# Cross-Evaluation of Surface Meteorological Data and GNSS-derived Water Vapor with Re-analysis Information for South Georgia Island, South Atlantic Ocean

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## Introduction

Fig. 1. Locations of KEP (BAS weather station) and BMT (KEPA GNSS) site.

## Data and Methods

to process GPS observations in a double difference network strategy. We employed the Vienna Mapping Function 1 (VMF1) (Boehm et al., 2006). Then, we calculated PWV by subtracting ZHD (calculated from VMF grided files) from the ZTD using the formula (Bevis et al., 1994).

$$PWV = \frac{(ZTD - ZHD)}{10^{-6}(K_2' + \frac{K_3}{T_m})R_v\rho}$$

where K'2 and K3 are reflectivity constants, Rv is the ideal gas constant, ρ is the density of the water vapor, and Tm is the weighted mean temperature of the atmosphere estimated from the station temperature.

- For the foehn case study our approach to identify

## Cross-Evaluation of Temperature and Pressure

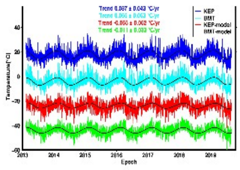


Fig. 2. Time-series of air temperature from KEP (BAS AWS, dark blue), BMT (KEPA GNSS station, cyan), and ERA-I reanalysis gridded data at KEP (red) and BMT (green) from February 2013 to December 2019. Time-series are offset for clarity.

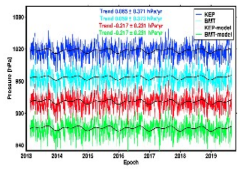


Fig. 3. Time-series of pressure from KEP (BAS AWS, dark blue), BMT (KEPA GNSS station, cyan), and ERA-I reanalysis gridded data at KEP (red) and BMT (green) from February 2013 to December 2019. Time-series are offset for clarity.

## Cross-Evaluation of Wind and PWV observations

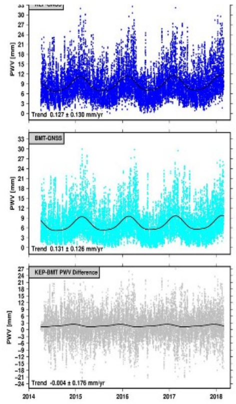
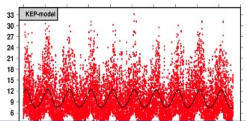


Fig. 8. PWV estimates of KEP(dark blue) and BMT (cyan) GNSS observations and the difference between the two stations.



## Cross-Evaluation of Foehn events

method. Statistically, this implies an event every 3-4 days. (Figure 11)

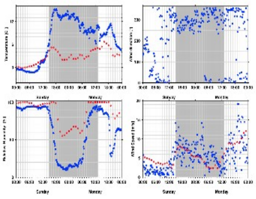


Fig. 11. BMT station observed (solid blue circles) and

## Conclusions and Acknowledgments

- We have performed a first investigation of the meteorological surface observations at BMT, which is co-located with the KEPA GNSS station.
- Through cross-evaluations of these data with those of KEP, which uses a WMO-certified AWS, we have established BMT to have been operating well from 2013 to 2020. We observed similar features in all time series.
- We observed temperature differences between the BMT and KEP sensors reaching up to 15°C. We attribute this most likely to the different topography at KEP and BMT, with KEP being at sea level and frequently in the shadows of nearby mountains, predominantly Mt Duse. For example, high temperature differences can be observed in the morning hours when

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## Introduction

South Georgia Island is a small and isolated island between the South Atlantic and Southern Oceans that is roughly 150 km long and 45 km wide, running roughly north-west to south-east. It is mostly glaciated with mountains rising to nearly 3000 m in altitude (19 peaks exceed 2000 m). In this location South Georgia lies in the zone of the circumpolar westerly winds and in the path of the Antarctic circumpolar current (ACC) and the associated Antarctic convergence (AC). Hence the island with its mountains together with its sub-oceanic base represents a significant barrier to both the westerly winds (Hosking et al., 2015; Vosper et. al., 2016) and the ocean current, which have to diverge from their predominant eastward direction. As a consequence of this both have a major impact on the climate of South Georgia island.

## Data and Methods

- The observational data used in this study are surface meteorological data and zenith total delay estimates derived from GNSS observations. Furthermore, we employ ERA-Interim re-analysis model data from TROPDB at the Geodetic Observatory Pecný (GOP) for our cross-evaluations (Table 1).

Table 1: Summary of data availabilities, station coordinates, and installations used in this study.

| Stations | Domes/WMO | Lat | Long | Height | Installation |
|---|---|---|---|---|---|
| Meteorological observations | | | | | |
| BMT | | -54.295 | -36.514 | 346.219 | Feb/2013 |
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| KRSA | 42702M001 | -54.284 | -36.495 | 24.935 | Mar/2014 |
| ECMWF re-analysis gridded data | | | | | |
| ERA-Interim gridded model | | | | | |

- Observations by the two meteorological stations such

## Cross-Evaluation of Temperature and Pressure

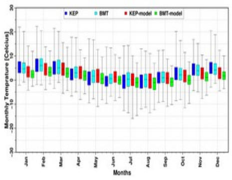
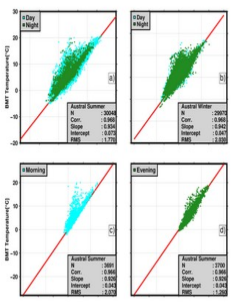


Fig. 5. Monthly air temperature from observations at KEP (BAS AWS, dark blue) and BMT (KEPA GNSS station, cyan), and ERA-I re-analysis gridded model at KEP and BMT stations from February 2013 to December 2020. The box indicates the median, minimum, maximum, first and third quartiles.



## Cross-Evaluation of Wind and PWV observations

Fig. 9. PWV estimates of KEP and BMT from ERA-Interim model and the difference between the two.

- Figure 10, clearly illustrates the variations in PWV during the year, probably representing at least two distinct seasons on South Georgia Island. Generally, PWV variations exhibited significant seasonal dependence, with larger values in February and March and smaller values in July and August.

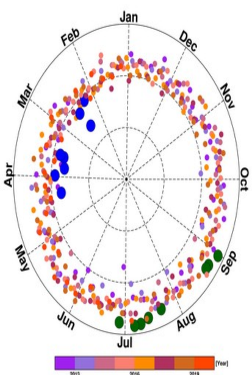
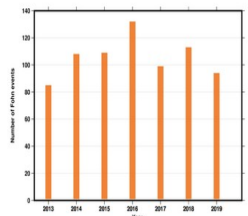


Fig. 10. PWV rose plot of BMT with large circles indicating minimum (dark green) and maximum (dark blue) values. The colour of the small circles repeats the year.

## Cross-Evaluation of Foehn events

| | | | | | | |
|---|---|---|---|---|---|---|
| Humidity change (%) | 12.64 | 41.10 | 0.10 | - | - | - |
| Wind speed change (m/s) | -0.54 | 33.30 | -17.80 | -2.32 | 22 | -31 |



## Conclusions and Acknowledgments

- The estimated PWV values decrease moderately from their maximum values in February and March, and their lowest values are observed during July and August. The PWV values clearly show the signature of the foehn events.

**Acknowledgments**

Dr. Hunegnaw is funded through the Luxembourg Fonds National de la Recherche Project VAPOUR (FNR Ref 12909050). The authors would like to thank the International GNSS Service community for data and products (Johnston et al., 2017).

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## *Abstract*

As one of the most important components of the global hydrologic cycle, atmospheric water vapor shows significant variability in both space and time over a large range of scales. This variability results from the interactions of many different factors, including topography and the presence of specific atmospheric processes. One of the key regions for affecting global climatic variations lies in the sub-Antarctic zone over the Southern Ocean with its Antarctic Circumpolar Current and the associated Antarctic Convergence. There, in this cold and maritime region, lies South Georgia Island with its weather and climate being largely affected by both the dominating ocean currents and the strong east ward blowing winds in this zone. While the island forms an important outpost for various surface observations in this largely under-sampled and extremely remote region, it also forms a barrier for these winds due to its high topography, which, in turn, leads to various local meteorological phenomena, such as foehn winds. Surface meteorological data have been available for several stations near King Edward Point (KEP) on South Georgia for much of the 20th century. Since 2013 and 2014, Global Navigation Satellite System (GNSS) data have been available at five locations around the periphery of the island and during a few months in 2016 also radiosonde data have been collected at KEP.

This study aims at investigating the consistency between the different surface meteorological data sets such as temperature, pressure and wind direction/speed that have been collected at KEP and a nearby GNSS station on Brown Mountain (BMT) for which we also compare the precipitable water vapor estimates. A cross-evaluation of these data sets with model values from the ERA-Interim re-analyses is carried out to further investigate the performance of both instruments and models.

Overall, our preliminary results show high consistency between the surface meteorological observations and the re-analysis model values. It was our main objective to investigate the homogeneity and accuracy of the BMT observation time series through cross-evaluation with the series of the official WMO station at KEP.

Air temperature and pressure at both sites from observation and model data are strongly correlated at hourly intervals, reaching correlation coefficients in the range of 0.966 - 0.968 for the former data set. The difference temperature time series shows seasonal variations but no obvious steps. The difference pressure time series is flat, also indicating no discontinuities. A cross-evaluation of the wind observations shows the distinct directional feature at KEP for a station in a valley where the winds are funneled through the valley. For BMT the wind observations confirm the main directions of winds but also show the openness of the station from all directions. The observations of temperature, pressure, humidity and GNSS-derived PWV clearly show the signatures of the frequent foehn events.

# *Introduction*

South Georgia Island is a small and isolated island between the South Atlantic and Southern Oceans that is roughly 150 km long and 45 km wide, running roughly north-west to south-east. It is mostly glaciated with mountains rising to nearly 3000 m in altitude (19 peaks exceed 2000 m). In this location South Georgia lies in the zone of the circumpolar westerly winds and in the path of the Antarctic circumpolar current (ACC) and the associated Antarctic convergence (AC). Hence the island with its mountains together with its sub-oceanic base represents a significant barrier to both the westerly winds (Hosking et al., 2015; Vosper et. al., 2016) and the ocean current, which have to diverge from their predominant eastward direction. As a consequence of this both have a major impact on the climate of South Georgia island.

As one of the most important components of the global hydrologic cycle, information on atmospheric water vapor is vital to understanding global climatic changes. However, water vapor shows significant variability in both space and time over a large range of scales due to it resulting from the interactions of many atmospheric processes. Processes such as air resistance and convection, cloud formation and precipitation are highly influenced by local and large-scale variability in tropospheric water vapour (Bock et al., 2007).

The climate of South Georgia is classified as maritime with relatively cool temperatures, moist air and windy conditions (Shanklin et al., 2009; Thomas et al., 2018). According to Thomas et al. (2018) Grytviken's historic record of temperature and precipitation, compared to regional datasets and historical reanalysis, showed a shift towards increasingly warmer daytime extremes, starting in the mid-twentieth century and followed by warmer night temperatures, with average temperatures rising by 0.13 ‰ per decade over 1907-2016. Furthermore, in more recent years studies have also shown a significant impact of foehn events on the local climate, especially on the lee side of the central mountain ranges (Bannister and King, 2015; 2019).

In this first study, we aim at investigating the consistency and homogeneity between the different surface meteorological data sets such as temperature, pressure, and wind direction/speed that have been collected at the Automatic Weather Station (AWS) at King Edward Point (KEP) and our nearby GNSS station on Brown Mountain (BMT). The GNSS observations at BMT allow us also to investigate the precipitable water vapor estimates in general and during the reported foehn events. A cross-evaluation of these data sets with model values from the ERA-Interim re-analyses is carried out to further study the performance of both instruments and models.

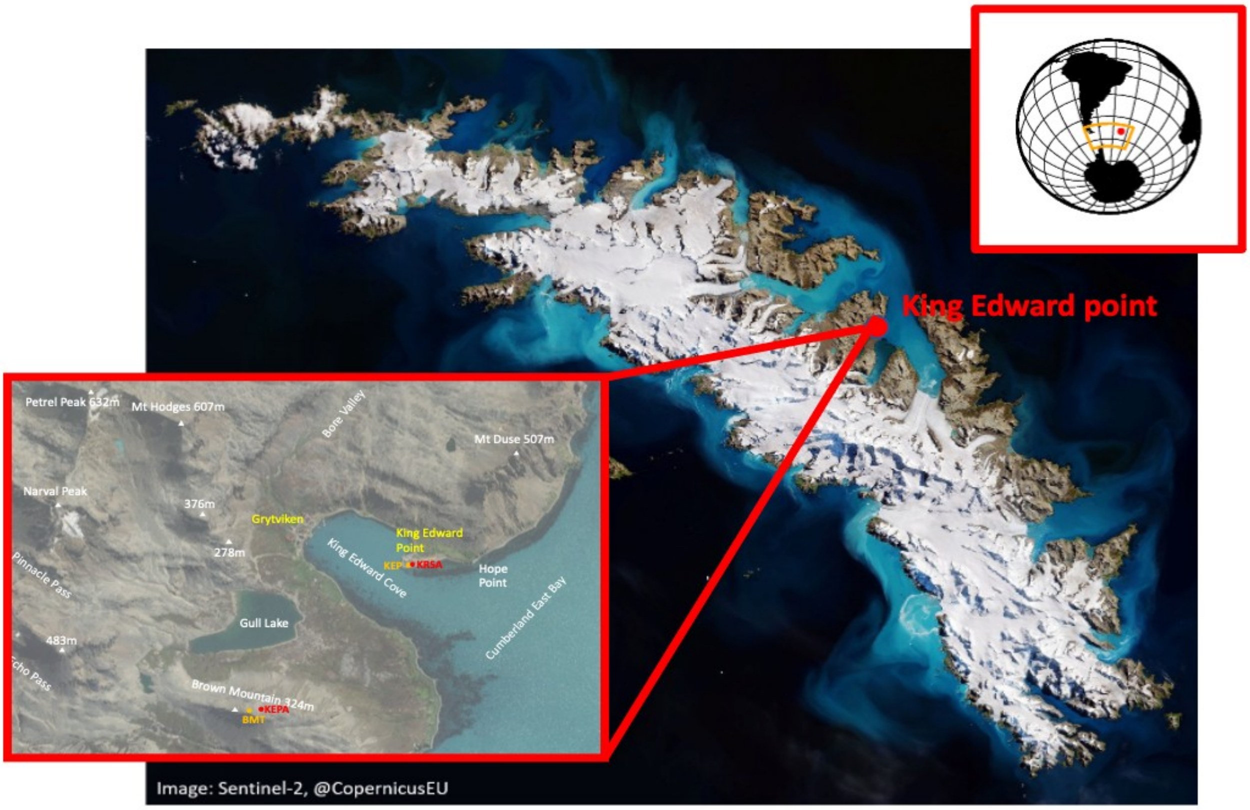


**Fig. 1. Locations of KEP (BAS weather station) and BMT (KEPA GNSS) site.**

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- The observational data used in this study are surface meteorological data and zenith total delay estimates derived from GNSS observations. Furthermore, we employ ERA-Interim re-analysis model data from TROPDB at the Geodetic Observatory Pecný (GOP) for our cross-evaluations (Table 1).

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| ERA-Interim gridded model | | | | | |

- Observations by the two meteorological stations such as temperature, pressure and humidity were reduced to mean sea-level using standard lapse rate formulae before the comparison. For this, we used the geodetically derived heights for the sensors at KEP and BMT stations.
- Observation and model data are typically provided at different time intervals, hence we compared observations at hourly intervals and model values at 6 hourly intervals.
- We used the standard procedures for the computation of precipitable water vapor (PWV) from the GNSS-derived zenith total delay (ZTD) estimates. For more information on the GNSS processing see Ejigu et al. (2020). We have used the observed surface temperature and pressure data for the estimation of the dimensionless constant that is used for the conversion of GPS-derived ZWD to PWV. The Bernese GNSS Software Version. 5.2 (Dach et al., 2015) was employed to process GPS observations in a double difference network strategy. We employed the Vienna Mapping Function 1 (VMF1) (Boehm et al., 2006). Then, we calculated PWV by subtracting ZHD (calculated from VMF grided files) from the ZTD using the formula (Bevis et al., 1994).

$$PWV = \frac{(ZTD - ZHD)}{10^{-6}(K_2' + \frac{K_3}{T_m})R_v \rho}$$

where K'2 and K3 are reflectivity constants, Rv is the ideal gas constant, ρ is the density of the water vapor, and Tm is the weighted mean temperature of the atmosphere estimated from the station temperature.

- For the foehn case study our approach to identify events followed that of Bannister and King (2019). First, we detected a rapid change in temperature of more than 2°C and then we looked for a sudden change in relative humidity and wind speed. Using this approach in parallel at KEP and BMT allowed us to automatically identify the events below.

## *Cross-Evaluation of Temperature and Pressure*

- The time series of air temperature and pressure recorded at and modelled for KEP and BMT show consistent seasonal variations with similar amplitudes and small linear trends. Observations show more scatter than the model values. (Figures 2 and 3)
- The difference time series of air temperature and pressure between KEP and BMT show no obvious discontinuities and trends, implying homogeneous series with no drift for BMT using the WXT420 weather station. The difference temperature time series shows seasonal variations and the differences can reach -15°C. (Figure 4)
- The monthly mean temperature from observations and model show good agreement. However, during the Austral summer, the mean model temperature remains below the observed temperature. We assume this to be a consequence of the model resolution being too low, which leads to these grid cells being modelled as ocean-cells rather than land-cells. (Figure 5)
- The correlation analysis suggests temperature observations to be frequently higher at BMT than at KEP, despite the difference in altitude. This is particularly evident for daytime temperature during the Austral summer, which shows larger variability than during winter. Larger temperature differences can also be observed during the morning hours in the Austral summer, and morning and evening hours during the Austral winter. We suspect this to be either a feature of topography (KEP being in the shadow of mountains and close to the cold water), foehn events reaching BMT before KEP (we have identified some occasions of high temperature differences during these warm and strong wind events) and differences in the sensors or their installation. It was not possible to follow all WMO requirements at BMT. (Figure 6)

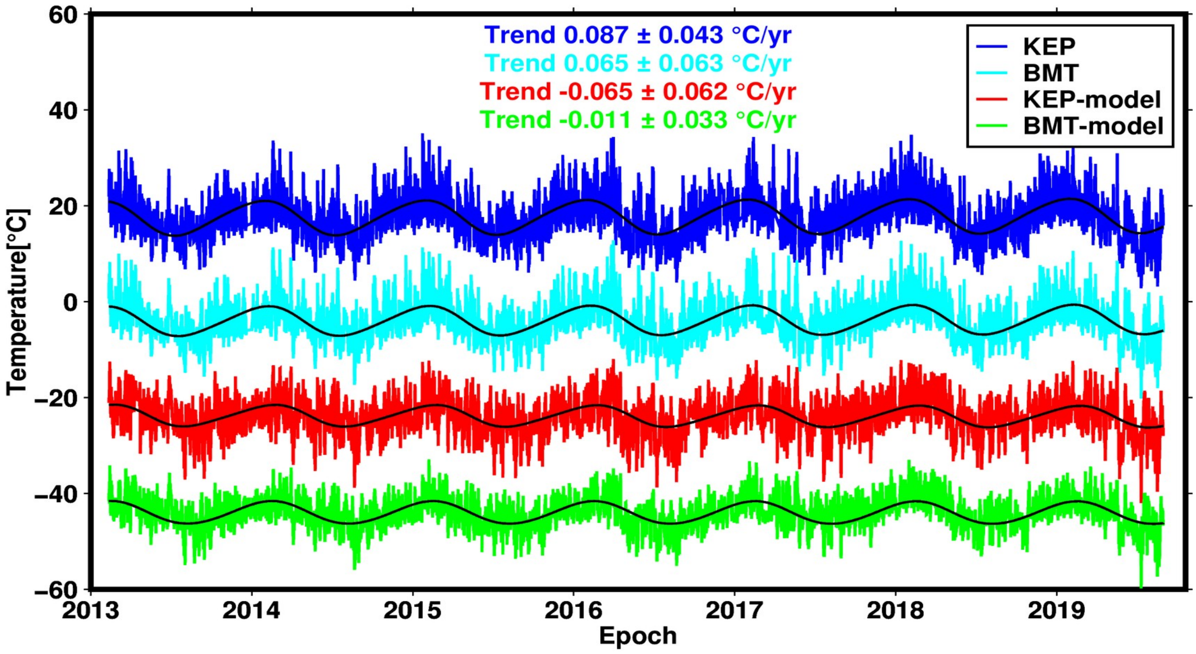



**Fig. 2. Time-series of air temperature from KEP (BAS AWS, dark blue), BMT (KEPA GNSS station, cyan), and ERA-I reanalysis gridded data at KEP (red) and BMT (green) from February 2013 to December 2019. Time-series are offset for clarity.**

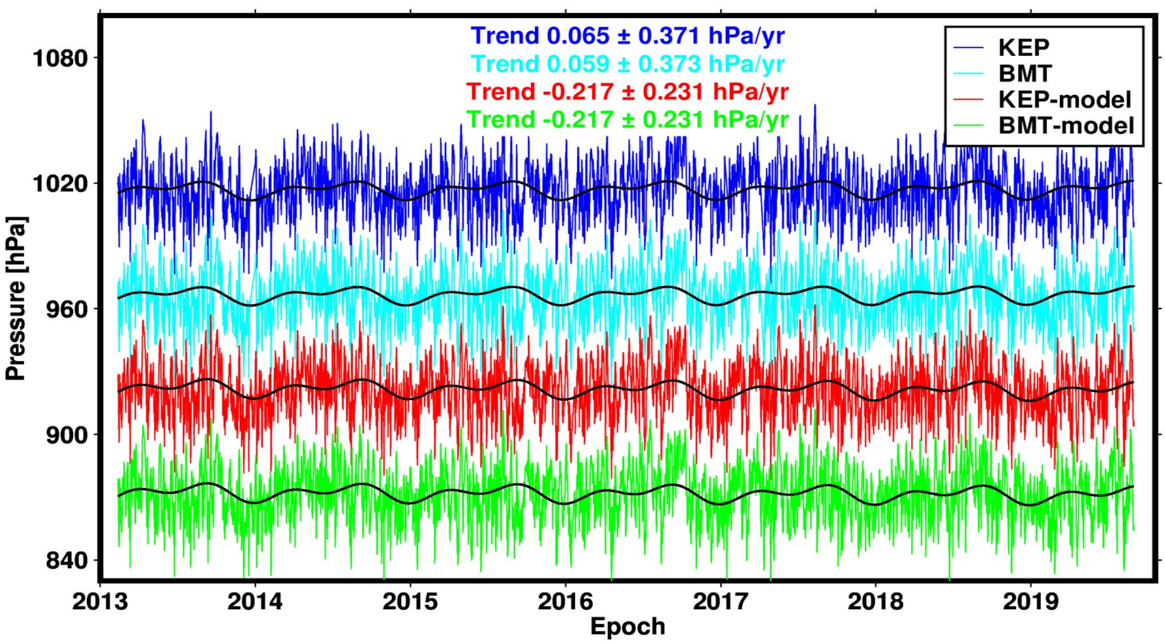



**Fig. 3. Time-series of pressure from KEP (BAS AWS, dark blue), BMT (KEPA GNSS station, cyan), and ERA-I reanalysis gridded data at KEP (red) and BMT**

(green) from February 2013 to December 2019. Time-series are offset for clarity.

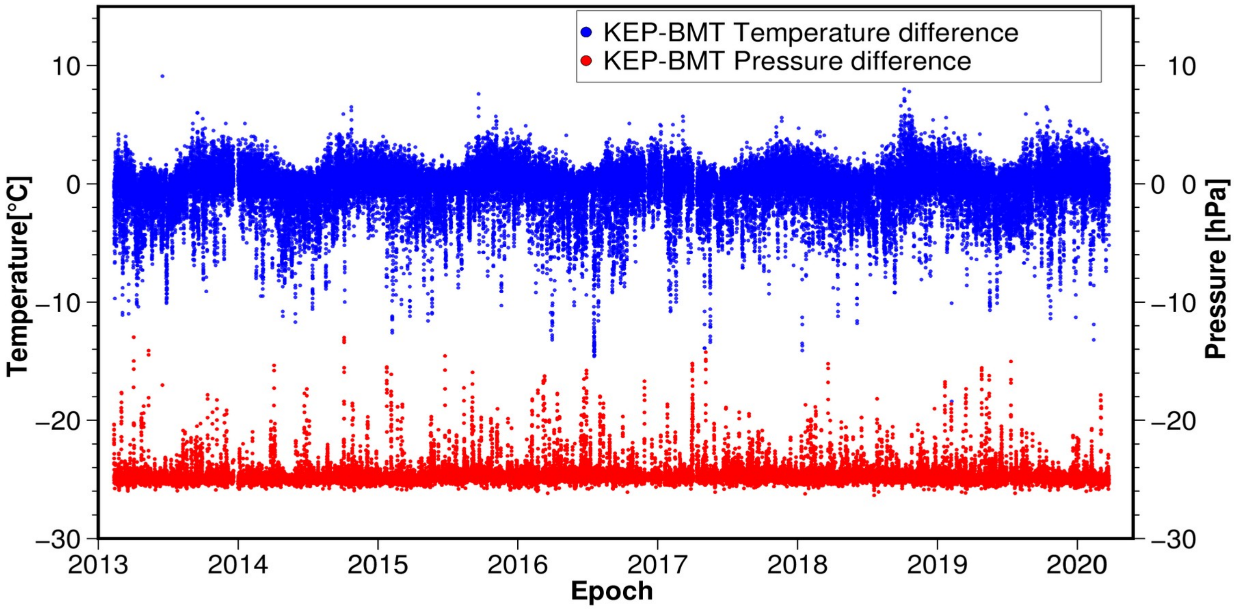
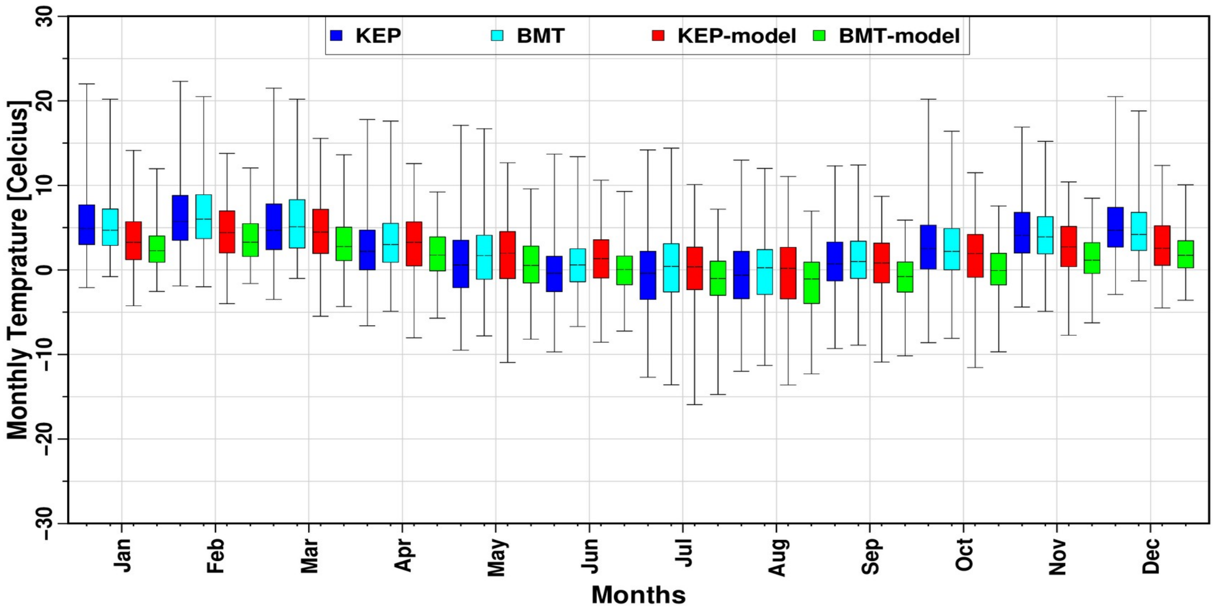



**Fig. 4. Difference between KEP and BMT temperature reading (blue) and the difference between KEP and BMT pressure observation (red). Time series are offset for clarity.**

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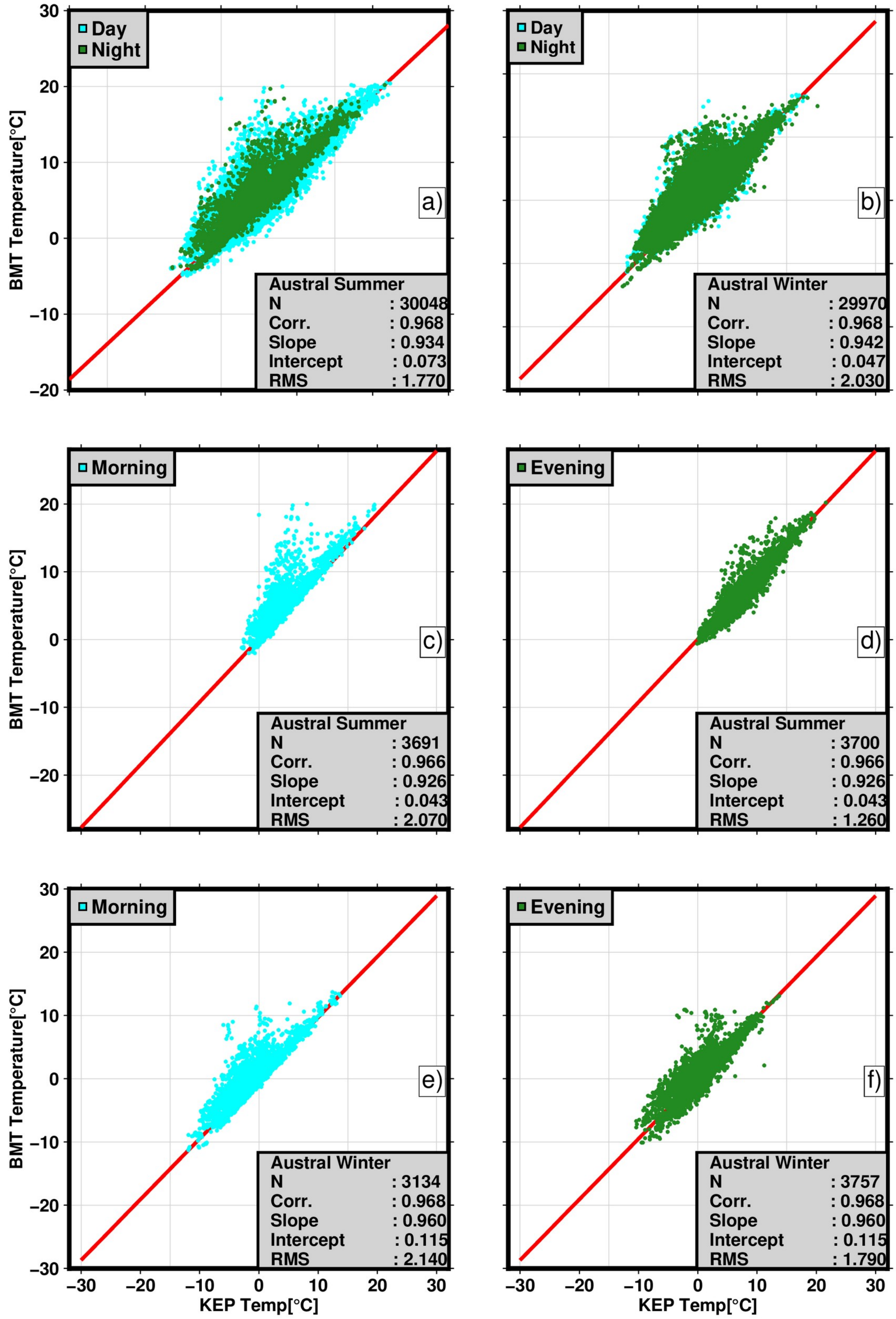



**Fig. 6. Temperature correlation plots for KEP and BMT observations, separating observations for Austral summer and winter, day and night, morning and evening periods.**

## *Cross-Evaluation of Wind and PWV observations*

- Wind roses, showing the distribution of winds at KEP and BMT, demonstrate the dominance of funneled winds at KEP due to its location in King Edward Cove whereas for BMT this effect is less pronounced. The KEP wind rose confirms the results of Bannister et al (2015). For both stations, the dominant wind direction is for northwesterly winds. As the sensors are different we cannot rule out small differences due to the differing instrumentation. (Figure 7)
- The PWV estimates for BMT derived from GNSS and those for KEP and BMT from the reanalysis model show seasonal variations with similar amplitudes and trends. Overall, a good agreement is evident. (Figure 8)
- The rose diagram of monthly PWV values shows the maximum values to cluster during February to early April while the minimum values show two distinct clusters, the first one in July and the second in late August. The maximum values reach around 20 mm while the minimum values are slightly above 0 mm. (Figure 10)

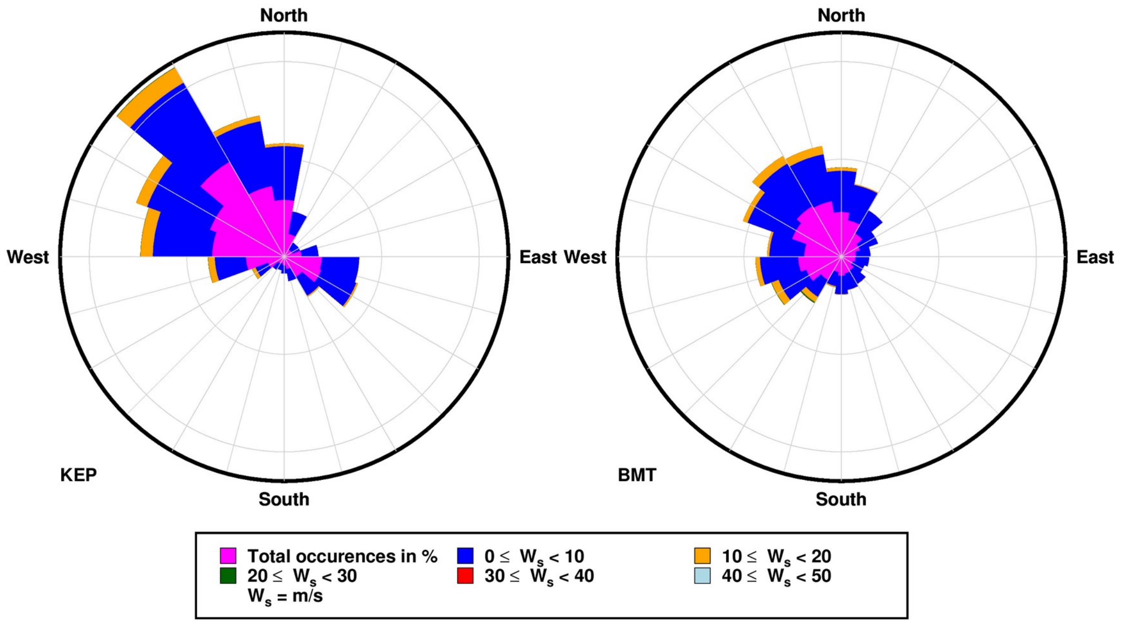
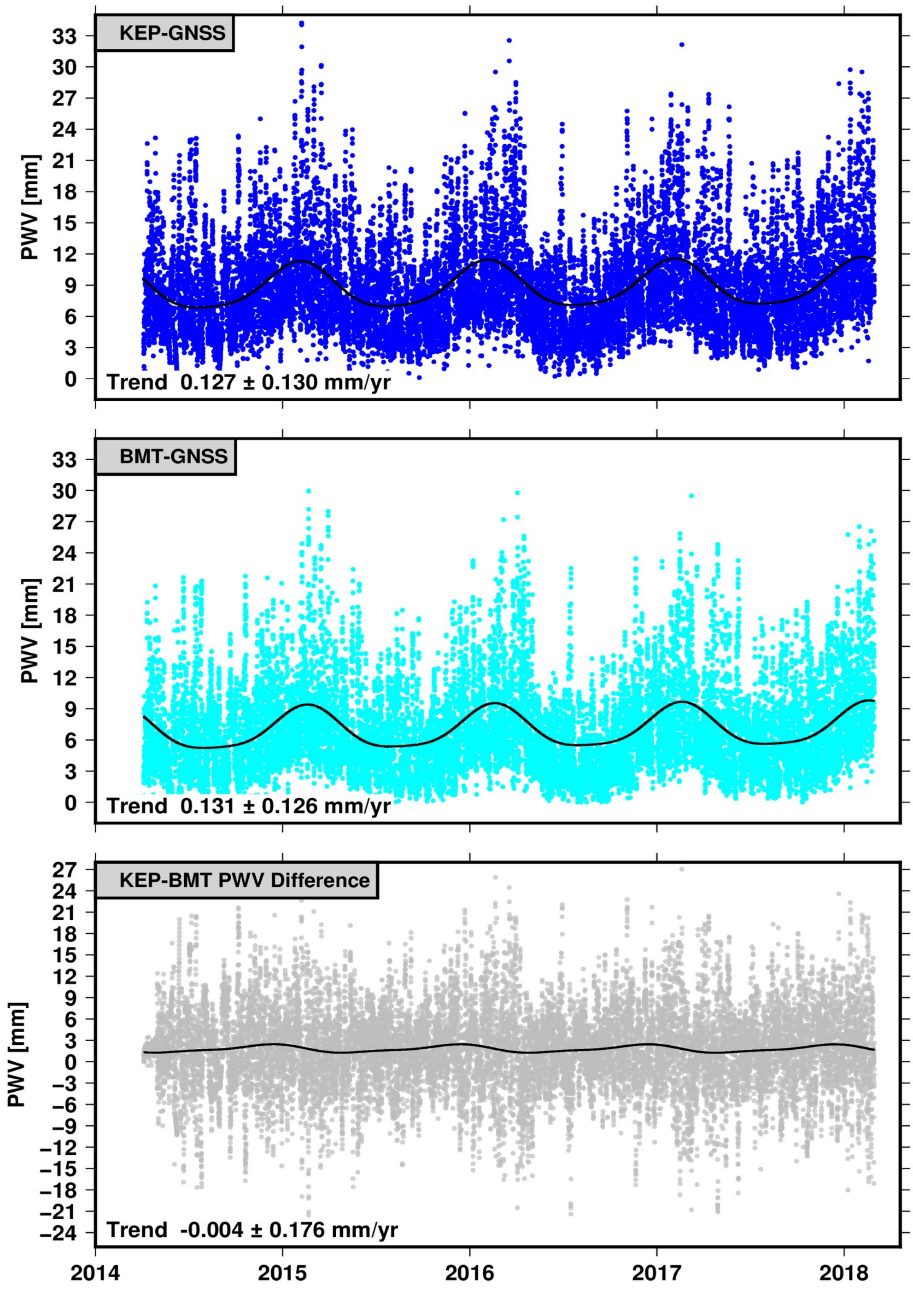



**Fig. 7. Wind rose histogram showing frequency (%), strength (m/s) of winds blowing from a particular wind direction (°) recorded at KEP and BMT from February 2013 to December 2020.**

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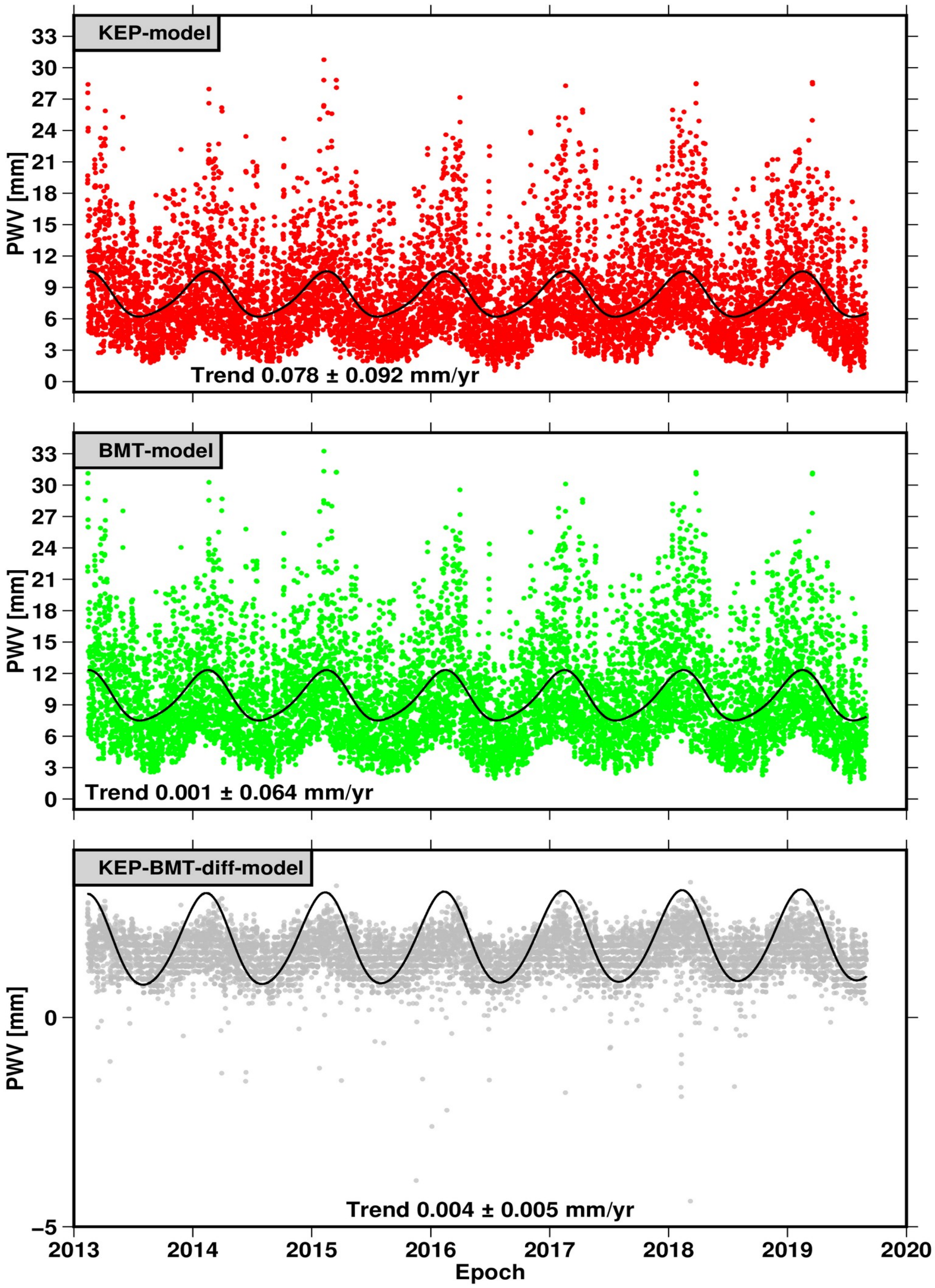


**Fig. 9. PWV estimates of KEP and BMT from ERA-Interim model and the difference between the two.**

- Figure 10, clearly illustrates the variations in PWV during the year, probably representing at least two distinct seasons on South Georgia Island. Generally, PWV variations exhibited significant seasonal dependence, with larger values in February and March and smaller values in July and August.

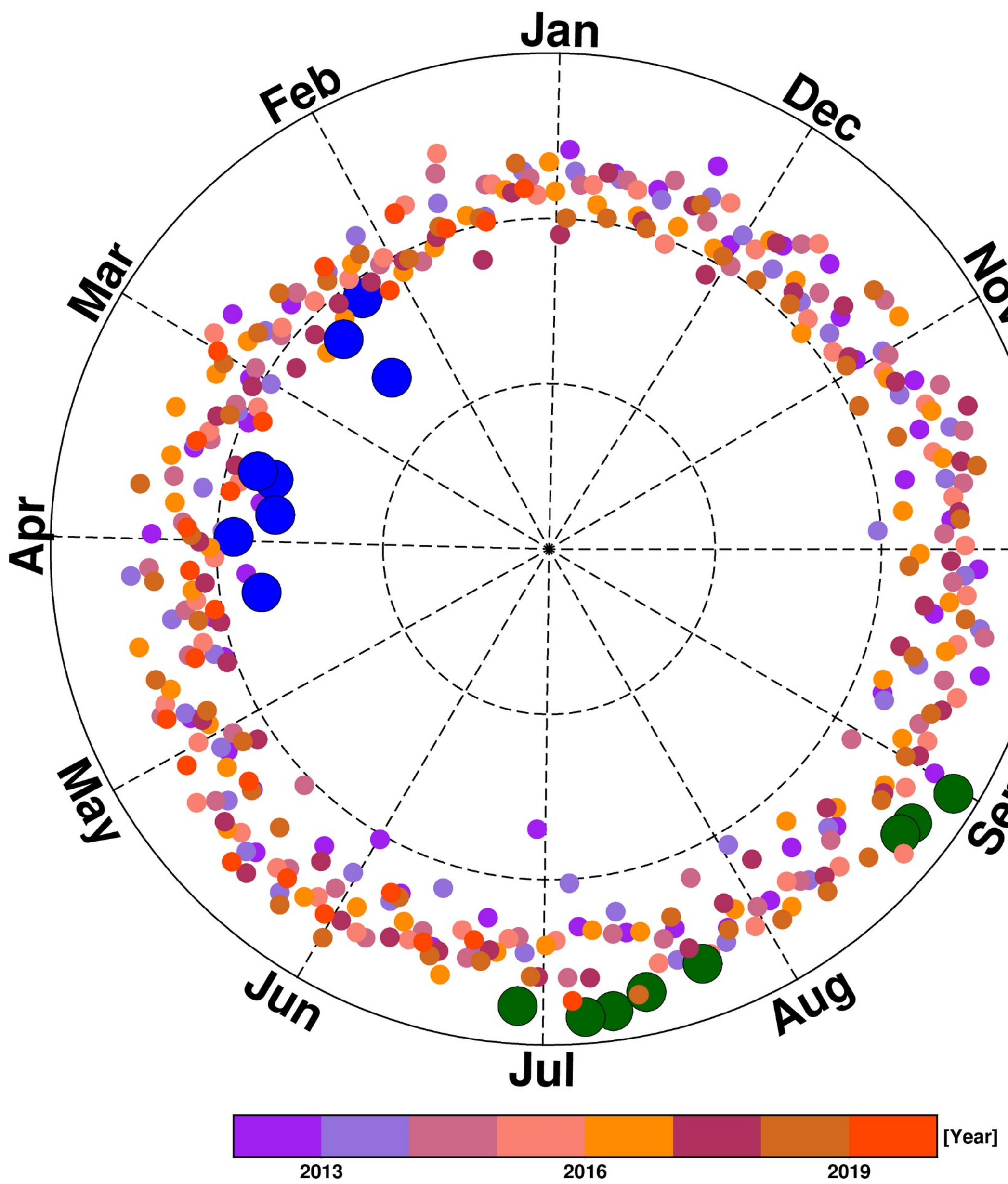


**Fig. 10. PWV rose plot of BMT with large circles indicating minimum (dark green) and maximum (dark blue) values. The colour of the small circles repeats the year.**

- The foehn case study shows that the events are clearly visible in the surface meteorological observations but to a lesser degree in the model values. We assume the model cannot represent these local events due to the grid resolution of the ERA-Interim reanalysis. PWV and ZWD from GNSS both clearly show the signature of the foehn events, however, the horizontal gradients cannot pinpoint these. During the foehn event, the predominant wind direction is northwestern, i.e. blowing from the central range of the mountains and likely passing over the Pinnacle and Echo passes. During the 30-31 March 2014 foehn event wind speeds of nearly 15 m/s were observed at BMT (Figure 11)

- Around 100 foehn events per year can be detected in the meteorological observations using our employed method. Statistically, this implies an event every 3-4 days. (Figure 11)

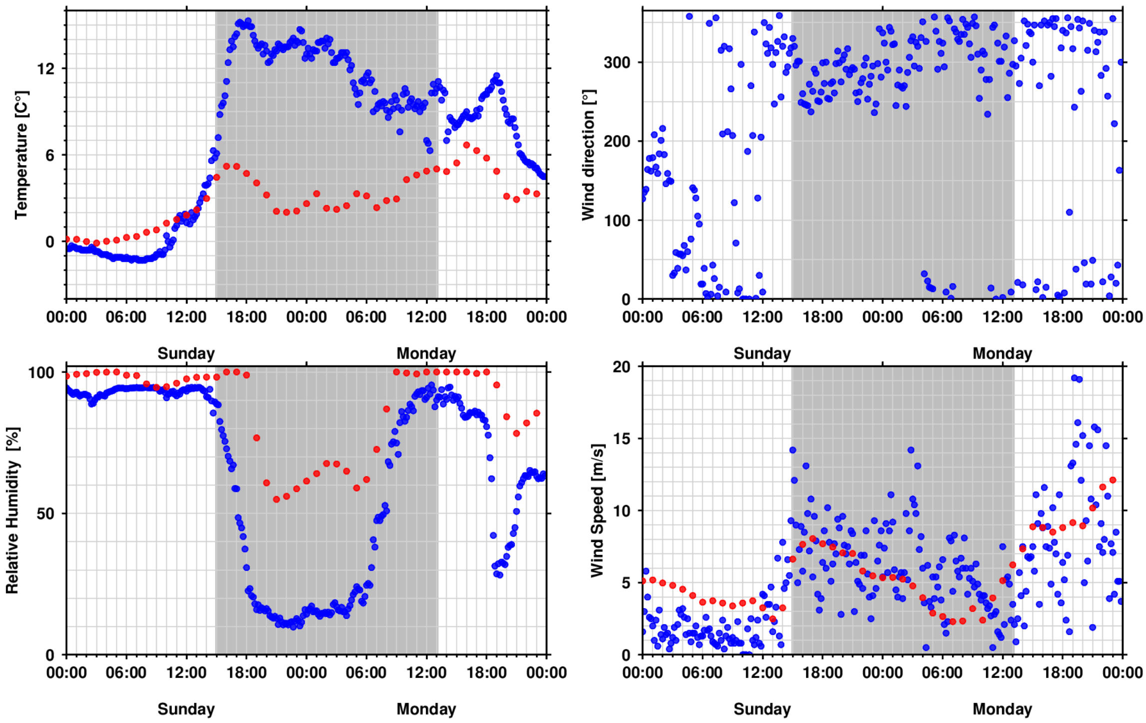


**Fig. 11. BMT station observed (solid blue circles) and modelled (red circles) represents European Centre for Medium-Range Weather Forecasts (ERA5) model air temperature, relative humidity, wind direction and wind speed for the 30-31 March 2014 foehn event. The gray shaded regions highlight the foehn event.**

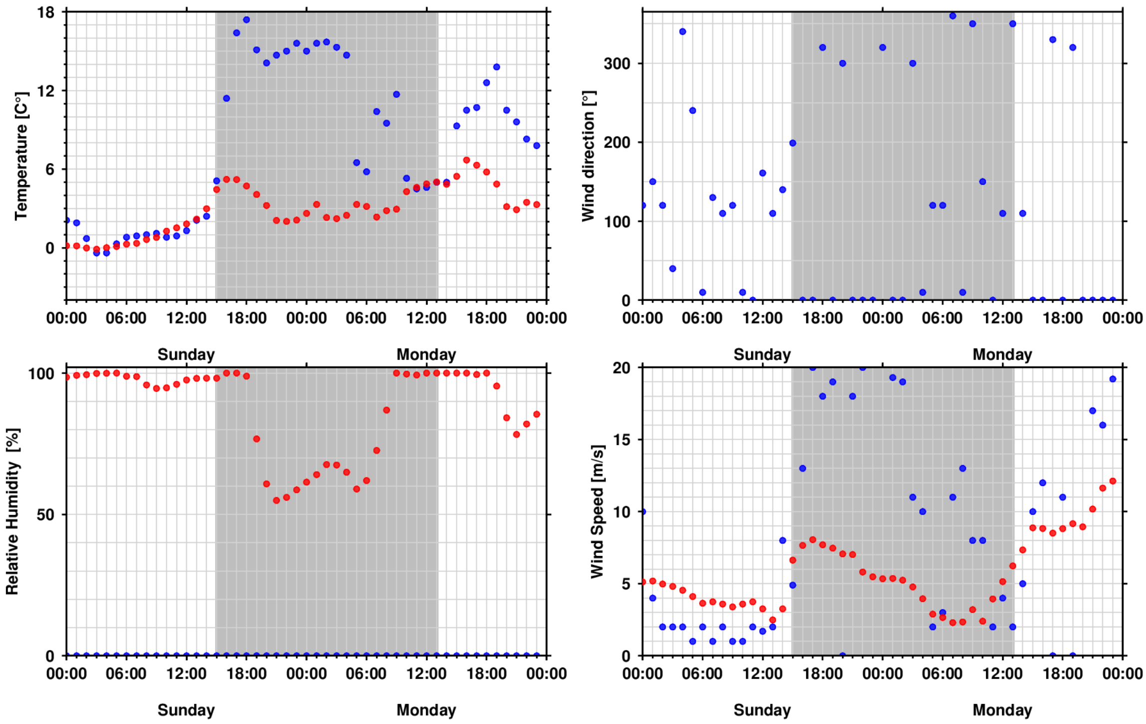


**Fig. 12. KEP station observed (solid blue circles) and modelled (red circles) represents European Centre for Medium-Range Weather Forecasts (ERA5) model air temperature, relative humidity, wind direction and wind speed for the 30-31 March 2014 foehn event. The gray shaded regions highlight the foehn event.**

**Table 2: The statistical conditions of the 772 and 1986 number of observed foehn events at the BMT and KEP stations. All change values shown here are relative to values observed at the time of foehn.**

| | BMT | | | KEP | | |
|---|---|---|---|---|---|---|
| **Descriptions** | **Mean** | **Maximum** | **Minimum** | **Mean** | **Maximum** | **Minimum** |
| Temperature (ºC) | 6.01 | 18.20 | -7.50 | 6.58 | 21.50 | -8.50 |
| Relative humidity (%) | 76.68 | 95.90 | 17.30 | - | - | - |
| Wind speed (m/s) | 4.85 | 49.60 | 0.00 | 8.58 | 30.87 | 0.00 |
| Wind Direction (º) | 196.00 | 360.00 | 0.00 | 213.67 | 360.00 | 0.00 |
| Temperature change(ºC) | 2.83 | 10.10 | 2.00 | 3.23 | 15.70 | 2.00 |
| Humidity change (%) | 12.64 | 41.10 | 0.10 | - | - | - |
| Wind speed change (m/s) | -0.54 | 33.30 | -17.80 | -2.32 | 22 | -31 |

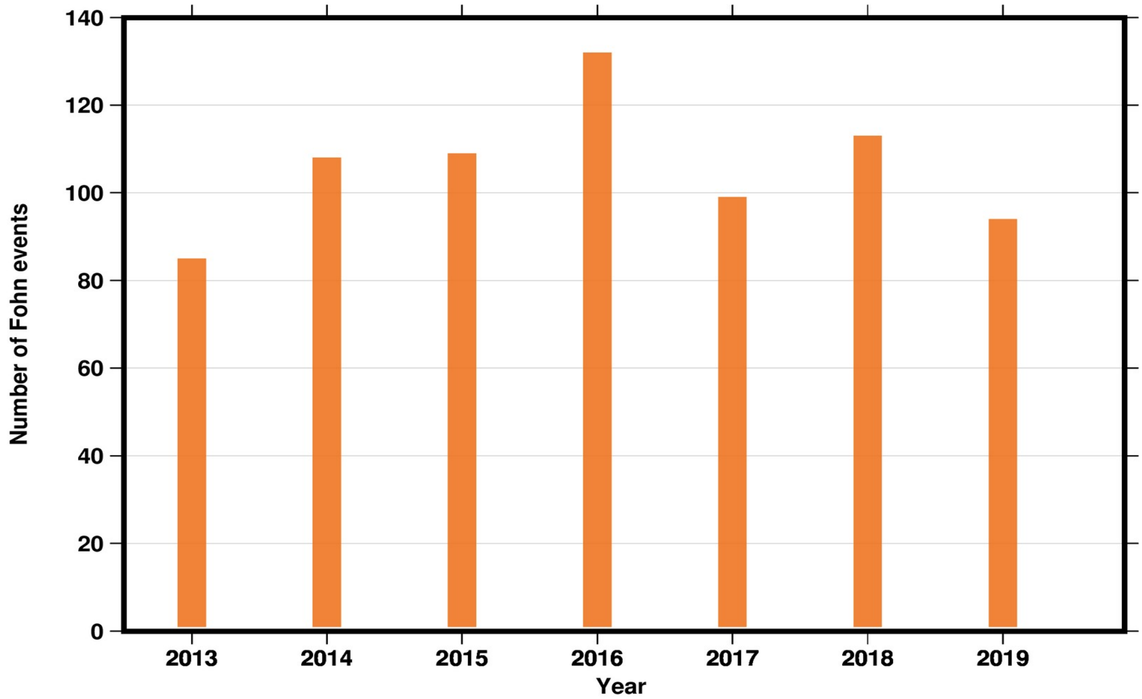


**Fig. 13. The yearly number of foehn events as identified by the above method recorded at BMT between February 2013 and March 2020 For 2020 only data from January to March were used.**

## *Conclusions and Acknowledgments*

- We have performed a first investigation of the meteorological surface observations at BMT, which is co-located with the KEPA GNSS station.
- Through cross-evaluations of these data with those of KEP, which uses a WMO-certified AWS, we have established BMT to have been operating well from 2013 to 2020. We observed similar features in all time series.
- We observed temperature differences between the BMT and KEP sensors reaching up to 15°C. We attribute this most likely to the different topography at KEP and BMT, with KEP being at sea level and frequently in the shadows of nearby mountains, predominantly Mt Duse. For example, high temperature differences can be observed in the morning hours when KEP will be in the shadow but BMT already receives direct sunlight. Other times of large temperature differences may be during foehn events.
- Compared to KEP, the wind recorded at BMT is suggested to be more omni-directional while maintaining the main wind direction as northwesterly. This is in line with the foehn winds coming off the central mountain range and passing over several passes.

- Moreover, we confirm the existence of warm, dry, and windy conditions at the unobstructed site BMT, which is consistent with the lee-side foehn events reported for KEP.
- The estimated PWV values decrease moderately from their maximum values in February and March, and their lowest values are observed during July and August. The PWV values clearly show the signature of the foehn events.

# Acknowledgments

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