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Influence of atmospheric winds and tides on the propagation direction of mesospheric gravity waves observed in OH airglow in the Alpine Region

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Scientific aim

- Statistical investigation of gravity waves observed in the UMLT (upper mesosphere, lower thermosphere) in the Alpine region.
- Questions:
  - Geographical and temporal differences?
  - Influence of wind on GW propagation direction?
  - Influence of atmospheric tides on GW propagation?

Scientific background

- Gravity waves transport large amounts of energy and momentum.
- Among others responsible for pole-to-pole circulation in the mesopause.
- Knowledge about them important for atm. models.

Data

- focus on high frequency (periods < 1h), small scale ($\lambda_h = 5 - 60$km) gravity waves.
- 3 FAIM (Fast Airglow IMager)-instruments
- 4 Locations (in and around Alpine Region) → **Fig. 1**
- 5 years of observations
  - Dec 2013 to Jule 2019
- Over 30 million single airglow images
  - equivalent of 5000 observed airglow hours
- Analysis reveals 30000 wave events with derived gravity wave parameters.

- Hourly resolved wind data sets are used for further investigation.
  - Subset of ERA 5:
    - wind in troposphere and stratosphere (up to 50km) at (47.5N, 10.5E).
  - Meteorradar data:
    - wind in mesosphere and mesopause (from 80 to 96km) at (51N, 13E).

Methodology

- 2D-Fouriertransform for image analysis.
- Automatic peak extraction from spectra with derivation of gravity wave parameters:
  - horizontal wavelength,
  - horizontal propagation direction,
  - observed horizontal phase speed,
  - observed wave period.

Results

- Gravity waves propagation direction per season (Summer = Apr to Sept), Winter = Oct to Mar) → **Fig. 2**
- wind direction/wind speed per season → **Fig. 3**
- Correlation analysis of
  - mesospheric/mesopause winds separated in N, E, S, W quadrants with
  - gravity wave propagation directions separated in N, E, S, W quadrants.

  → **Fig. 5 (summer) and 6 (winter)**

  → Tidal influence on GW visible

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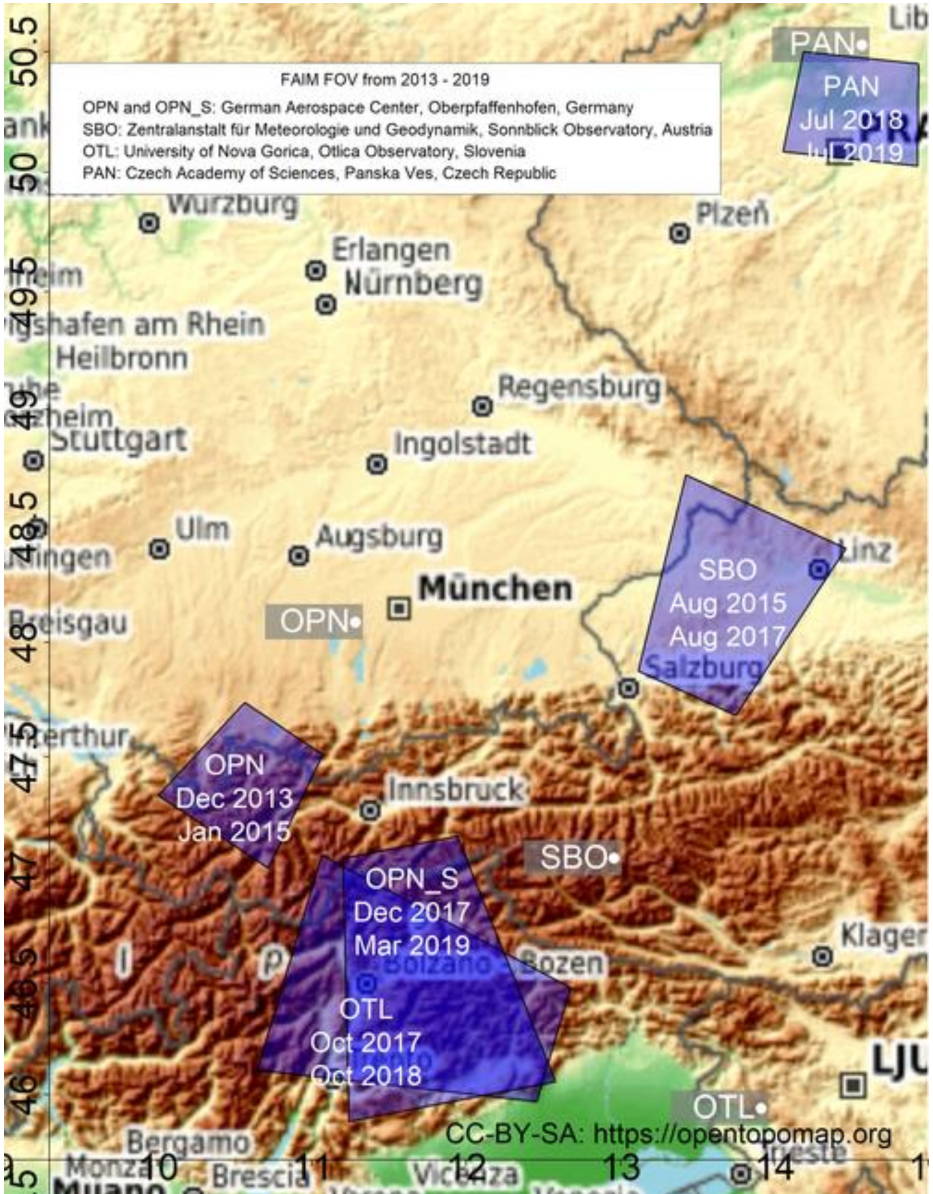

Fig. 1:

Map with the FOVs from the three FAIM systems in the course of about five years. The locations of the instruments are noted in the white box. The data set names and time interval of observations are noted at the respective FOV.

Great thanks to our colleagues from the observatories for hosting our instruments and thus, making these observations possible!

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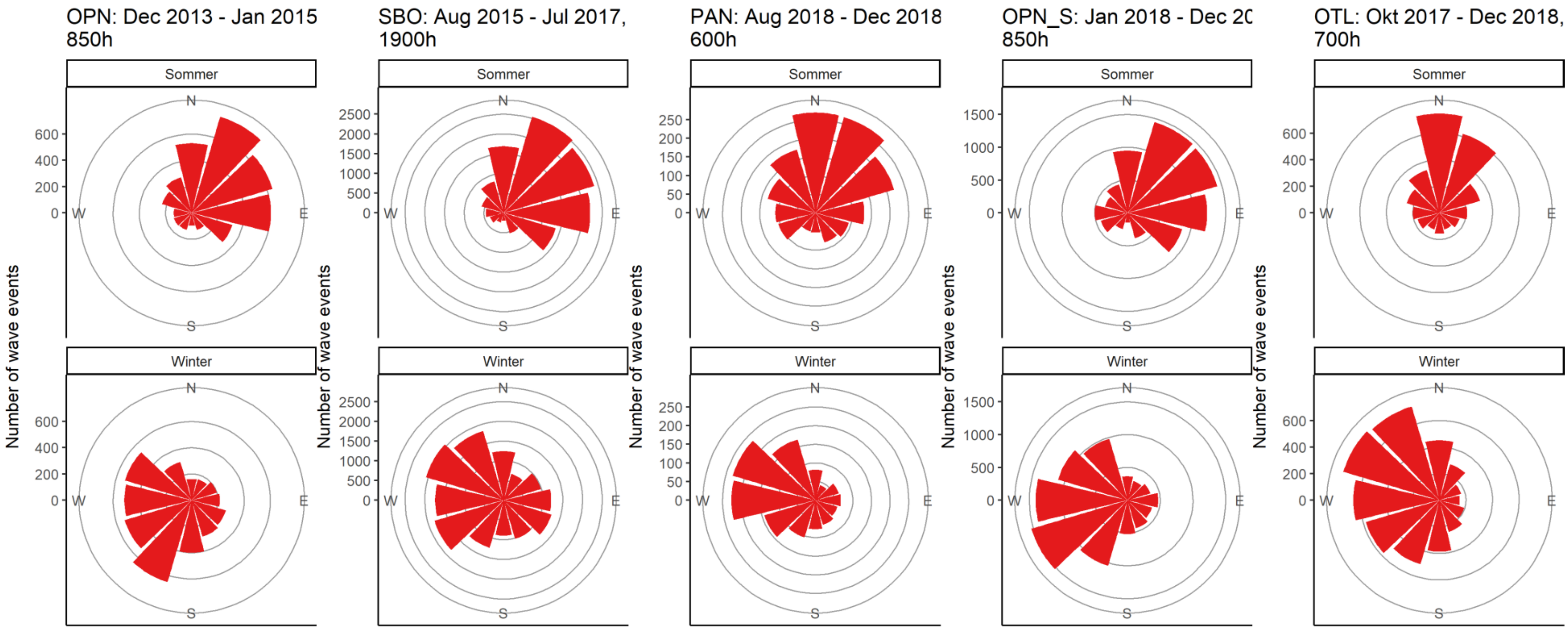

Fig. 2: Seasonal variability of gravity wave propagation direction

Propagation direction of gravity waves in summer (April to September, top row) and winter (October to March, bottom row). The number of hours of airglow data per data set and the respective time span is given in the title.

Especially in summer, a clear seasonal dependency is visible with a consistent propagation direction to East (zonal direction) and North (meridional direction). In winter, the zonal direction is to the West, the meridional direction differs with the data sets (OPN and OPN_S slightly more to the South, SBO, PAN and OTL slightly more to the North).

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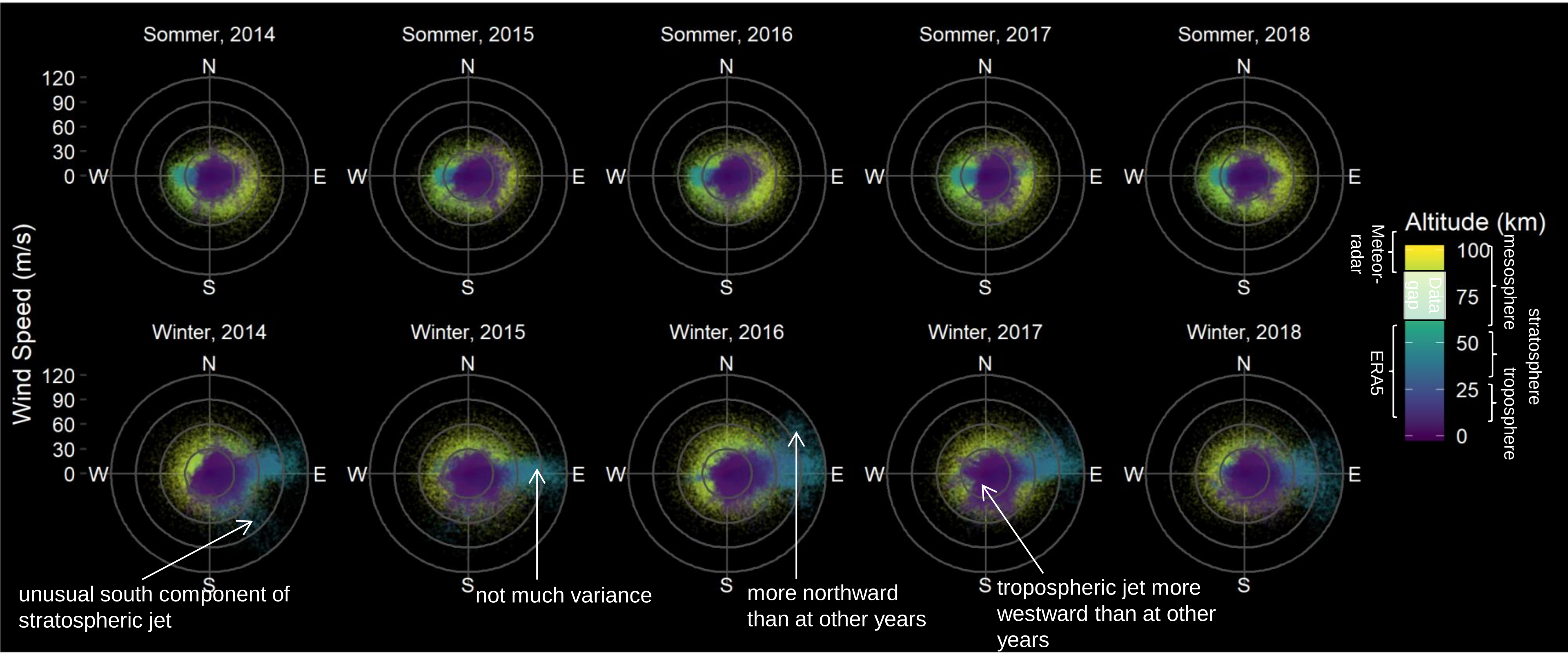

Fig. 3: Wind direction and wind speed for the years 2014 to 2018

Wind speed and direction per year (2014 to 2018) for summer (April to September, top row) and winter (October to March, bottom row). The altitude of the wind is color-coded. Remark: No data is available for 50 to 80km! Wind data from ERA5 and meteor wind radar from University of Leipzig.

In summer, the tropospheric eastward jets are obvious (in violet) as well as the stratospheric westward winds (turquoise). The upper mesospheric (greenish yellow) and mesopause winds (yellow) switch from westward to eastward winds. In winter, the tropospheric wind is occasionally also in westward direction, e.g. in Winter 2017. A strong stratospheric eastward wind can be seen, however it varies in meridional direction (e.g. SE component in 2014, only eastward in 2015). The upper mesospheric wind has the tendency to reverse from east to west.

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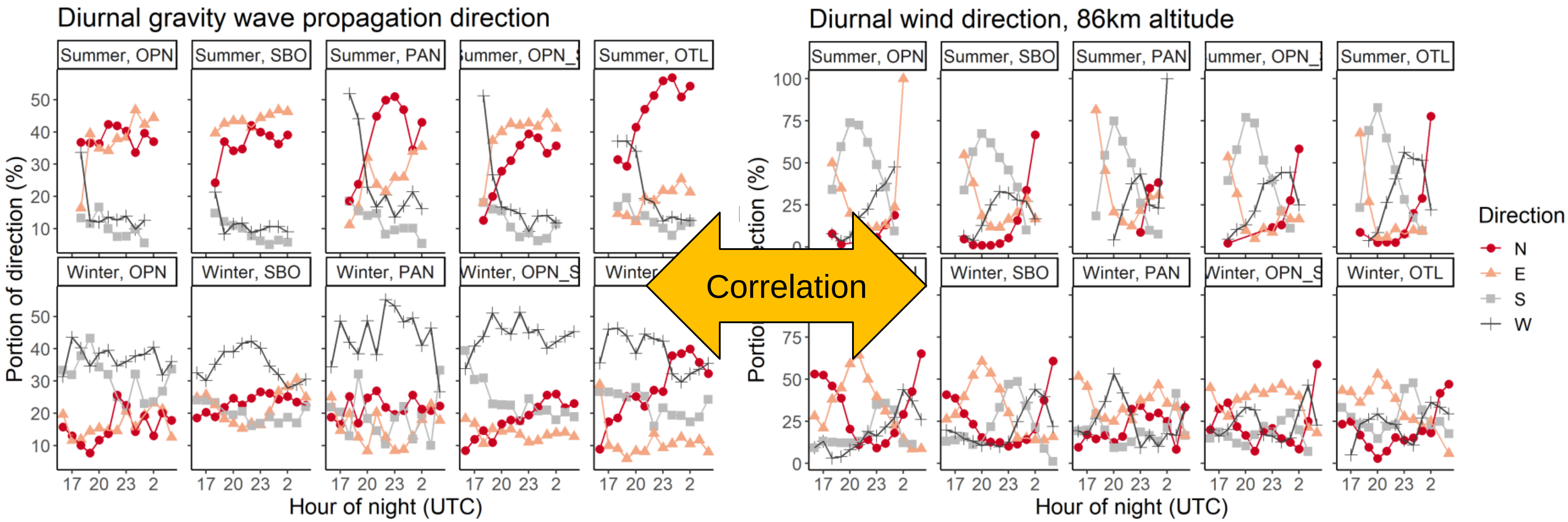

Oscillations in gravity wave propagation direction

Oscillations in wind direction known to be from atmospheric tides

Fig. 4: Intra-diurnal variability of gravity wave propagation direction and wind direction

Left: Gravity wave propagation direction throughout the nights (hours 16 to 5 o'clock)

Right: Direction of the wind throughout the night for the same hours as for gravity waves (just times considered where there is airglow data available).

For each data set, each altitude of the wind, and for time lags from -12h to +12h by 2h between GW propagation direction and wind direction: calculate the correlation coefficients between gravity wave direction and wind direction.

→ Fig. 5 and 6

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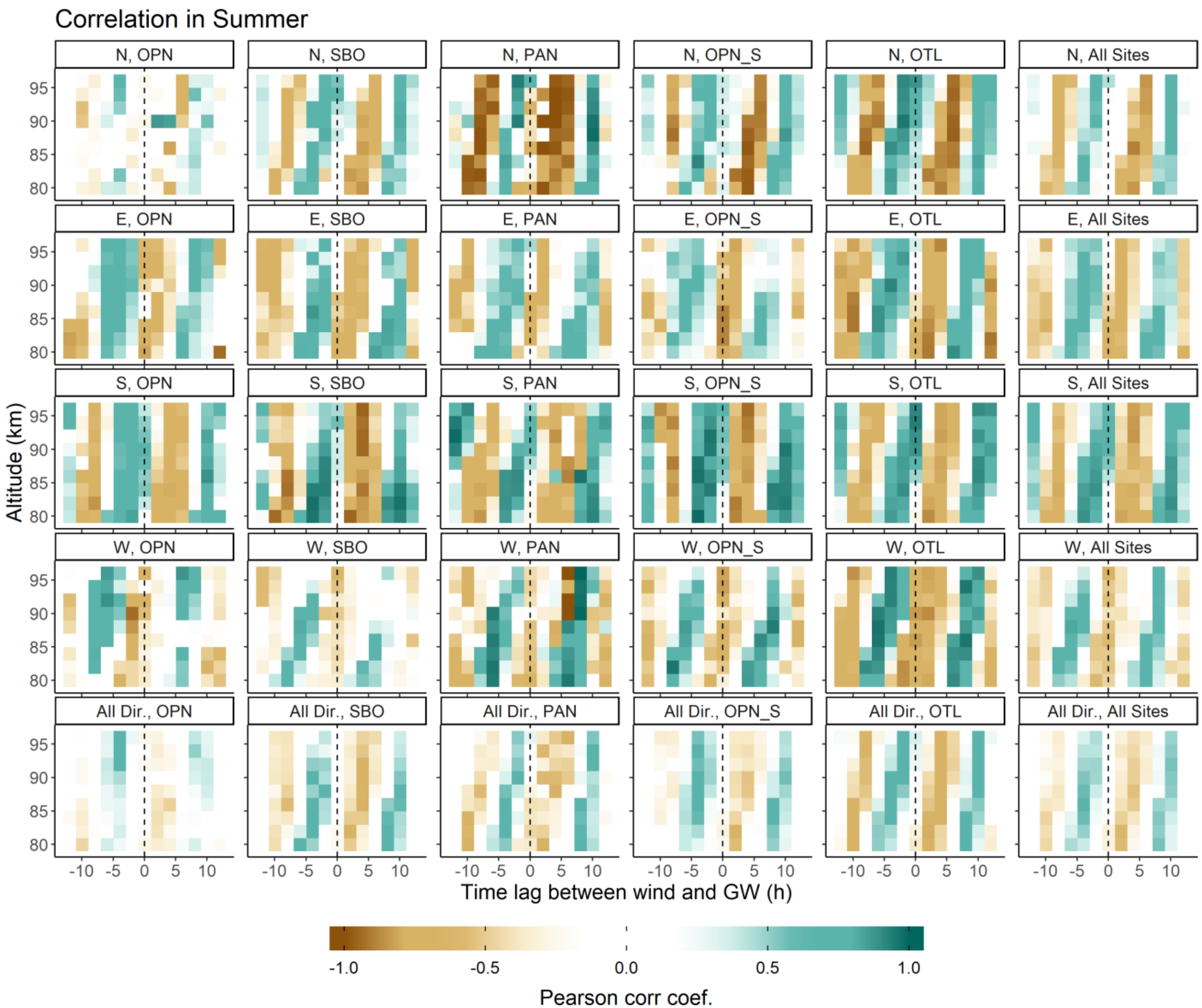

Fig. 5: Influence of mesopause winds on gravity wave propagation – Summer

Time shifted altitude-dependent correlation patterns between gravity wave propagation direction and wind direction (separated into quadrants around cardinal directions).

Clear oscillations in the structure of the correlation coefficients can be seen. A FFT analysis of these patterns (not shown) reveals periods of 12h (most dominant), periods between 6-8h (less dominant) and frequently periods of a few hours.

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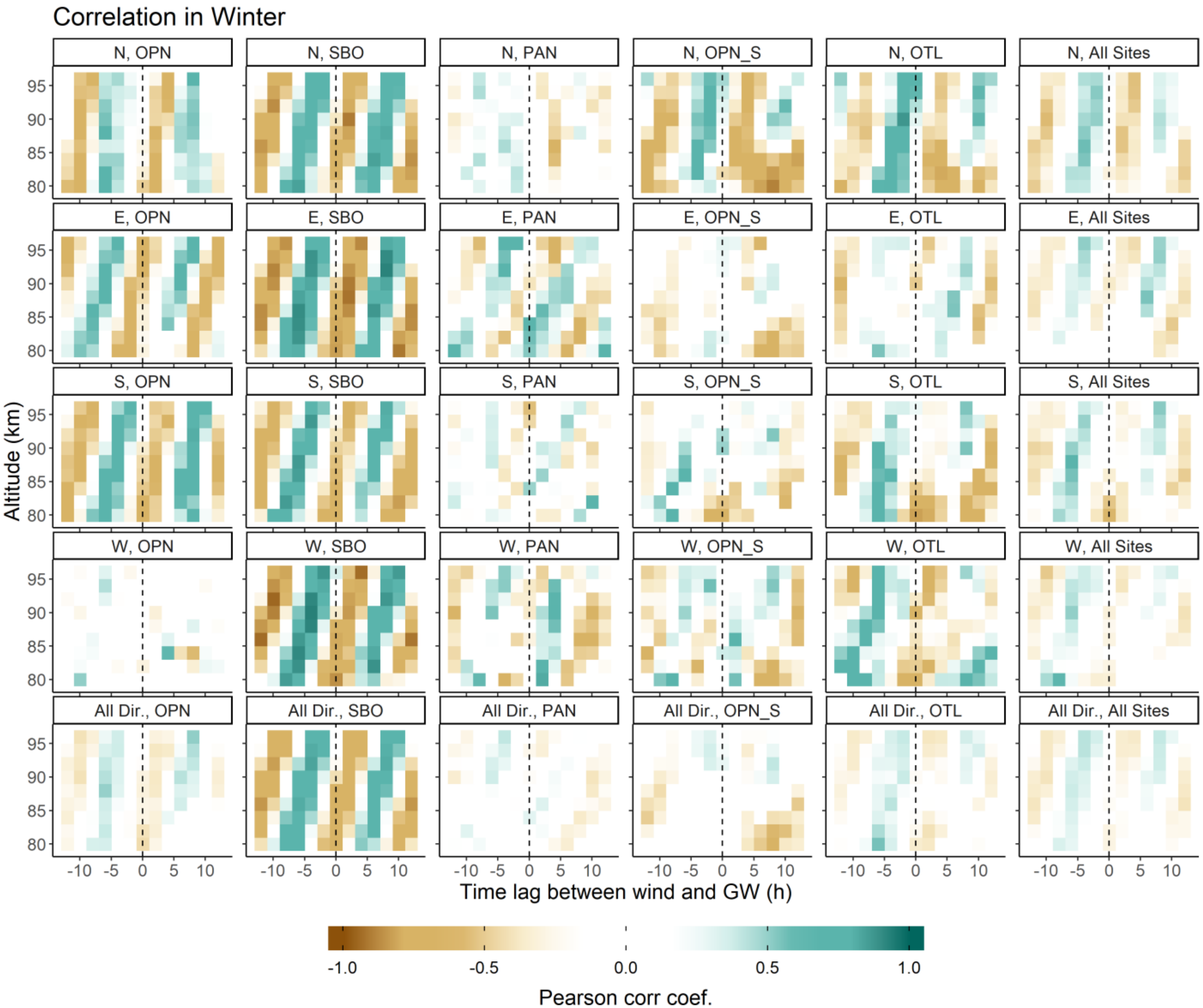

Fig. 6: Influence of mesopause winds on gravity wave propagation – Winter

Time shifted altitude-dependent correlation patterns between gravity wave propagation direction and wind direction (separated into quadrants around cardinal directions).

Oscillations are especially clear for SBO (largest data basis) and OPN (related to the year 2014). They are not so evident for PAN (shortest data basis: only 3 winter months contribute to this part of the analysis), OPN_S and OTL.

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Discussion

Seasonal variability

- Most probably stratospheric wind filtering leads to observed zonal propagation direction:
    - Westward stratospheric wind in summer filters out tropospheric gravity waves in this direction → observations of eastward GW.
    - Eastward stratospheric wind in winter filters out tropospheric gravity waves in this direction → observations of westward GW.
- Reason for meridional propagation direction not fully understood.
    - Influence of meridional wind filtering of mesopause winds expected, but generally too weak to be the only reason.
    - Different GW sources in winter could lead to the observed propagation directions, e.g. mountain waves that may generate secondary gravity waves. Heale et al. 2020 show the effects of breaking mountain waves in the Alpine region. Vargas et al. 2015 suggest ducted waves to contribute to the observed wave spectrum.

Diurnal variability

- Observed periods in the correlation patterns are expected to be due to tides. Periods are mainly 12h and also 6-8h. This is interpreted as the influence of the semi-, ter- and quarter-diurnal tides on the propagation direction of the gravity waves.
    - The diurnal tide can not be resolved due to the temporal coverage.
- The semidiurnal tide is dominant for almost every directions and site which is consistent with findings in literature (Sandford et al. 2006, Hibbins et al. 2007 and others).
- Jacobi et al. 2017 investigate the quarterdiurnal tide and show that it can reach amplitudes of 7m/s. The data, especially in winter (e.g. East direction at OPN) show clear indications of the quarterdiurnal tide.
- The slant of the periodic structures (Fig. 5 and 6) could be seen as phase velocity. Further preliminary investigations (not shown) suggest that the phase velocity peaks at 3 km/h and 7 km/h where the 7 km/h peak is more dominant in summer and the 3 km/h peak more dominant in winter.

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Summary

- In focus of the investigation: high-frequency, smaller-scale gravity waves and their direction of propagation. The influence of the wind on the direction of propagation is investigated.
- Predominant gravity wave propagation direction to NE in summer and SW/NW in winter.
- Zonal propagation direction due to zonal wind filtering by stratospheric winds.
- Meridional propagation direction could be influenced by meridional wind and additionally by a differing source spectrum in winter. E.g. mountain waves can propagate up to the mesosphere in winter.
- Influence of atmospheric tides visible in correlation patterns between wind and GW propagation direction.
- Major influence of semidiurnal tide. But also influence of terdiurnal and quarterdiurnal tide. The diurnal tide couldn‘t be resolved by analysis.
- Preliminary results show main phase velocities of the tides in the correlation patterns of 3km/h and 7km/h.

Further reading

Hannawald et al., 2019, AMT : Description of image preprocessing, 2D-FFT analysis and findings for data sets OPN and SBO

Hannawald et al., 2016, AMT: Description of the used FAIM systems

Jacobi et al., 2007, Adv. Spa. Res.: Description of meteor radar

Lilienthal and Jacobi, 2015, ACP: Ten years of observations with meteor radar

Sedlak et al., 2016, AMT: Results from a high spatial resolution FAIM system regarding turbulence

Wüst et al., 2019, ACP: FAIM observations from ground and airplane