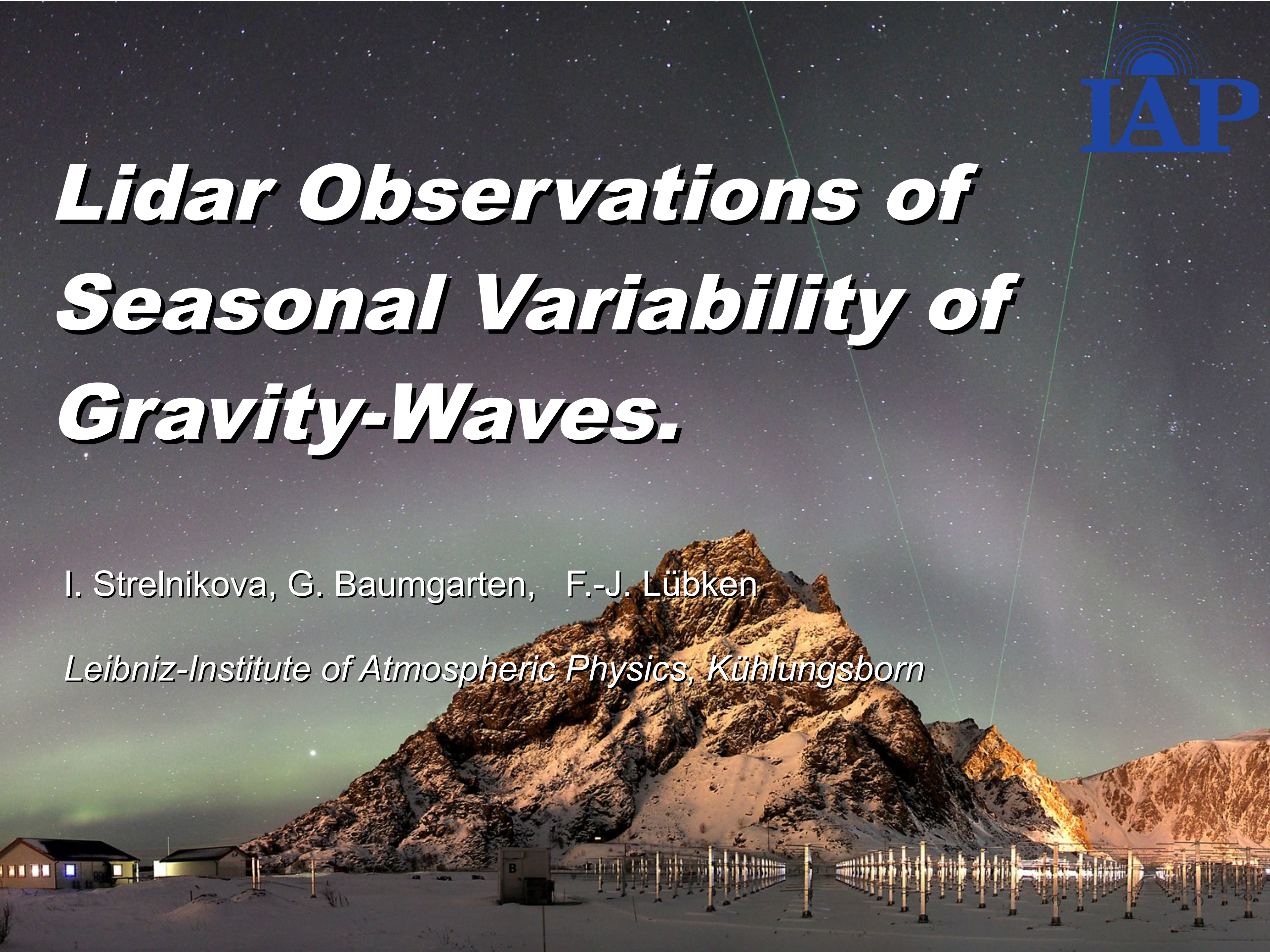

Lidar Observations of Seasonal Variability of Gravity-Waves.

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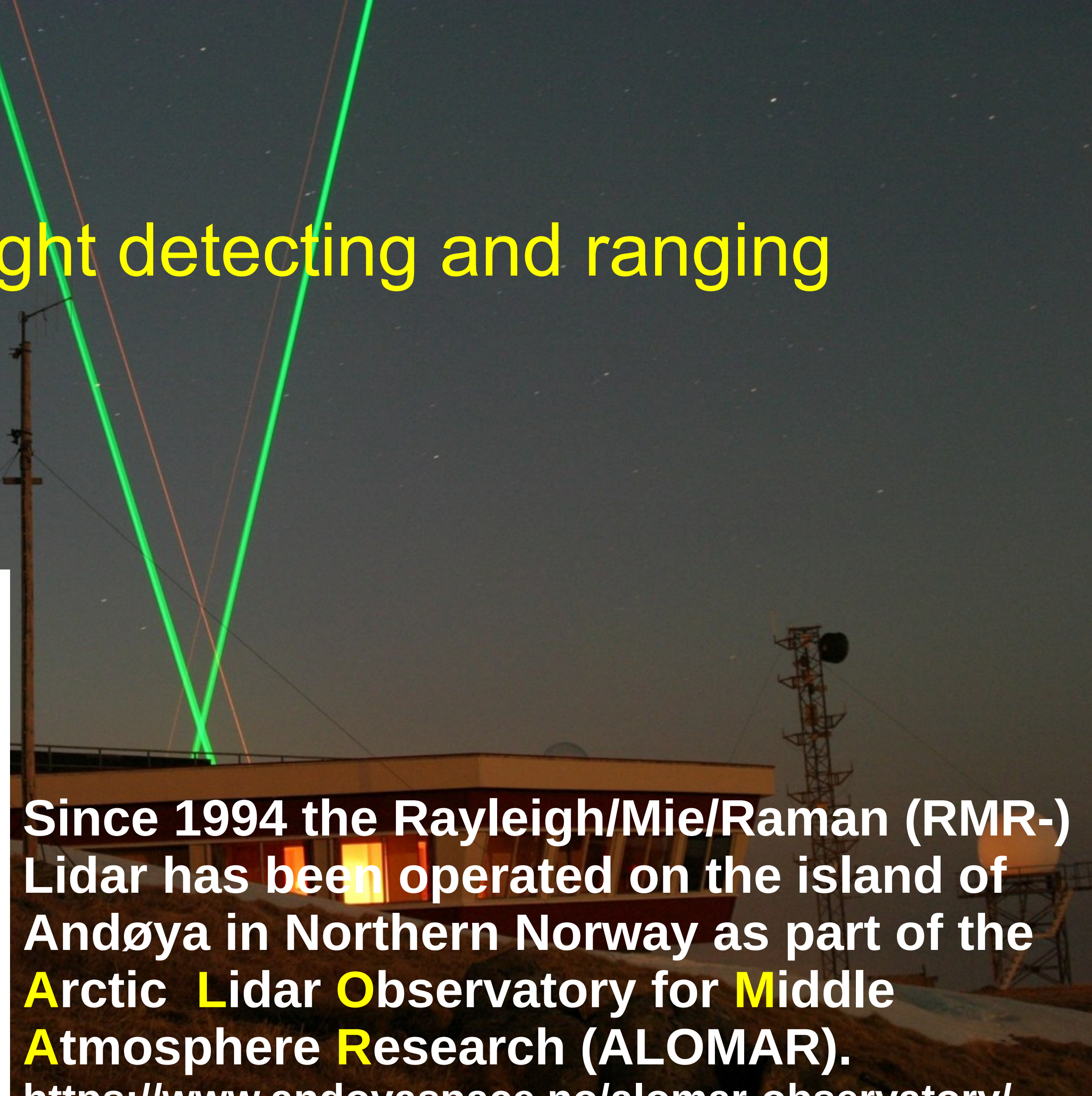
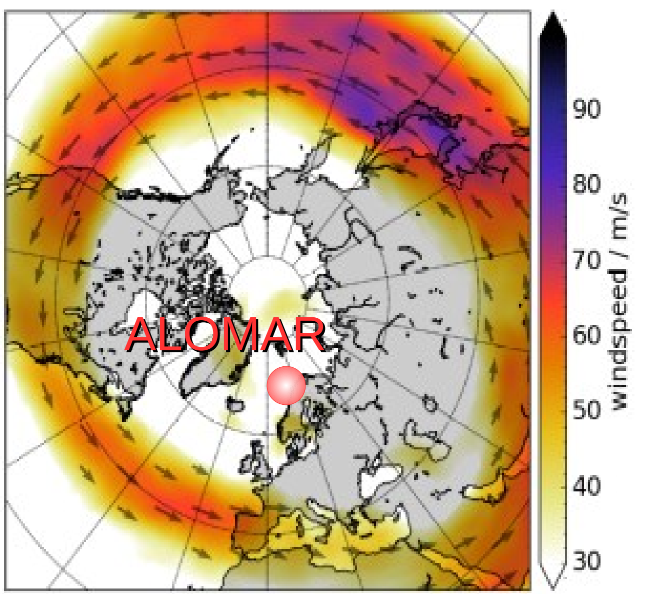
Lidar – Light detecting and ranging



(69.3^{0}N, 16.0^0 E)



Since 1994 the Rayleigh/Mie/Raman (RMR-) Lidar has been operated on the island of Andøya in Northern Norway as part of the Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR).

https://www.andoyaspace.no/alomar-observatory/

GW potential energy density:

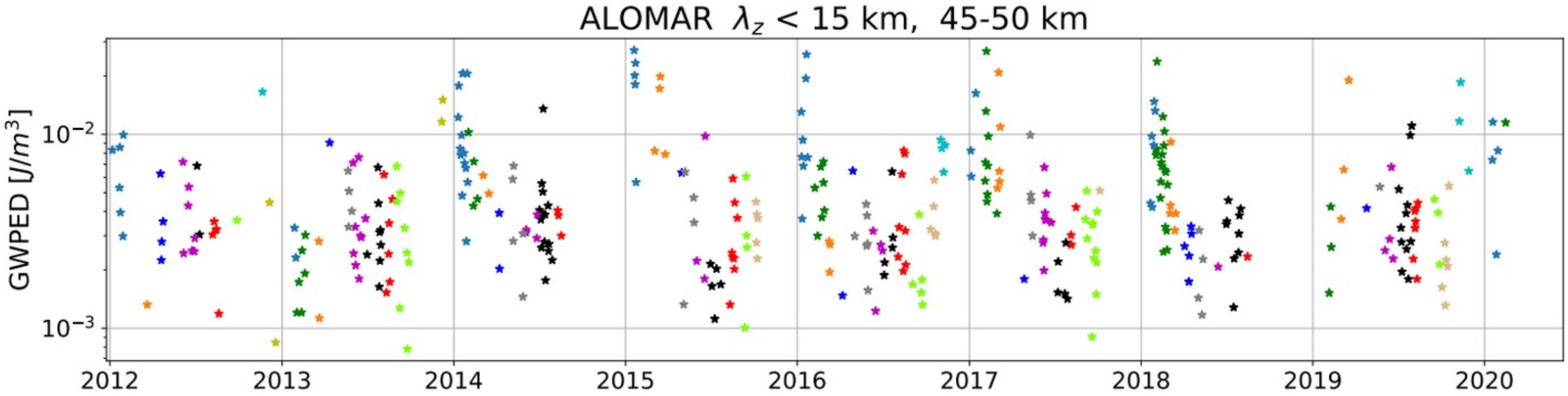
Mesured lidar temperature data contain tidal and GW perturbations on top of a background that contains only slow variations, such as the seasonal cycle or planetary waves. In order to extract temperature fluctuations due to GWs from lidar soundings the atmospheric background temperature has to be removed. For this purpose we use 3 methods: **1.** Temporal mean over a time span of the observation segment is subtracted from the measured temperature. **2.** Applying a high-pass filter with cut-off vertical wavelength $\boldsymbol{\lambda}_z$<15 km **3.** Applying a high-pass filter with cut-off period τ < 8 h.

From the obtained temperature fluctuations, the GW Potential Energy Density (GWPED) can be estimated:

$$E_{pV} = E_{pm} \cdot \bar{\rho} = \frac{1}{2}\frac{g^2}{N^2}\overline{\left(\frac{T'}{T_0}\right)^2}\bar{\rho}$$

g is the gravitational acceleration; T' and T_0 are residual and background temperature measurements, respectively; $\bar{\rho}$ is the daily average density profile of the atmosphere estimated from NRLMSISE-00 model. N is the Buoyancy frequency calculated from measured background temperatures.

Observations of GWPED in altitude range 45-50 km:

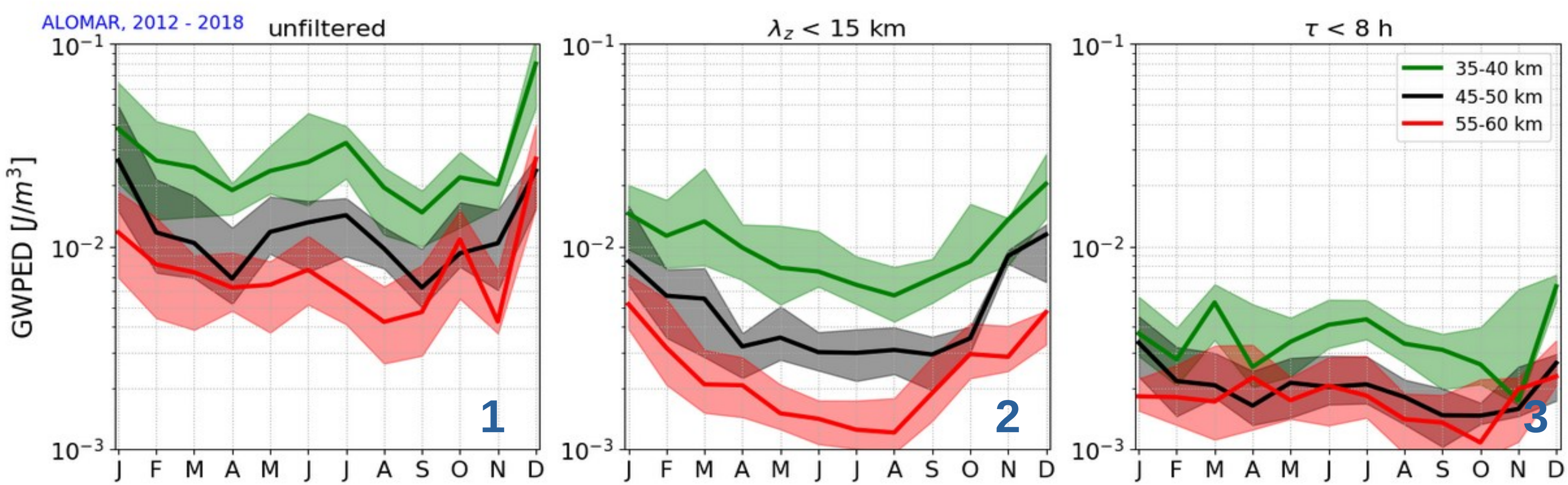


GW potential energy density:

Seasonal cycle of GWPED at ALOMAR at selected altitude ranges: 35-40 km (green), 45-50 km (black), and 55-60 km (red). Each panel represents method used for estimation of GWPED:
1. Unfiltered (left), **2.** Vertically filtered (middle) **3.** Temporally filtered (right).
Shaded regions show the standard deviations.
First 2 methods (panels **1** & **2**) show annual variability with maxima in winter and minimum in summer. The annual variability is very pronounced in vertically filtered data (**2**) and almost absent in temporally filtered data (**3**).

5044 h used:

Seasonal Variability of GWPED:

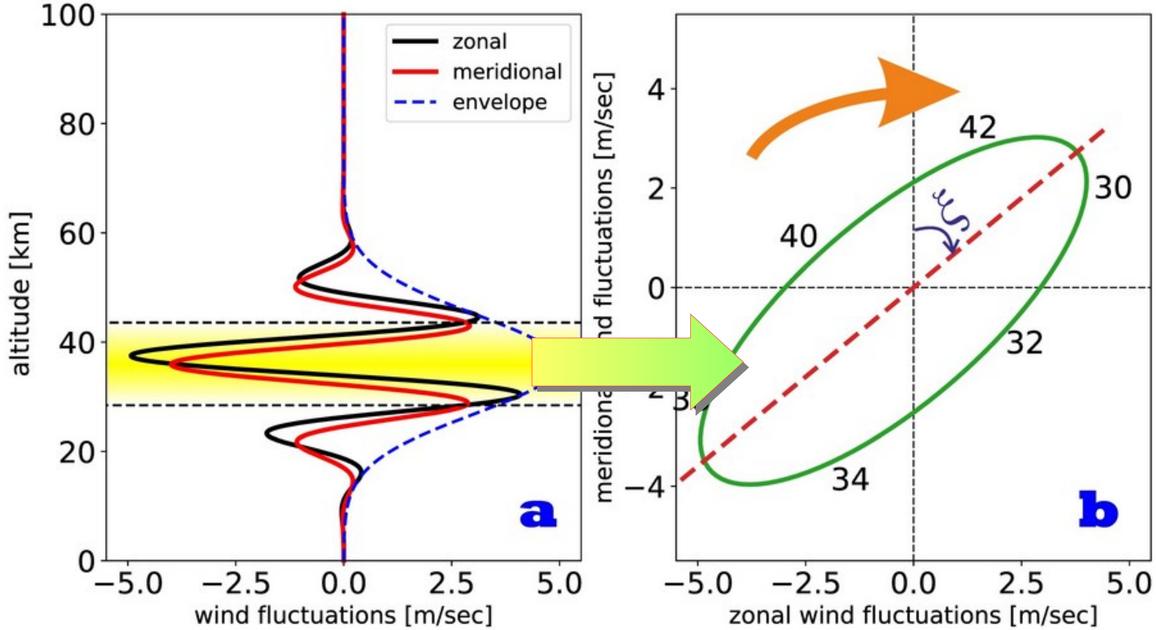


Hodograph: howto

For more detailed investigation of summer/winter difference, we apply Hodograph method (see details in *https://doi.org/10.5194/amt-13-479-2020*). Hodograph method is based on phase relation between both zonal and meridional wind components and temperature.

This technique allows us to unambiguously identify upward- and downward-propagating GWs and their parameters.

(**a**) Horizontal velocity fluctuations. Colored area marks altitude range of one wavelength where wave amplitude is most significant.



(**b**) Hodograph ellipse of IGW horizontal velocity variations taken from altitude range marked in plot (a).

Strelnikova et al., AMT, 2020

Two extensive case studies

We applied the Hodograph technique to a unique lidar measurements of temperature and horizontal winds measured in altitude range 30-70 km

For this study we used:

Winter

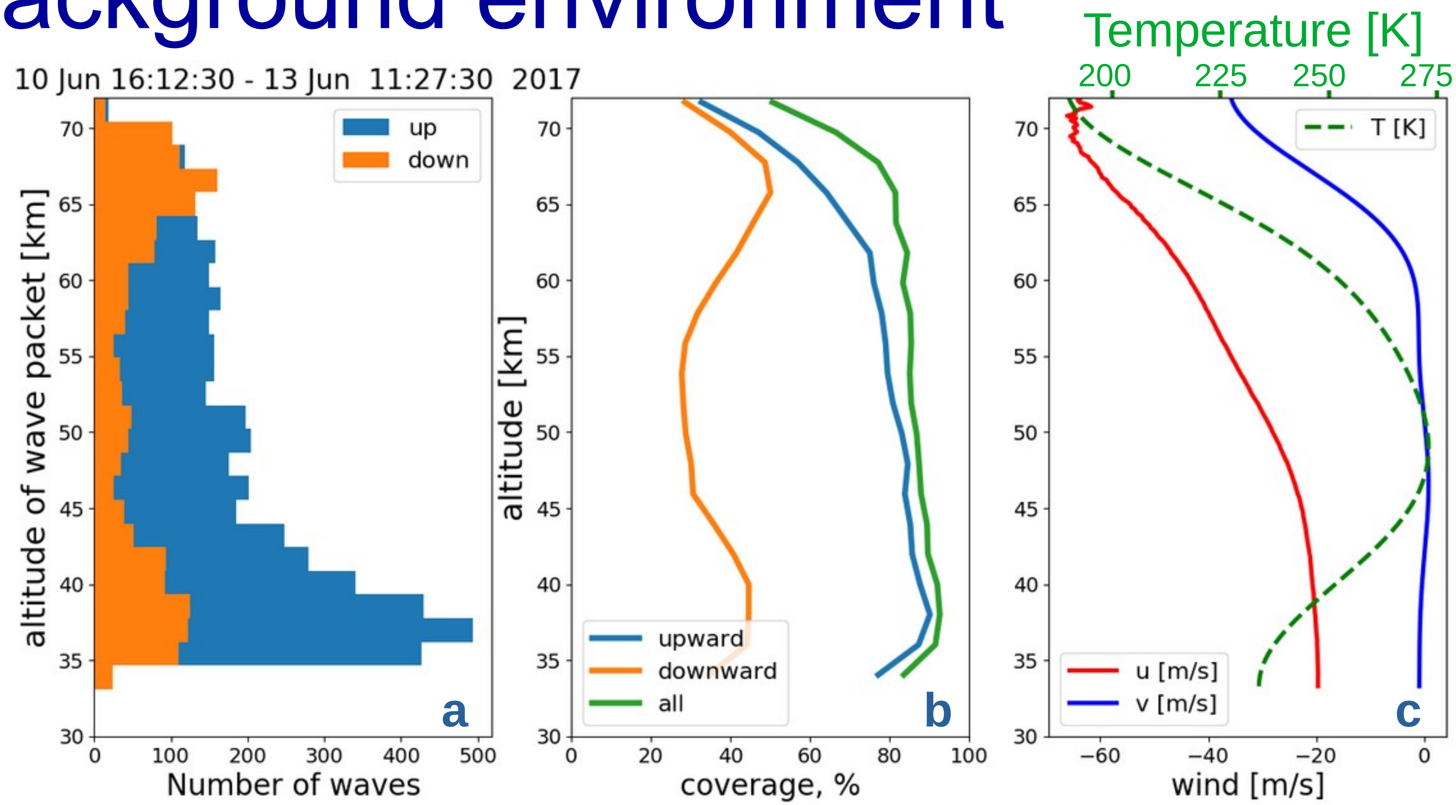
- **09 Jan – 14 Jan 2016**
  - 64 h + 45 h
  - 5109 upward wave detections
  - 2541 downward wave detections

Summer

- **10 Jun – 13 Jun 2017**
  - 70 h
  - 4867 upward wave detections
  - 1716 downward wave detections

Results: Altitude of detected waves and their background environment

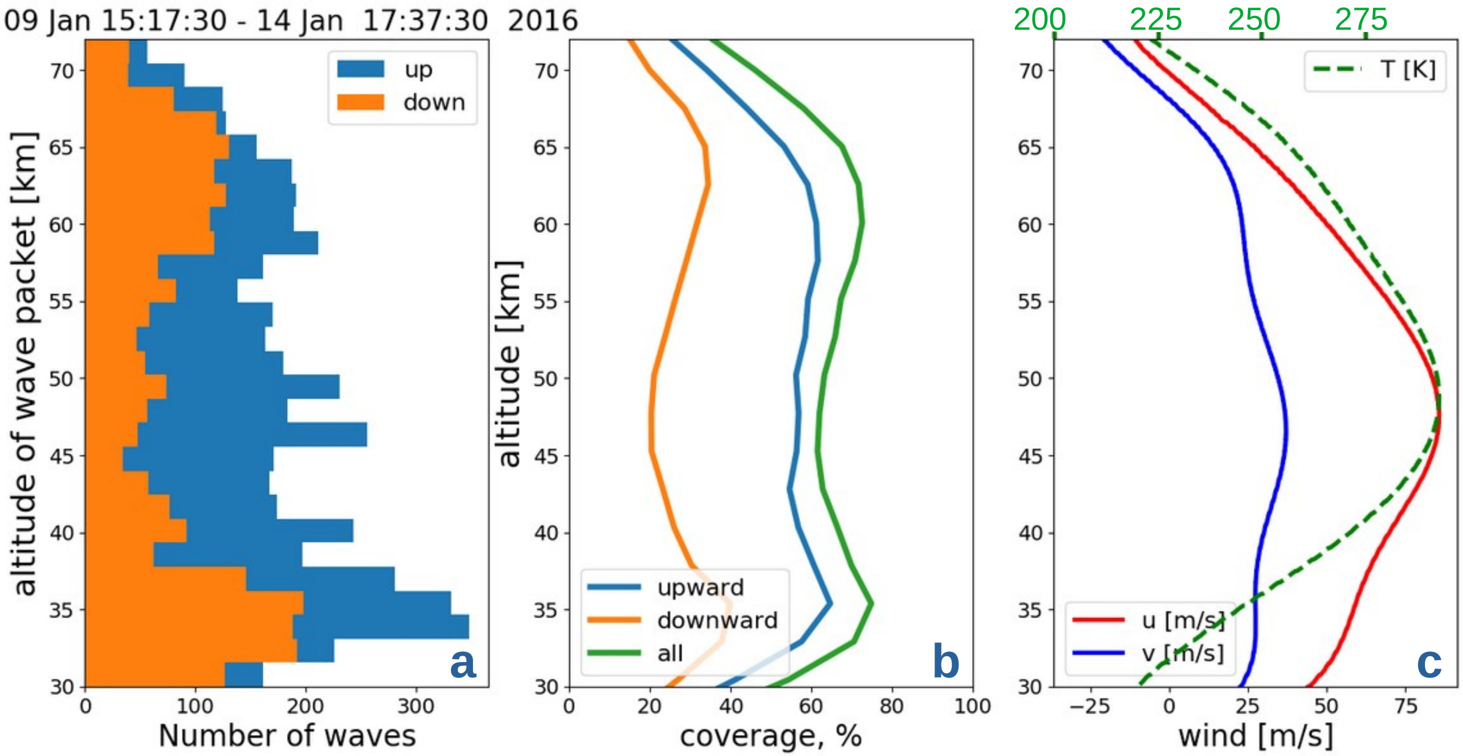
Summer



(**a**) Number of waves detected per 1.5 km altitude range bin. Blue (orange) bars mark upward- (downward-) propagating GWs. (**b**) Mean coverage by detected waves when taking the altitude extent of the waves into account. The green profile indicates whether a wave was found, whereas blue and orange lines are for upward- and downward-propagating waves, respectively. (**c**) Background mean wind and temperature.

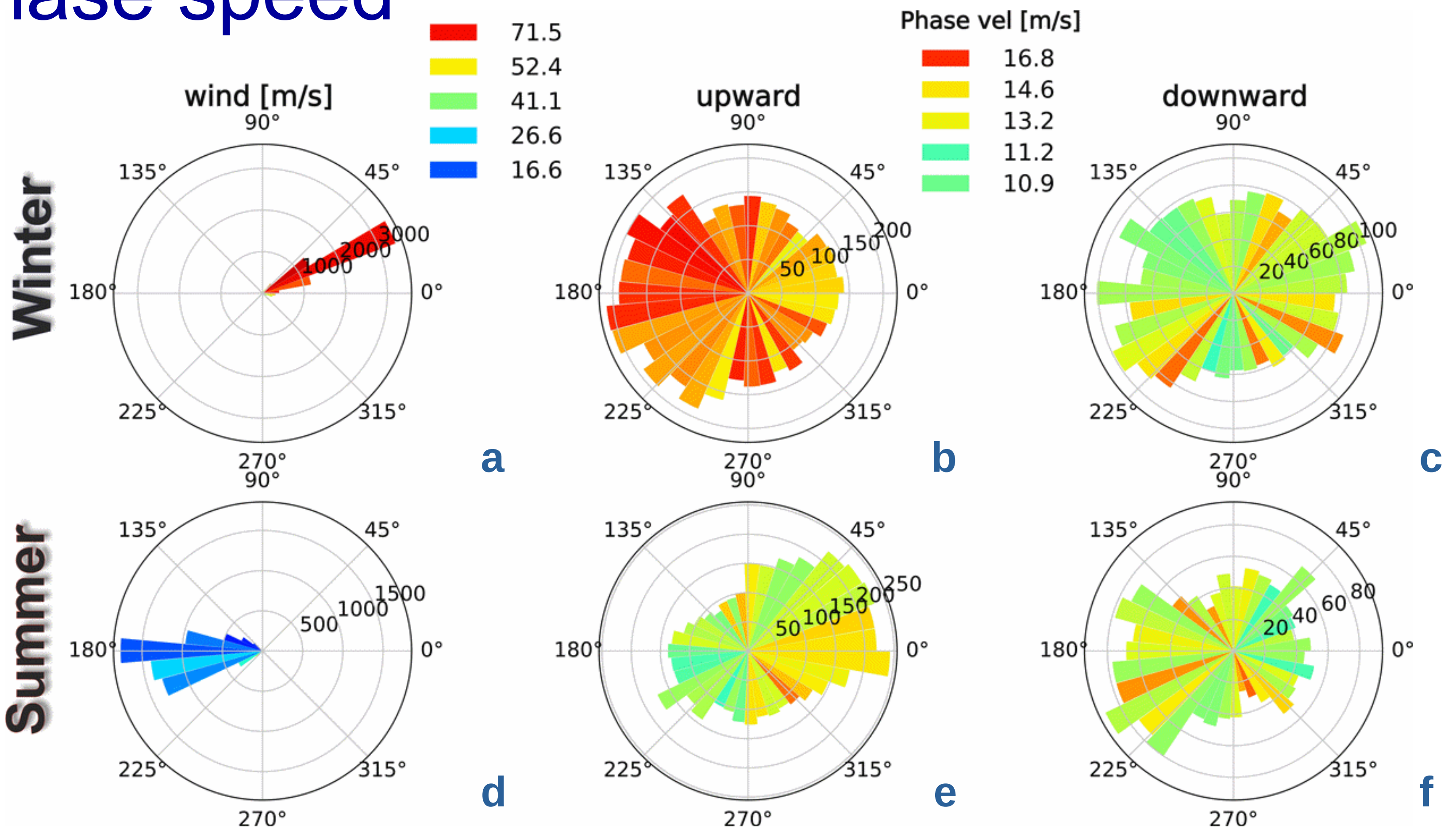
Results: Altitude of detected waves and their background environment

Winter



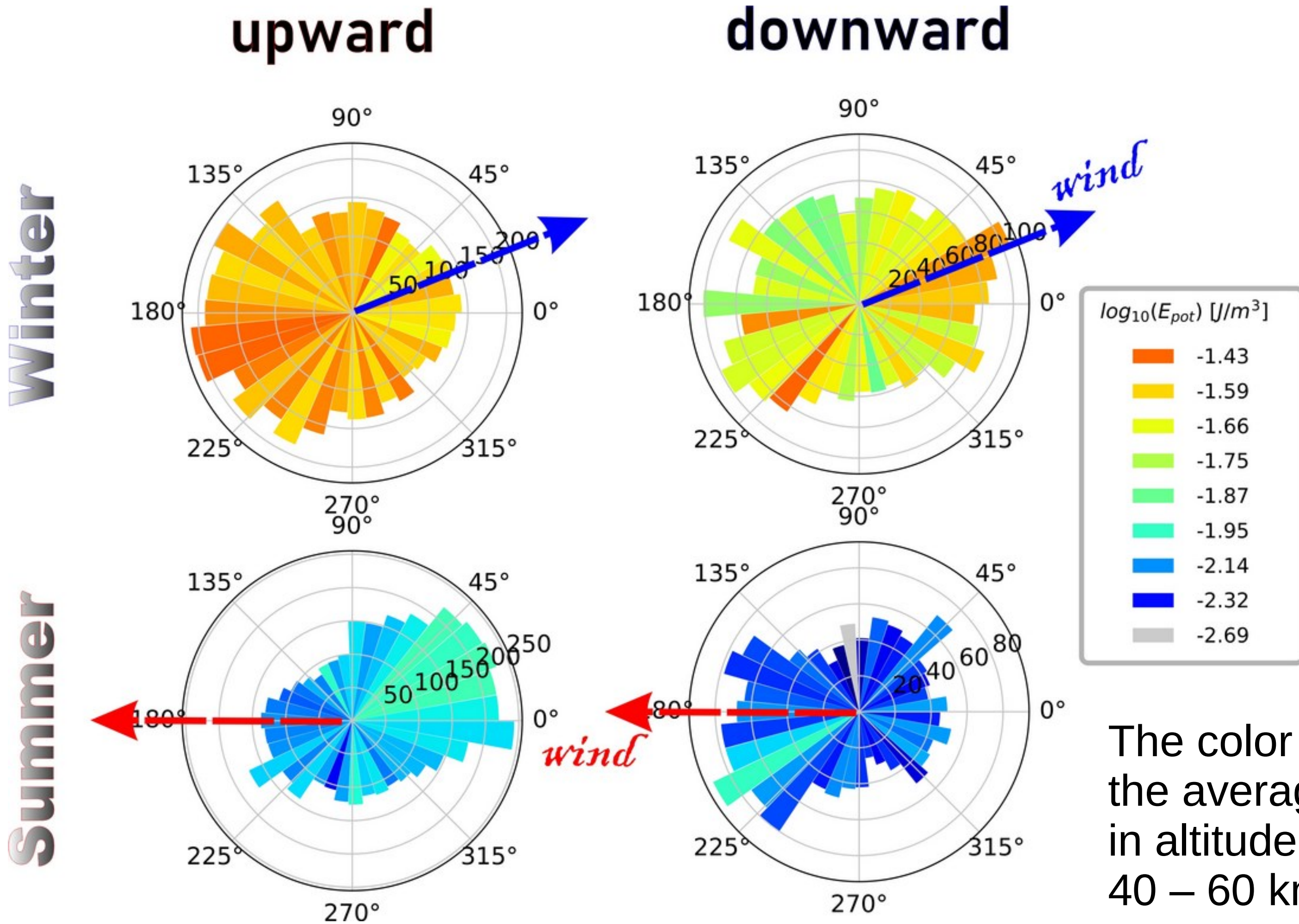
(**a**) Number of waves detected per 1.5 km altitude range bin. Blue (orange) bars mark upward- (downward-) propagating GWs. (**b**) Mean coverage by detected waves when taking the altitude extent of the waves into account. The green profile indicates whether a wave was found, whereas blue and orange lines are for upward- and downward-propagating waves, respectively. (**c**) Background mean wind and temperature.

Horizontal GW propagation directions and phase speed



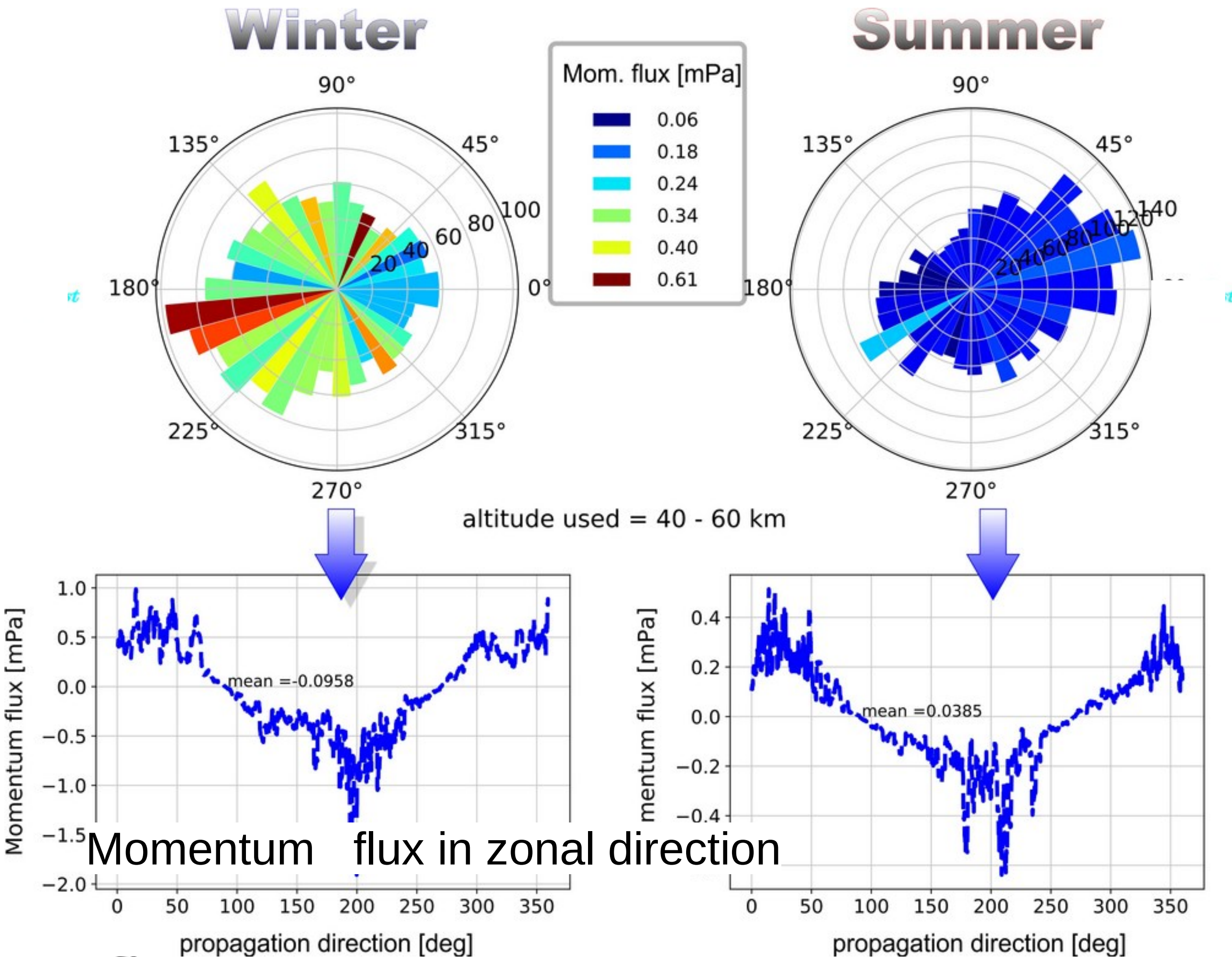
Direction of the background wind (**a**, **d**) and waves for upward-propagating (**b**,**e**) and downward-propagating (**c**, **f**) waves. Length of the bars represents the number of waves per 10° horizontal direction. The color represents the average wind (**a**,**d**) or average intrinsic phase speeds (**b**, **c**, **e**, **f**) or the respective directions. Upper plots (**a**-**c**) are for winter. Lower plots (**d**-**f**) are for summer.

Gravity wave potential energy density (GWPED)

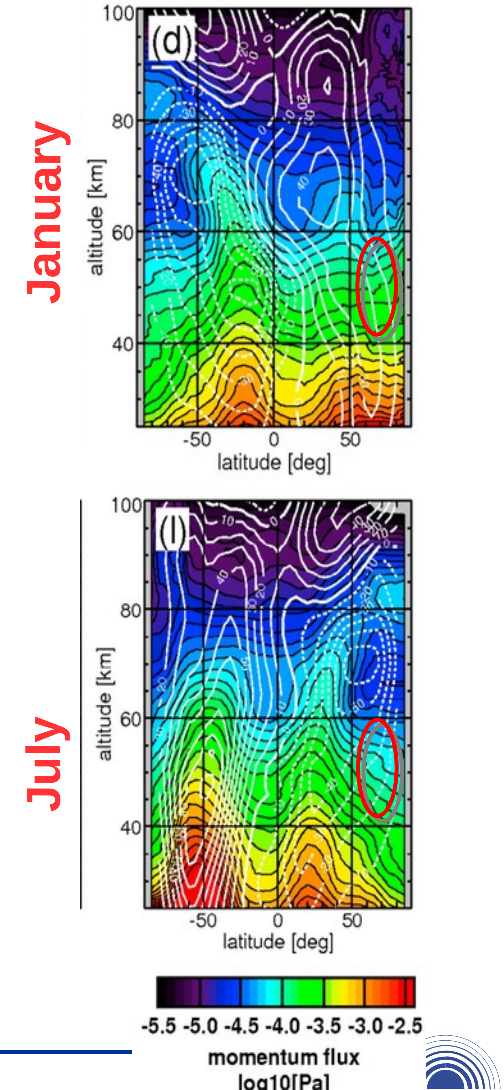


The color represents the averaged GWPED in altitude range 40 – 60 km

Momentum flux of upward propagating waves



M. Ern, et.al., JGR, 2011



Summary:

- An annual cycle with maximum in winter and minimum in summer is obvious in GWPED climatology measured by lidar
- Hodograph technique reveals presence of both up- and down propagating GWs with similar properties
- More downward propagating waves were observed in winter
- Phase speed of GWs is higher in Winter
- Energy of upward propagating waves is higher if they propagate against the background wind
- Momentum flux is higher in Winter (in agreement with SABER observations, M. Ern, et.al., JGR, 2011)