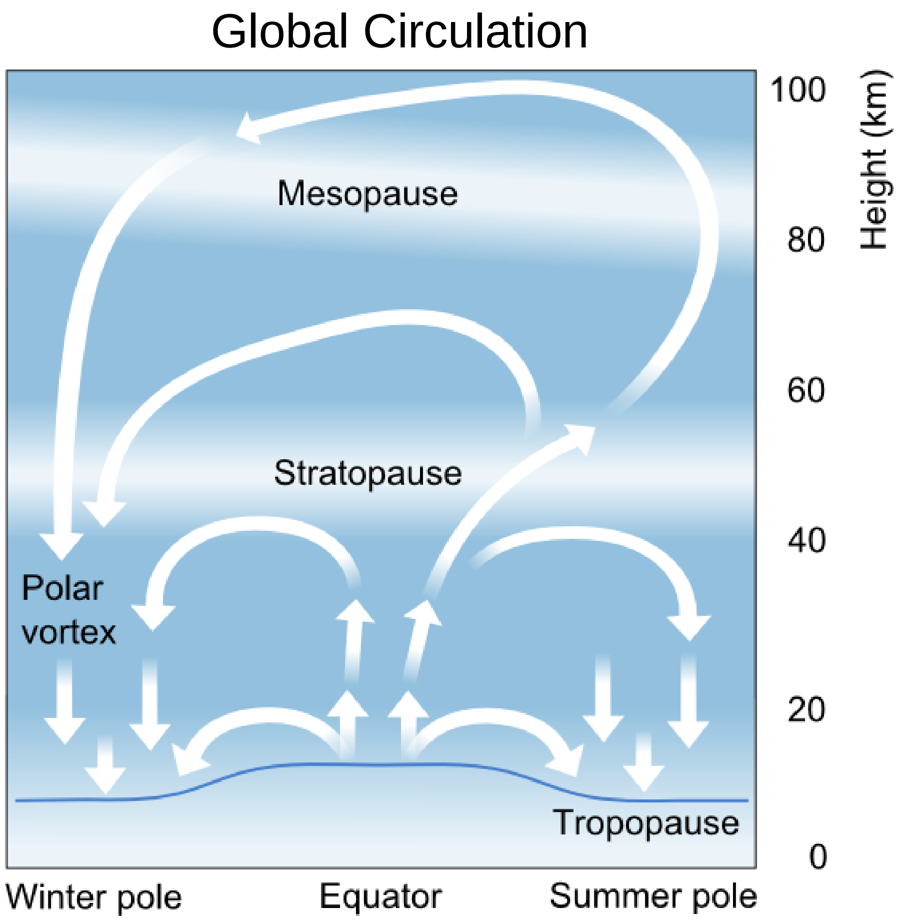
Idealized numeric



Amsterdam Island NASA

- Air parcels are pushed out of the equilibrium position
- The restoring force is the force of gravity (hence the name)
- Oscillations around the equilibrium position are excited
- These oscillations propagate: waves are formed

… and why are Gravity Waves important?



- Gravity waves carry energy and momentum
- Conservation of energy: wave amplitudes increase with increasing height due to the decreasing air density

$$E = \frac{1}{2}\rho\left(\overline{u'^2} + \overline{v'^2}\right) \propto \overline{T'^2}$$

- Large amplitudes lead to instabilities, breakdown and dissipation of waves

Overturning ocean wave
Source: Wikipedia/NOAA

- Momentum carried by waves is transferred to the mean flow
- The resulting force drives the wind system

Outline

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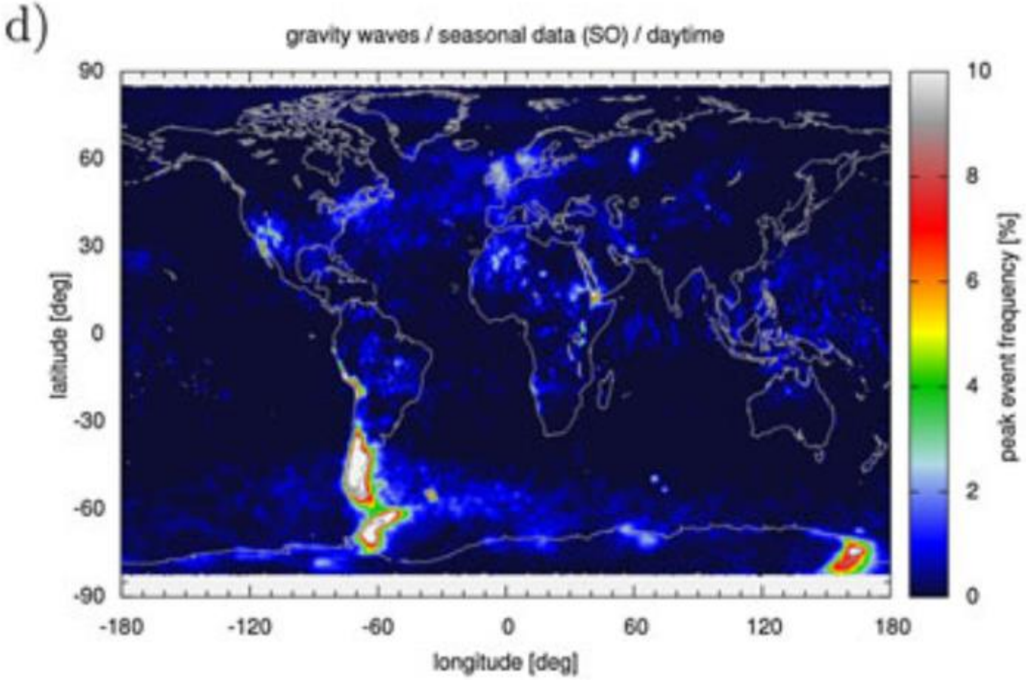
The Southern Andes – A Gravity Wave Hotspot

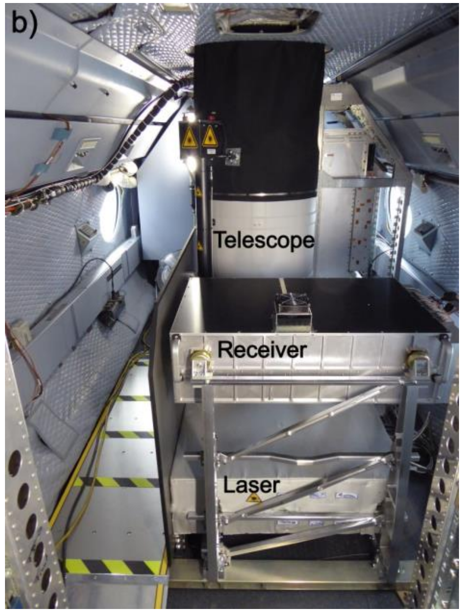
Global distribution of gravity wave event frequency in the stratosphere (September and October)

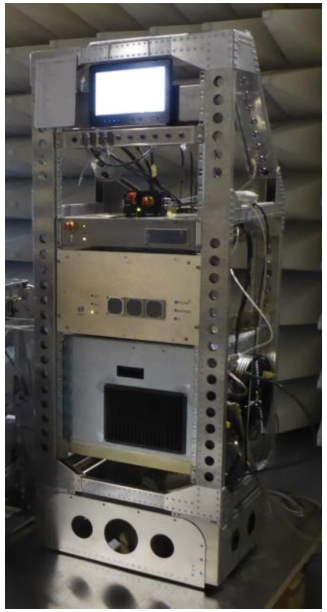


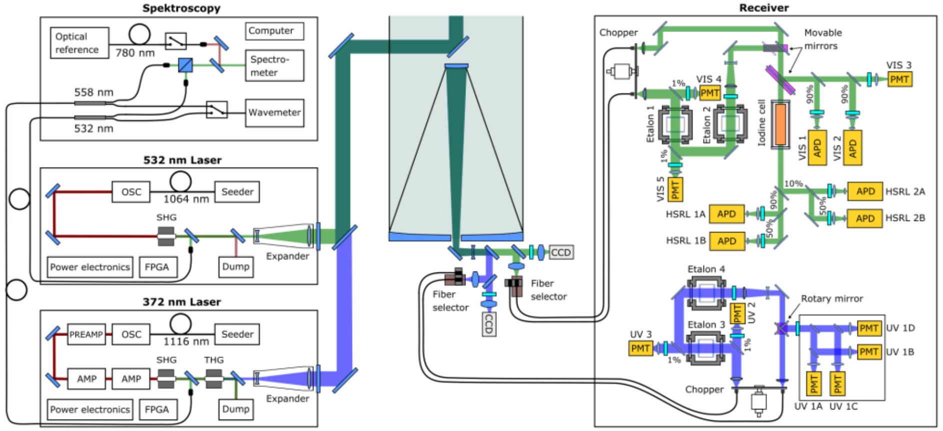
Hoffmann et al. (2013), *J. Geophys. Res. Atmos.* doi:10.1029/2012JD018658.

Airborne LiDAR Measurements

The HALO research aircraft with the laser beam emitted by the ALIMA instrument

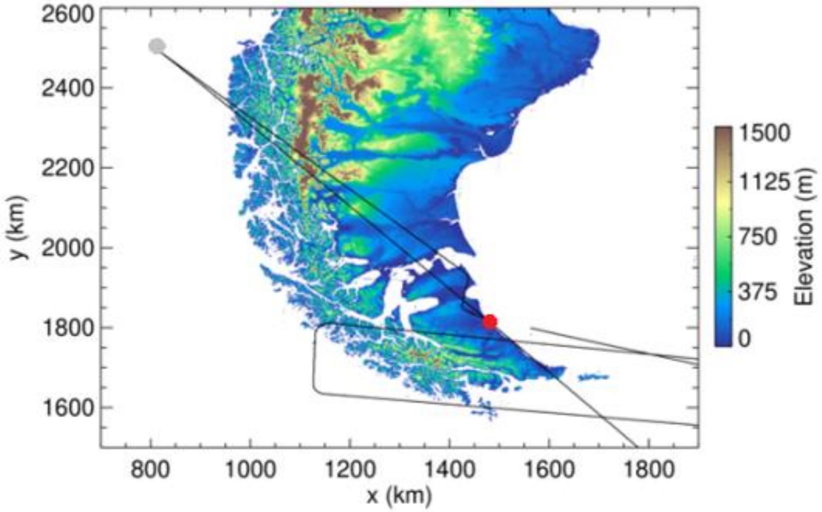




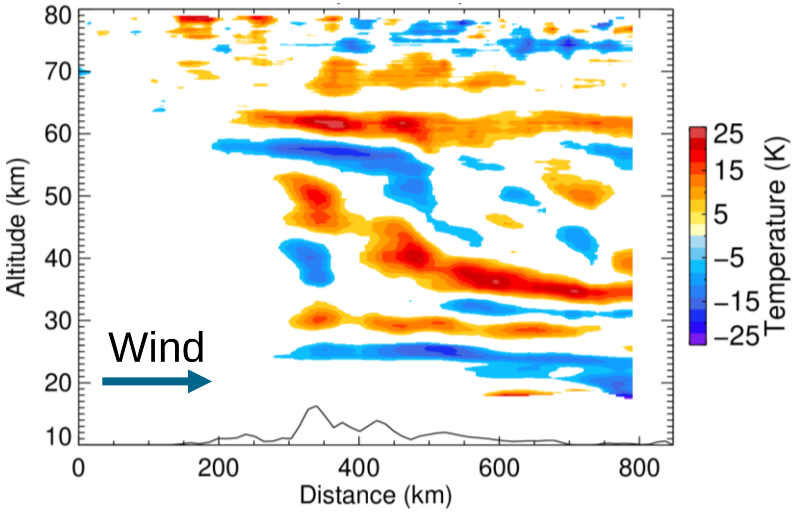


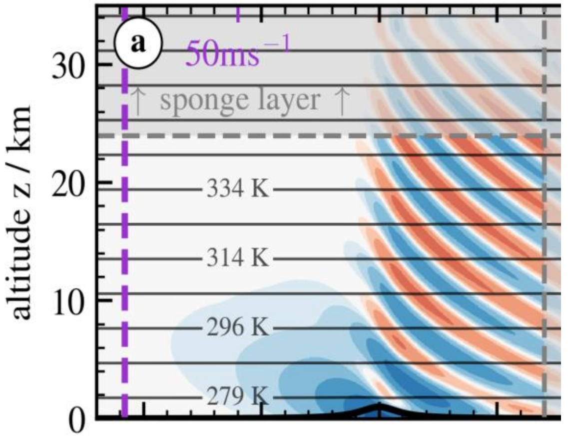
Mountain Waves above the Southern Andes

Topography with flight track



Temperature profiles with mean removed

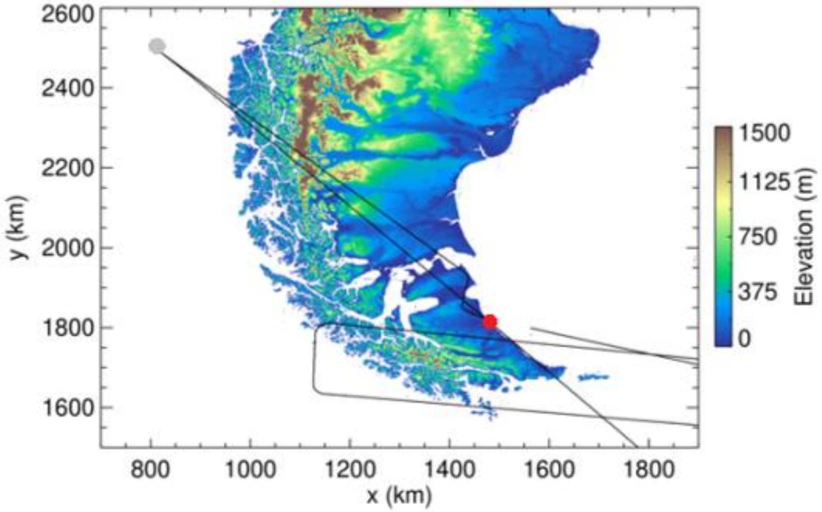




Mountain Waves above the Southern Andes

Spectral analysis

Topography with flight track



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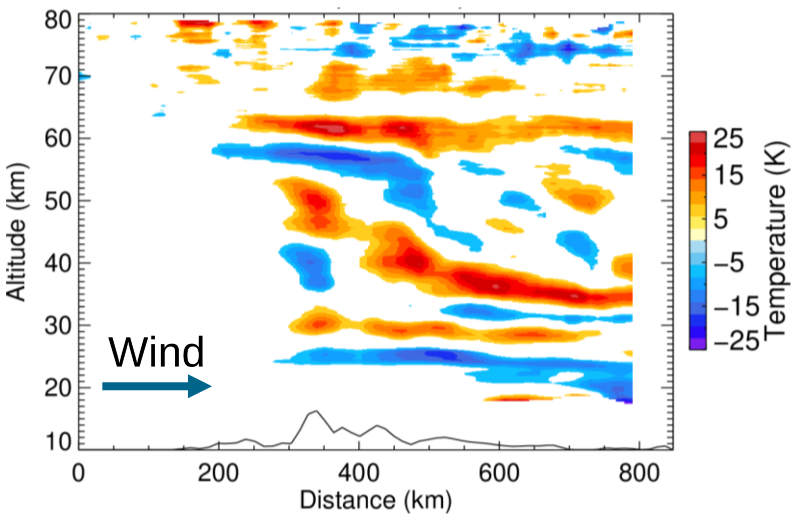
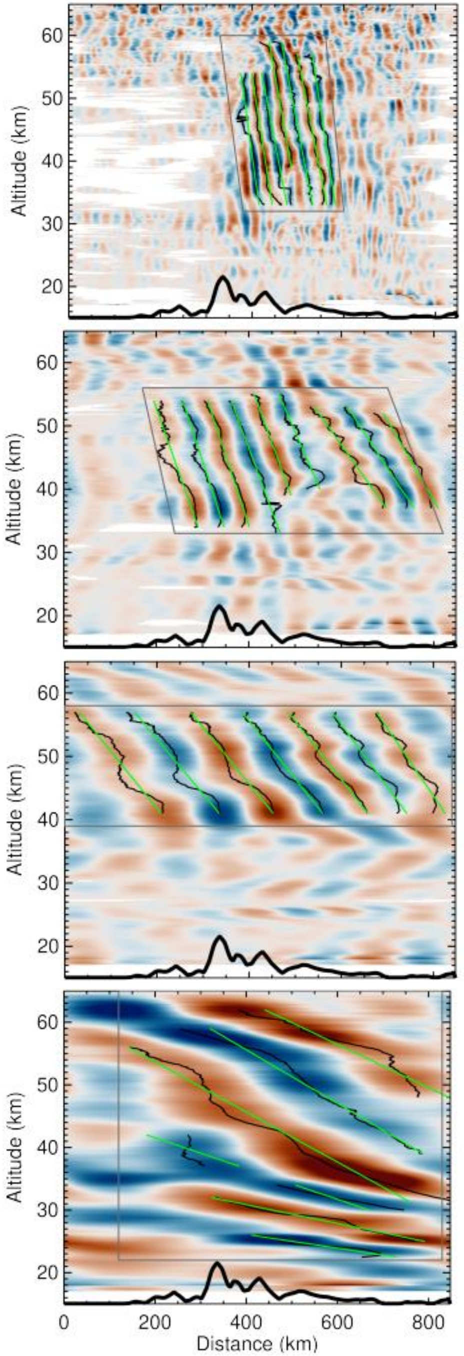
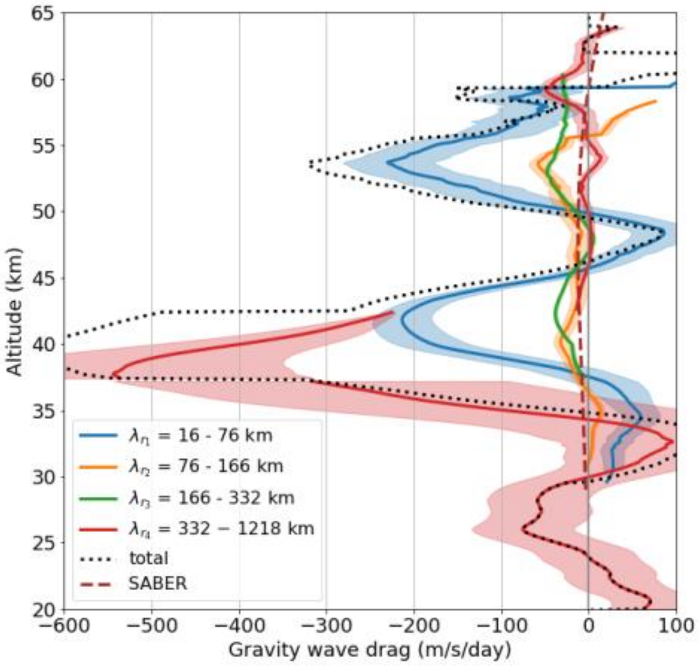




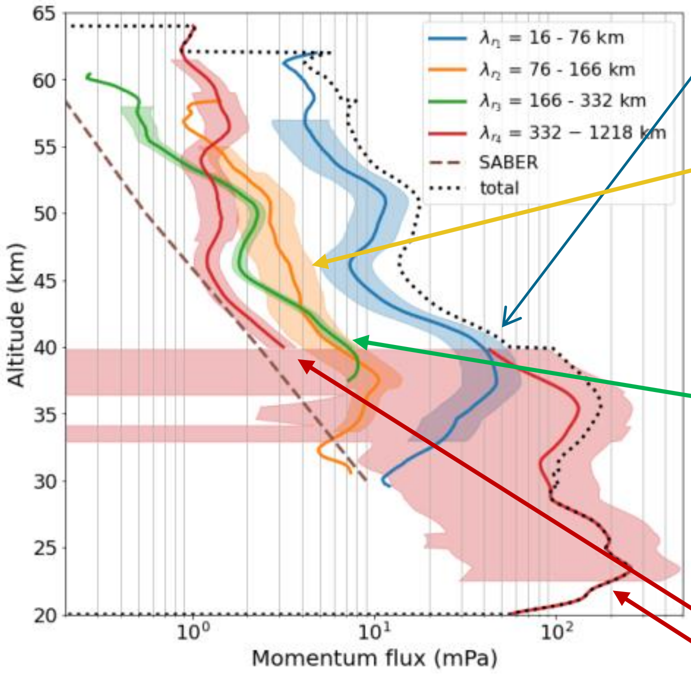
Manuscript in preparation

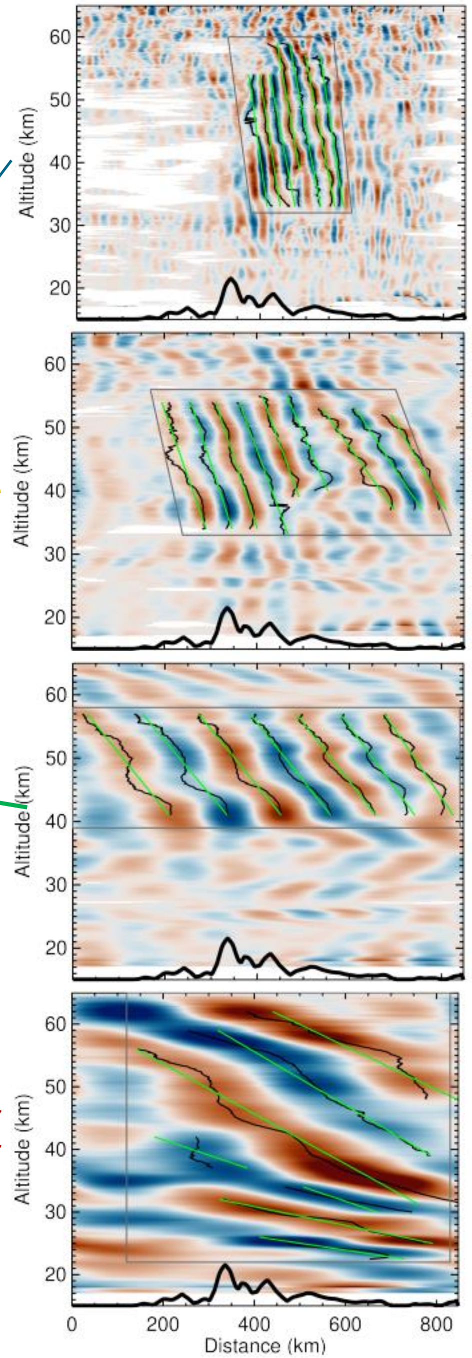
Mountain Waves above the Southern Andes

Gravity wave drag (force)



Gravity wave momentum flux





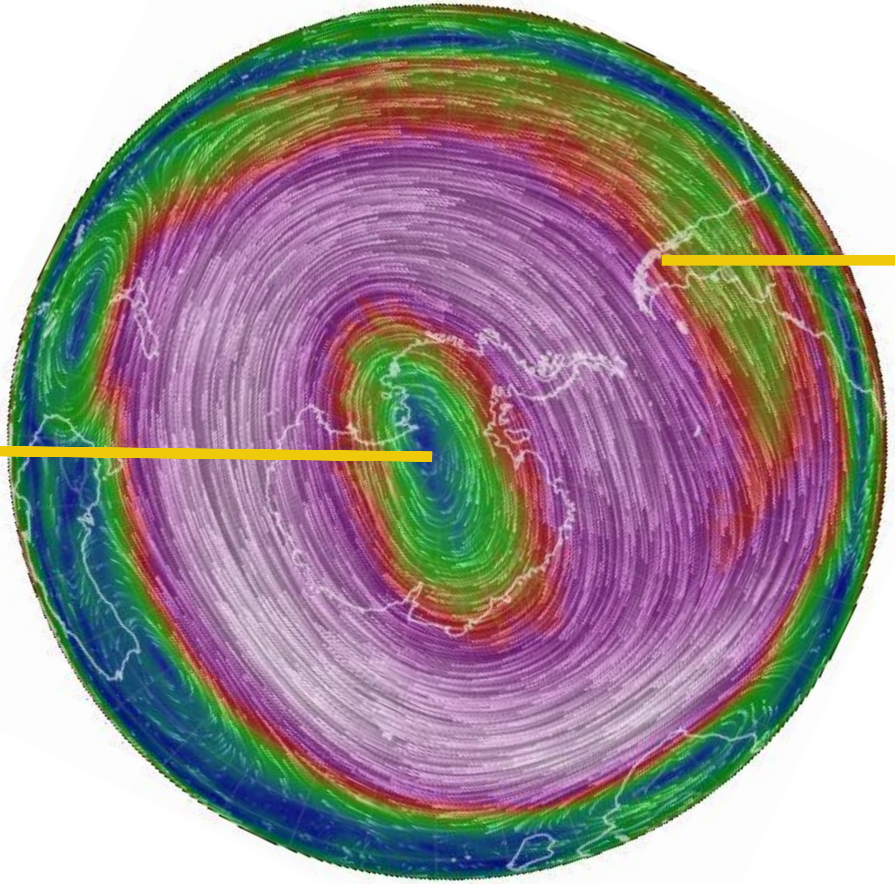
Manuscript in preparation

A place far away from local gravity wave sources: South Pole

South Pole

- Smooth ice plateau
- Low wind speed

=> **No gravity waves?**



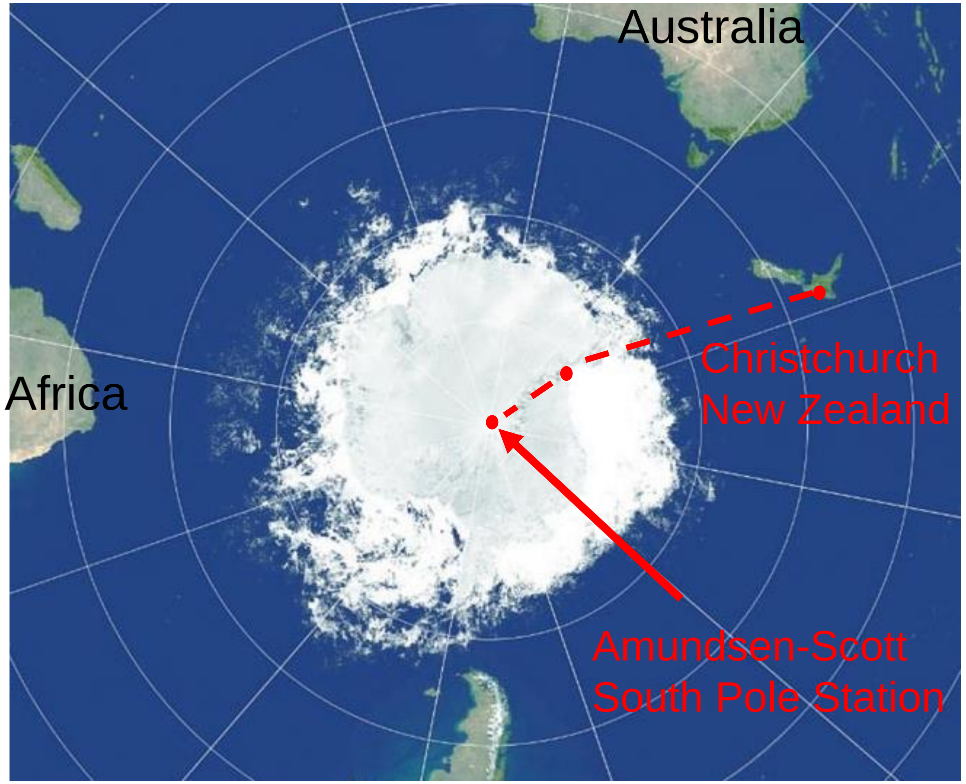
Wind at 10 hPa, 15 June 2023
GFS / NCEP / US National Weather Service

Southern Andes

- High mountains
- Strong winds

=> **Gravity Wave Hotspot**

Travelling to South Pole



South America

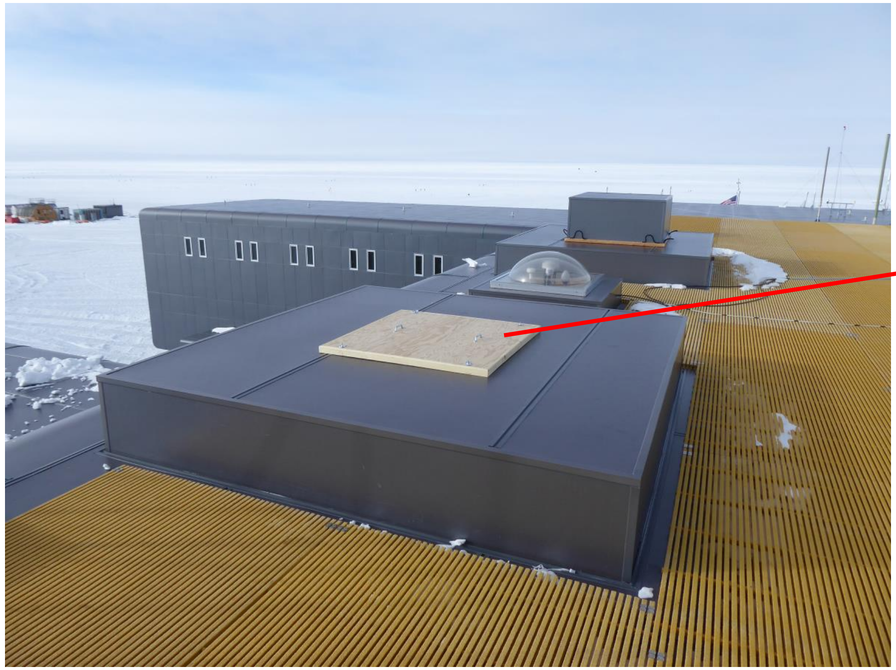
LC-130 Hercules
Ski-equipped aircraft

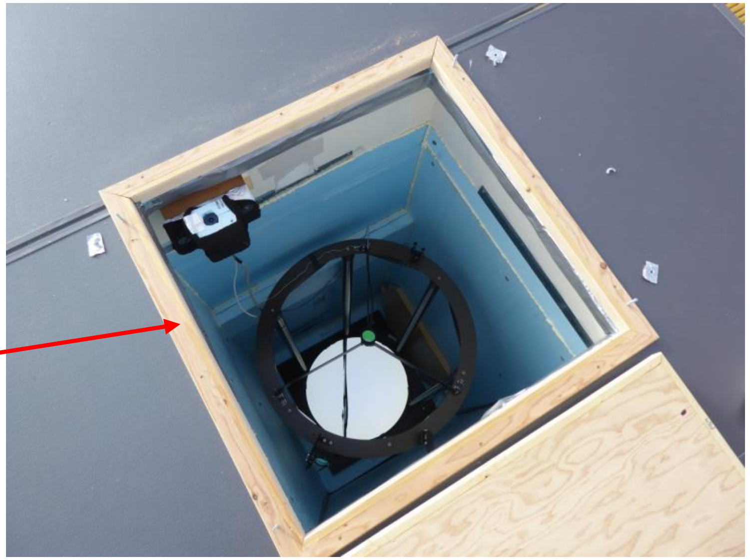
At the Pole

Arriving at South Pole Station

It is flat in every direction

The LiDAR Instrument





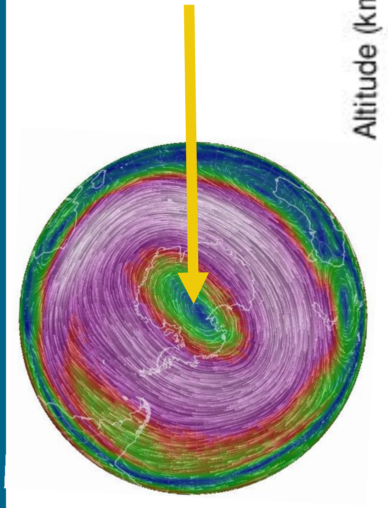
View of the telescope

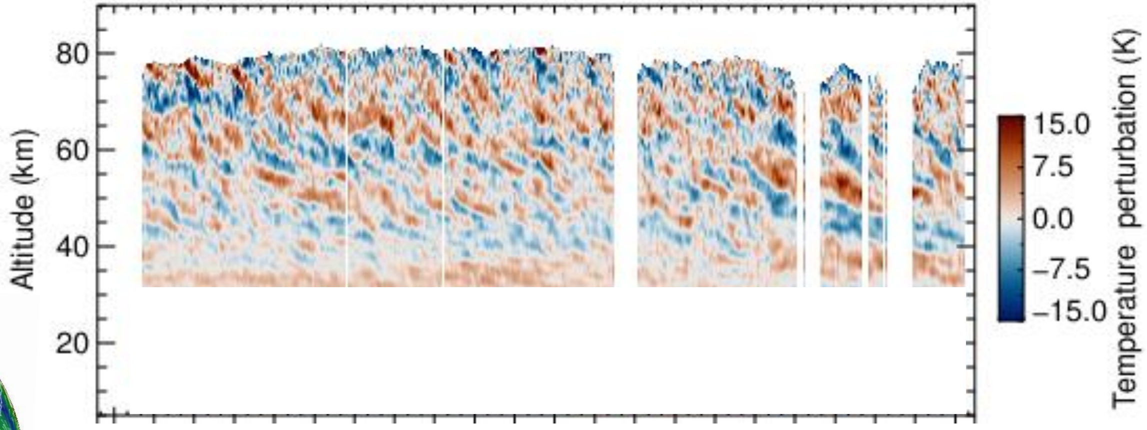
In the lab below:

Insulated box houses the telescope

Gravity Waves at South Pole

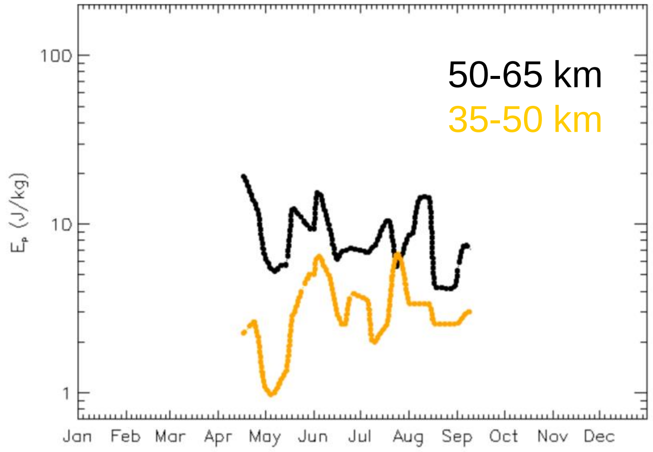
South Pole





15 – 20 June 2023

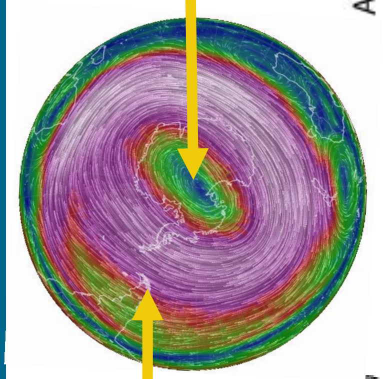
Gravity wave potential energy density



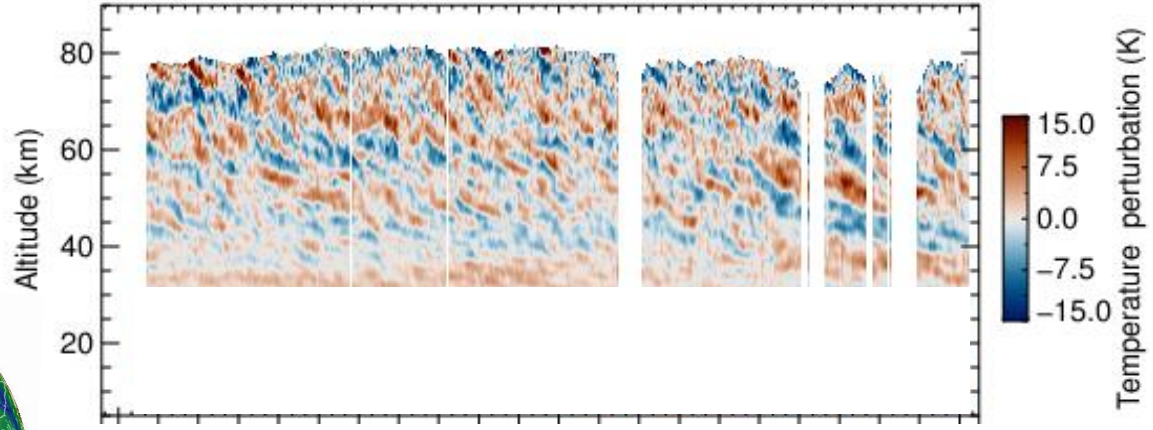
Gravity Waves at South Pole and the Southern Andes

Gravity wave potential energy density

South Pole



Southern Andes



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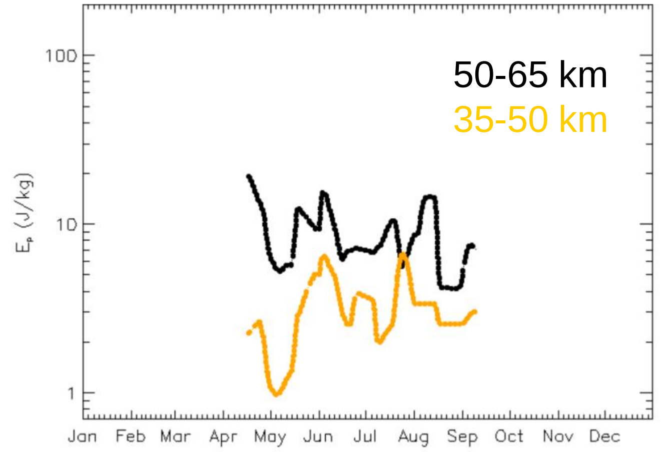

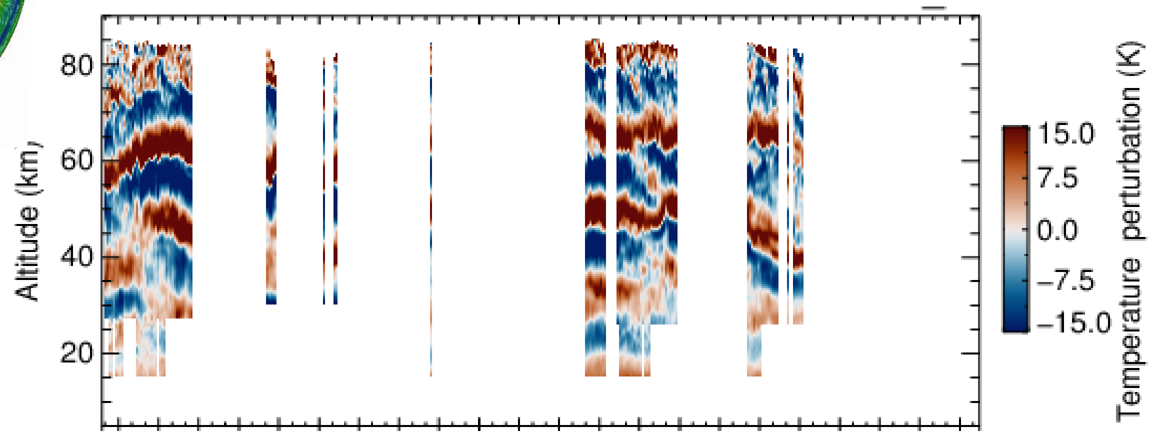

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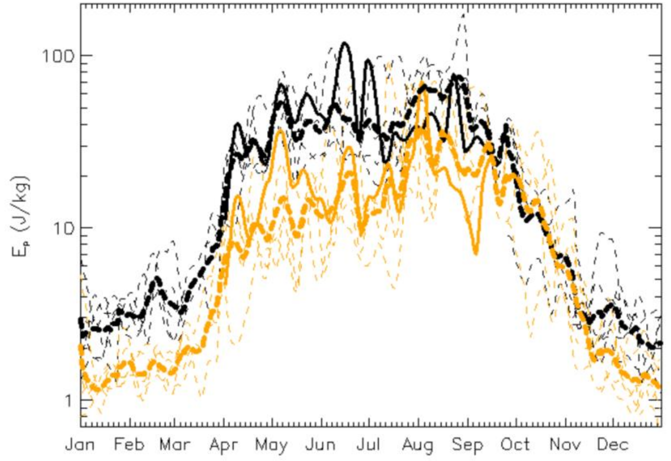
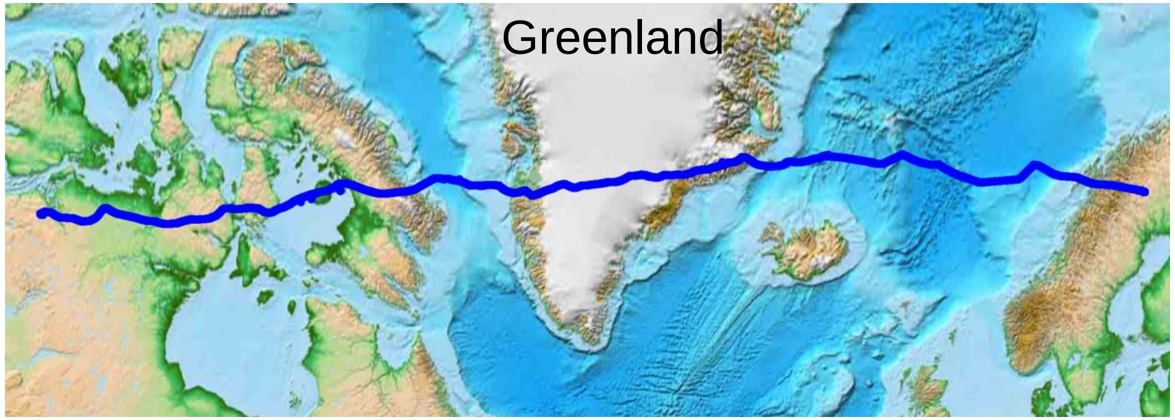
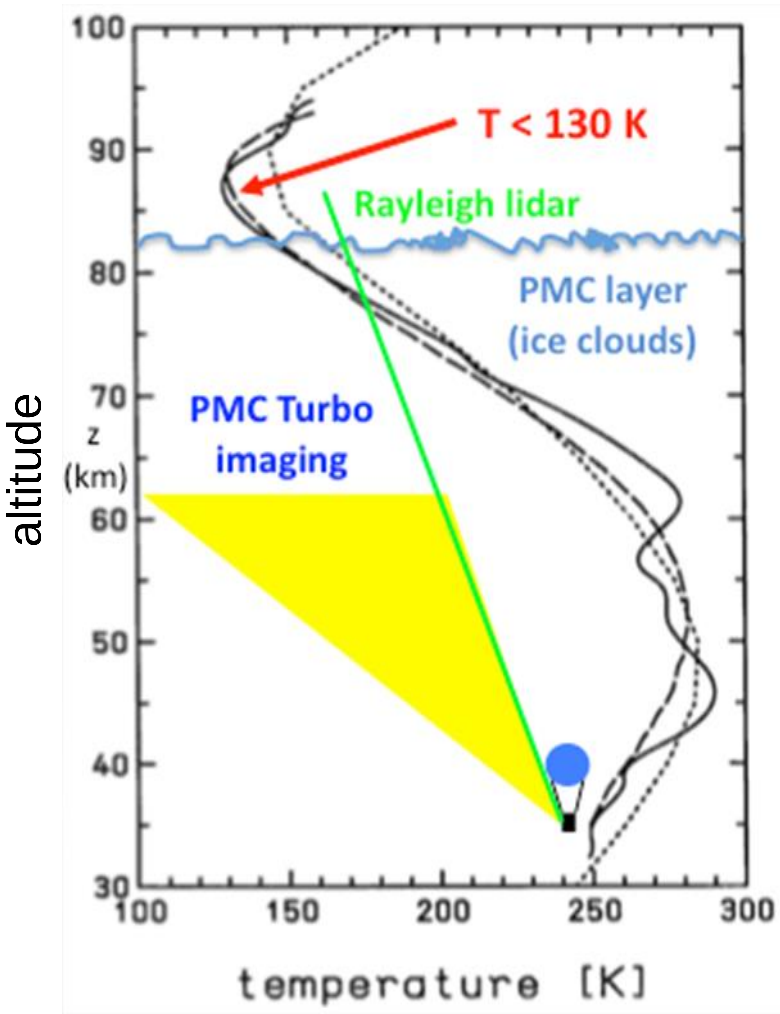


PMC Turbo: A Balloon Mission to Study Wave Instabilities

6 day flight from Scandinavia to Canada in July 2018





The LiDAR on board the PMC Turbo Gondola

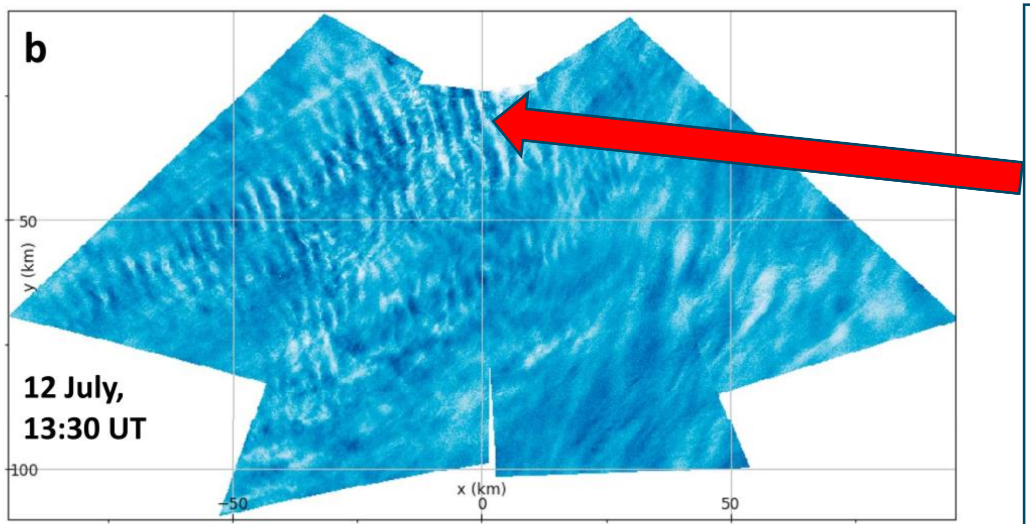
Kaifler et al. (2020), Atmos. Meas. Tech.

Launch of PMC Turbo

In flight picture (38 km altitude) of the telescope

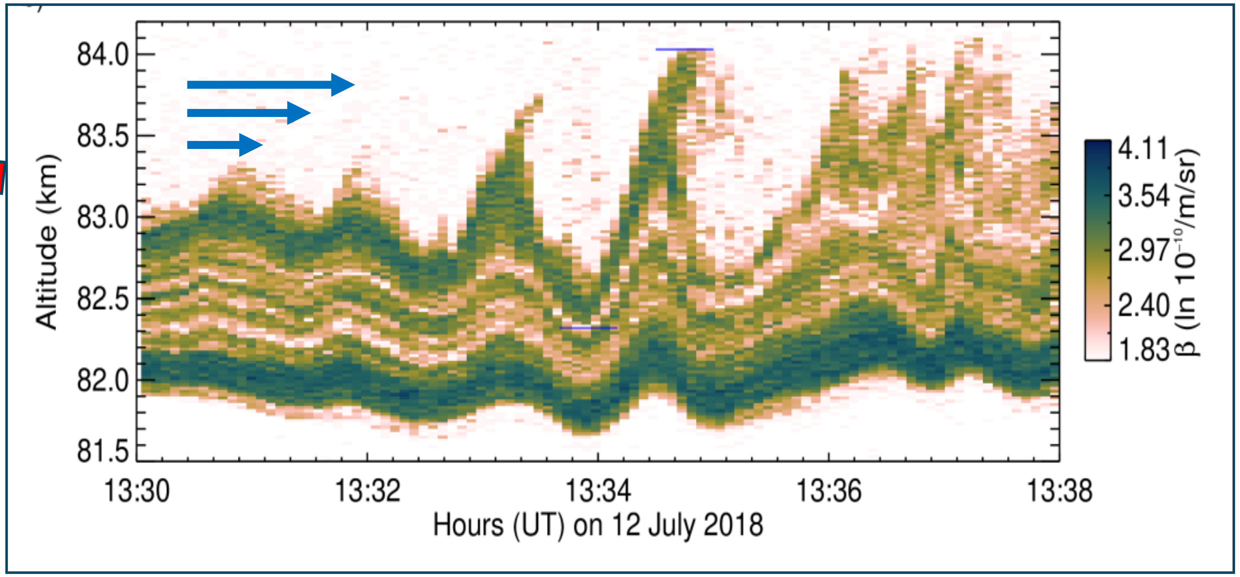
Kelvin-Helmholtz Instability

Wide-field camera composite



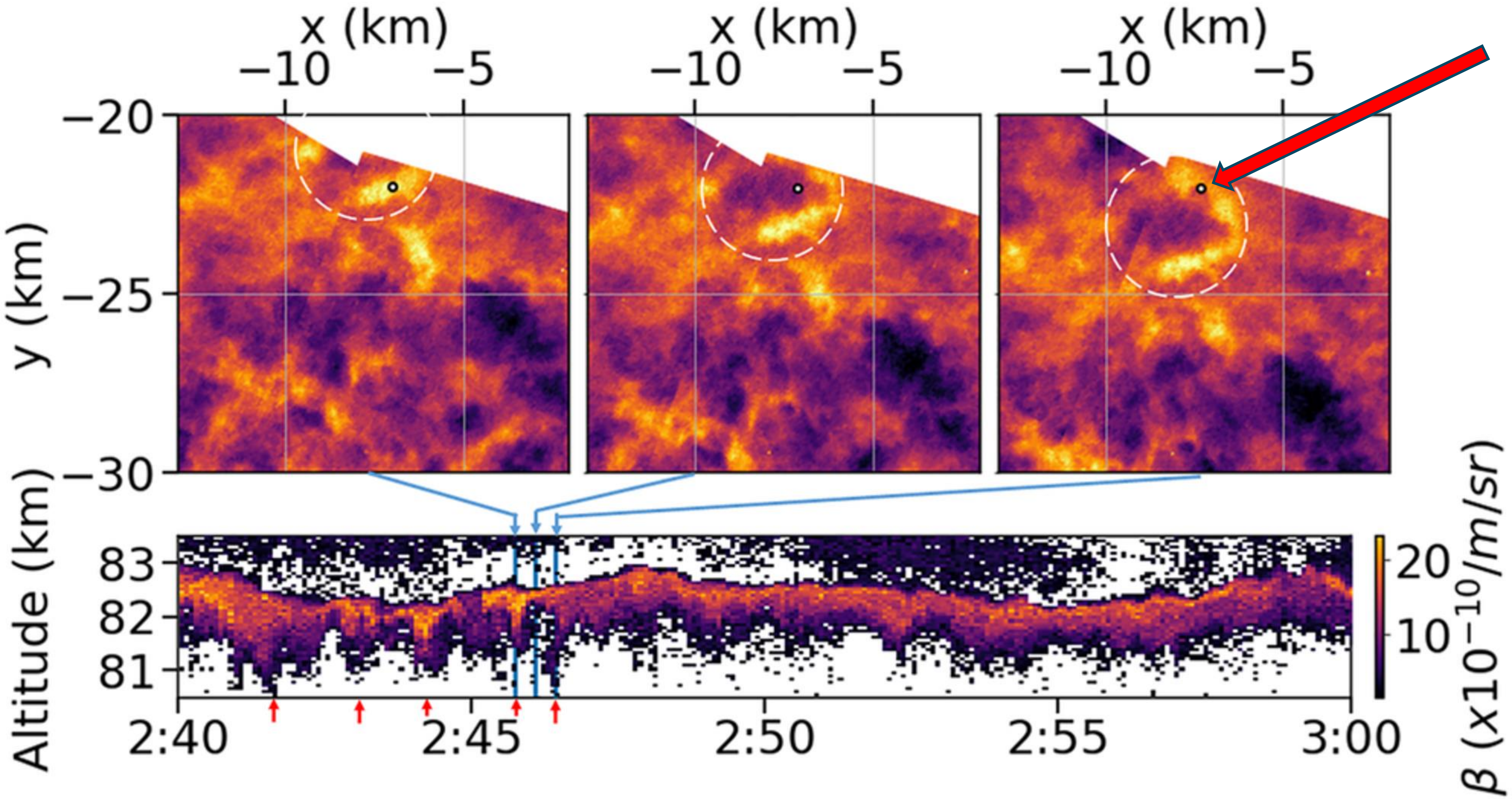
Fritts et al. (2019). *J. Geophys. Res. Atmos.*
https://doi.org/10.1029/2019JD030298

Vertical profiling by LiDAR



- Strong vertical gradient of the horizontal wind
- Initial perturbation due to gravity waves
- Bernoulli effect lifts crests up

3-D Structure of Vortex Rings



Position of LiDAR beam

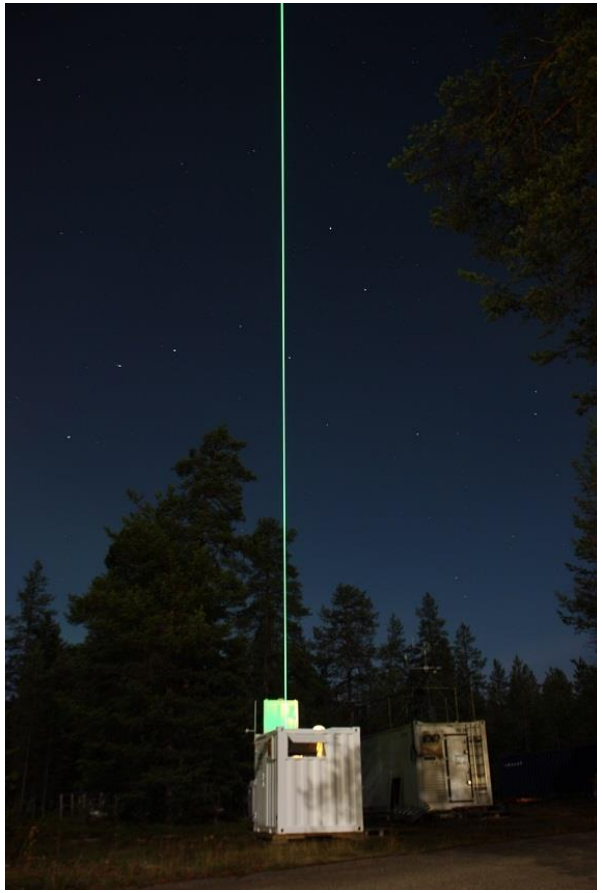
Imaging: x and y

Lidar profiling: z

Geach et al. (2020). *J. Geophys. Res. Atmos.*
https://doi.org/10.1029/2020JD033038

How good are numerical weather prediction models in predicting gravity waves?

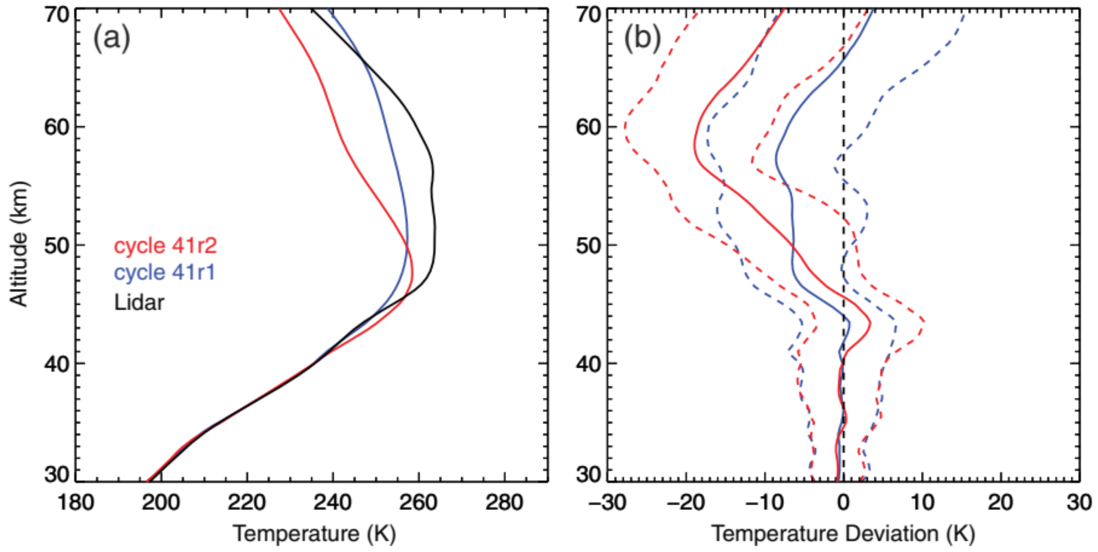
Source: Wikimedia



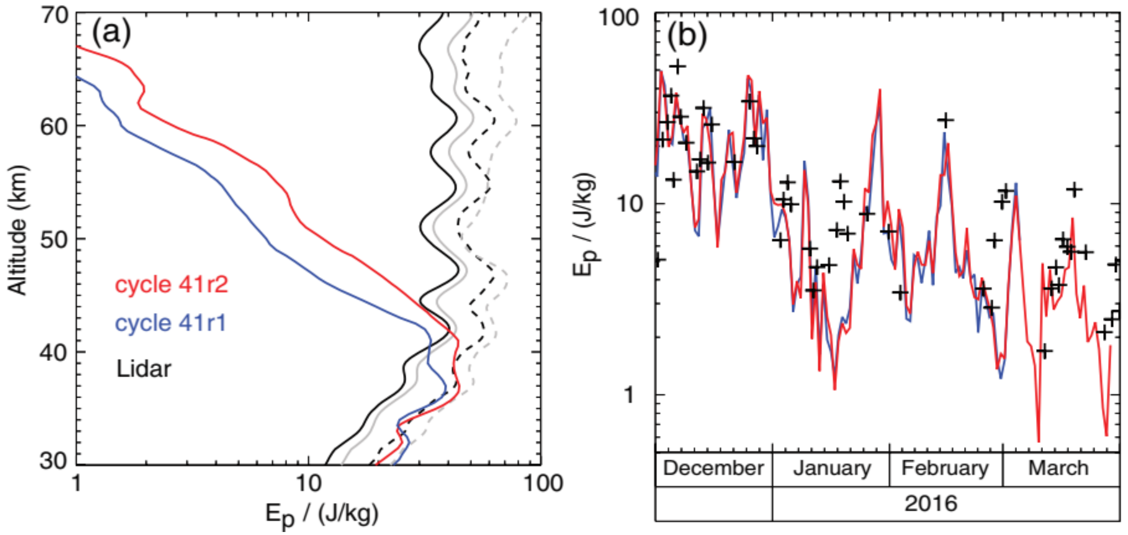
CORAL instrument at the
Finnish Meteorological Institute

Comparison with the Integrated Forecast System of the European Centre for Medium-Range Weather Forecasts

Temperature



Gravity Wave Potential Energy Density



Ehard et al. Q J R Meteorol Soc. 2018; https://doi.org/10.1002/qj.3206

Summary and Conclusions

- LiDAR is a valuable tool for studying atmospheric dynamics
- Investigating the upper mesosphere (75-90 km altitude) opens a unique „window on small-scale dynamics“
- More research is needed as numerical weather prediction and climate models still lack proper treatment of the effects of atmospheric gravity waves
- The work presented here is a team effort by many people

Michael Binder
Tanja Bodenbach
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Andreas Dörnbrack
Benedikt Ehard
Sonja Gisinger
Natalie Kaifler

Markus Rapp
Robert Reichert
Dimitry Rempel
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The PMC Turbo Team
The SouthTRAC Team