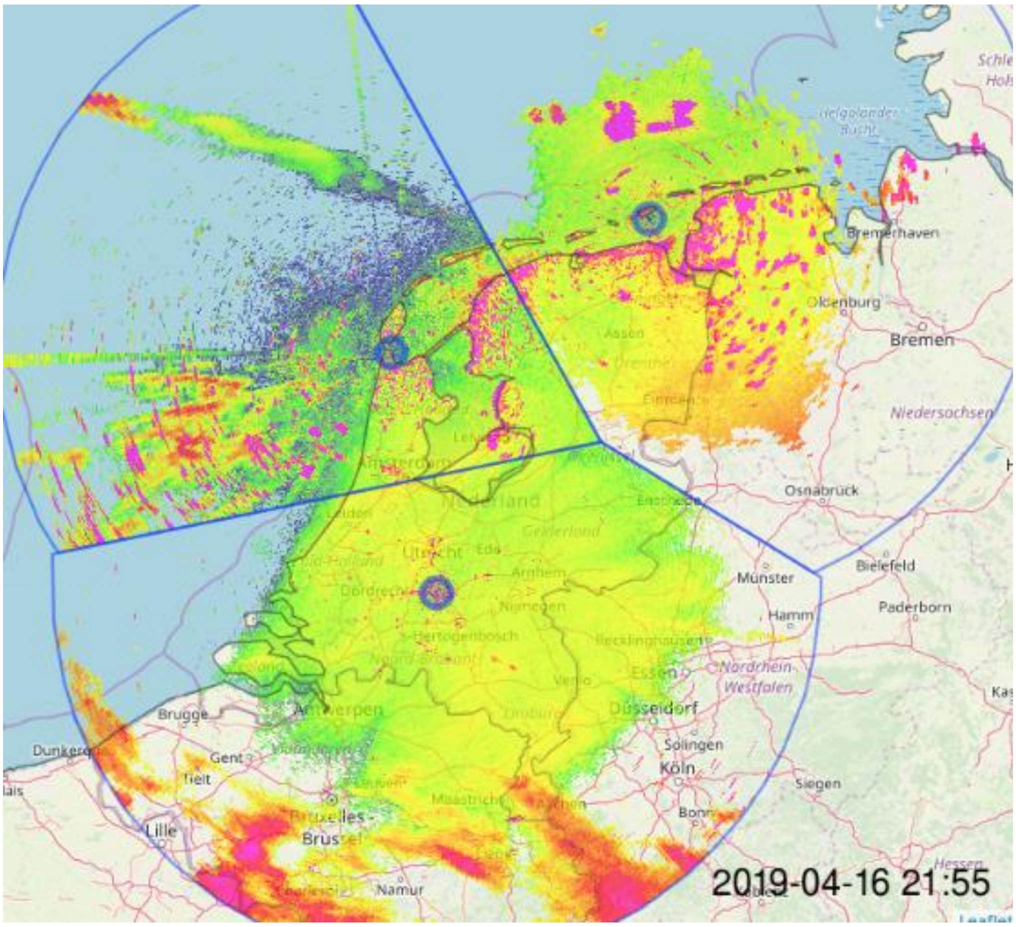
Prediction and measurement of high intensity bird migration using meteorological radar data in Eemshaven windpark

Shinneman, S.M., van Loon, E.E., Wijers, B.C., Bouten, W., 2020



UNIVERSITEIT VAN AMSTERDAM
Instituut voor Biodiversiteit en
Ecosysteem Dynamica

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1.0 Executive summary

The Eemshaven Showcase project was designed to explain how radar technologies can be used to monitor, understand and predict nocturnal passerine migration for the wind energy industry and to investigate how a system providing advance warning to initiate temporary shutdown procedures during peak nocturnal migration might be developed. The feasibility study and data analyses were commissioned the Province of Groningen, Rijkswaterstaat, the Ministry of Agriculture, Nature and Fishing, and the Ministry of Economic Affairs and Climate and carried out in 2018-2019 by a consortium consisting of 3 contractors: Bureau Waardenburg, Altenberg & Wymenga and the University of Amsterdam Institute of Biodiversity and Ecosystem Dynamics (IBED). Altenberg & Wymenga and Bureau Waardenburg describe their work in separate reports (Klop & Brenninkmeijer, 2020, Kleyheeg-Hartman, J.C. & A. Potiek, 2020), and the methodology and results related to those tasks carried out by IBED are detailed in this report. The integration report (Bouten, W. et al., 2020) presents a comparison of all the data collected for this project and provides a discussion of how results may be applied to the future development of a predictive model of migration specific to the Eemshaven wind farm.

A primary aim of this project was to investigate the feasibility of temporary shutdowns of wind turbines on nights with high intensity bird migration as a preferred mitigation measure for bird mortality during events of massive nocturnal migration. In order for a system supporting shutdowns to be operationally implemented by turbine operators in the future, the model must be able to forecast peak migration nights within the Eemshaven wind farm area with a lead time of 48 hours. During the autumn 2018 migration season, we were able to use weather forecasts, existing predictive models and expert knowledge about bird migration to forecast peak migration nights with a good degree of accuracy. These forecasts successfully supported 10 shutdown experiments. We predicted high intensity migration with a 48-hour lead time on 12 nights over the 10-week season; high bird densities were measured on 9 of the these predicted nights, and moderate densities were measured on 3 nights. On 3 nights we predicted high intensity migration when moderate or low migration was actually measured. During the spring 2019 migration season, the consortium carried out 12 collision casualty searches without shutdown experiments based on our forecasts. We were able to forecast 10 of 13 high intensity migration nights 48 hours in advance. On 5 nights we predicted high intensity migration when moderate or low migration was actually measured. Rain in Eemshaven or in the expected departure areas created more uncertainty in the spring forecasts.

Development of a future predictive model of bird migration for the Eemshaven wind farm will use bird movement data collected over multiple migration seasons with operational meteorological radars in Germany (located at Borkum and Emden) and the Netherlands (located at den Helder, Herwijnen and de Bilt). During this study, we were able to efficiently access, store and process raw data for these radars for autumn 2018 and spring 2019. We found occasional data gaps caused by radar outages and rain events, and static ground clutter such as wind farms and other large infrastructure created problems detecting biological signals at low altitudes along the coast at Eemshaven. However, data quality was high enough on most nights to use a bird detection algorithm to extract and visualize the desired biologically relevant information, including daily rhythms, altitude profiles and occurrence of peaks in migration intensity. The data showed daily patterns consistent with nocturnal passerine activity, with higher density peaks visible at low altitudes after sunrise and before sunset when nocturnal passerines are likely to be taking off or landing within the measured volume.

We used data from the meteorological radars to determine local and regional patterns of nocturnal passerine migration using variables derived from the data such as migration traffic rate, bird density and flight direction. In autumn 2018, very high intensity migration traffic rates were measured on 4 nights; weather conditions in the Netherlands and the North Sea region on those four nights were highly favourable to migration, with no rain and light winds under 5.0 m/s. These results indicate that adult and juvenile birds at nesting grounds and/or stopover areas in Norway, Sweden, and Denmark chose to depart at sunset in large numbers when weather conditions were favourable, especially after several days of unfavourable weather conditions, arriving at Eemshaven later in the night after crossing the North Sea. Most bird movement was measured below 2000 meters above mean sea level (amsl) and the highest densities were measured below 1000 meters amsl, which indicates that a significant portion of autumn migration could be occurring at altitudes relevant to the Eemshaven wind farm. When these results were compared to measurements from spring 2019, it appears that during autumn migration birds consistently flew at lower altitudes, possibly due to headwinds.

Bird migration traffic rates measured in spring 2019 were consistently lower than those measured in autumn 2018 indicating lower numbers of migrants in spring, which may be due to mortality of juveniles at wintering grounds or a greater use of migration routes located east of Eemshaven. Therefore, lower thresholds were used in the spring when classifying nights with high intensity migration. The spring peak migration season was about a week longer than in the autumn, and there were 10 nights when migration traffic rates calculated with data from the Borkum radar were considered high. Flight altitudes on peak nights at the end of March and in April were higher than in the autumn, with high intensities extending up to 3000 meters amsl. High intensity flows observed at higher altitudes (around 2000 meters amsl) may be indicative of migrants taking off outside of

the Borkum radar area and flying at high altitudes through the radar space during the night.
We compared migration patterns specific to Eemshaven with patterns in other areas of the Netherlands and with patterns predicted by the FlySafe model. Flight direction and altitudes recorded at the Borkum, Germany radar near Eemshaven and the Dutch radars were similar in autumn 2018 and spring 2019. There were 4 nights in autumn when high intensities were measured at all radars, suggesting that these were peak nights when pulses of mass migration were occurring regionally. However, migration intensities differed on other nights with higher intensities and a higher frequency of high intensity migration nights observed at the inland Herwijnen radar. During spring 2019, lower migration intensities were observed at all radars and there was much less overlap among peaks measured at different radars, suggesting that flow patterns are more spread out spatially and temporally in the spring. Comparison of the Borkum radar data with predictions from the existing FlySafe model of bird migration developed for the Netherlands and Belgium showed that a predictive model must be spatially and temporally specific in order to effectively support temporary shutdown operations at an individual wind farm.

This research is carried out in collaboration with Bureau Waardenburg and Altenburg & Wymenga under joint commission of the Province of Groningen, Rijkswaterstaat, the Ministry of Agriculture, Nature and Fishing, and the Ministry of Economic Affairs and Climate.

2.0 Forecasting bird migration peaks for temporary shutdown experiments and collision casualty searches

The purpose of developing a model that can predict high intensity bird migration is to support temporary shutdowns of wind turbines as a preferred mitigation measure for bird mortality. In order for a future model to be operationally implemented by turbine operators, the model must be able to forecast peak migration nights within the Eemshaven wind farm area with a lead time of 48 hours because operators must be able to adjust their energy budgets in advance to cope with temporary shutdowns.

This section describes our efforts to forecast peak migration nights triggering 10 temporary shutdown experiments during the autumn 2018 migration season and collision casualty searches on peak nights during the spring 2019 season. Shutdown experiments were not carried out in spring 2019. Methodology and results of the casualty searches are described in Klop & Brenninkmeijer, 2020; the integration report (Bouten, W. et al. 2020) includes comparisons of the search results with bird densities measured with radars.

Forecasting methodology

Prior to the autumn 2018 season, we developed a workflow designed to predict nights of high nocturnal migration 48 hours in advance. This workflow was based on a review of the literature, expert knowledge of seasonal patterns, spatial patterns and weather conditions favourable to regional migratory bird movements passing over or landing in Eemshaven. As part of the workflow, we checked two sources of information:

1. **FlySafe Bird Avoidance Model Service Centre website** (http://www.flysafe-birdtam.eu) which publishes hourly predicted migration intensities for two areas in the Netherlands and two areas in Belgium. This model is designed to alert military pilots to an increased possibility of collisions between aircraft and birds and does not predict migration in the Eemshaven area. However, it provides an indication of regional migration that is applicable to this project when combined with knowledge of local bird movements and forecasted weather conditions in Eemshaven. For example, the FlySafe model forecasted very high bird densities for the night of 18 October 2019, as shown in figure 2.0.

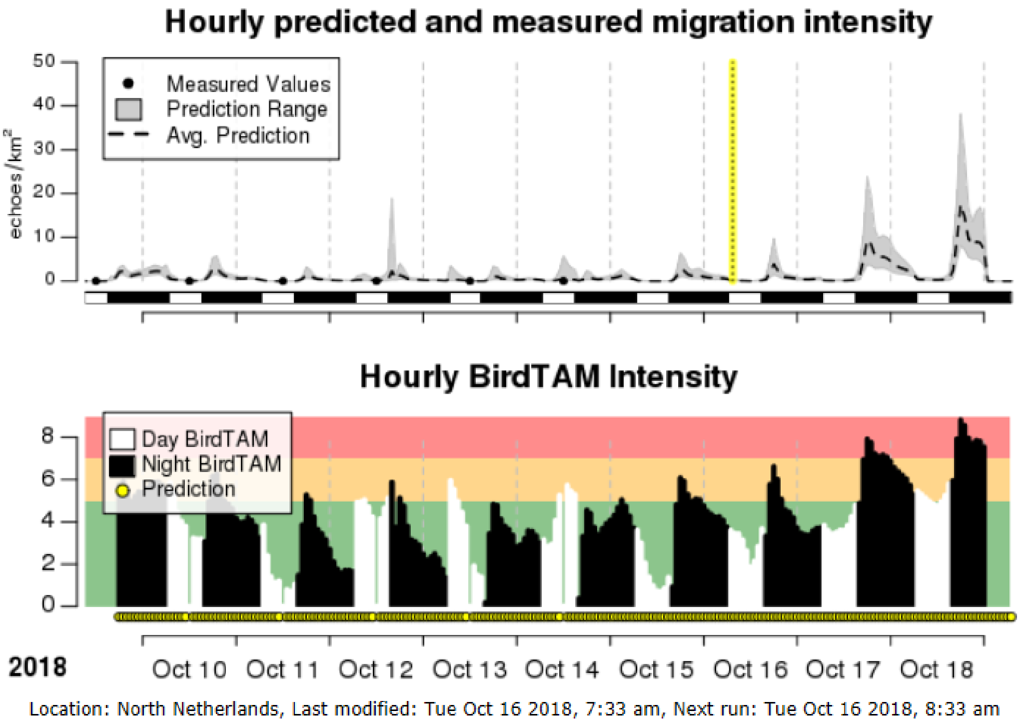


Figure 2.0. FlySafe Bird Avoidance Model forecast of bird densities for the North Netherlands location for the model run dated 16 October 2018 7:33 am, showing a very high forecast for 18 October 2019. Night hours are indicated with black bars. The model converts the predicted densities shown in the top graph to the BirdTAM warning values on the bottom graph. (http://www.flysafe-birdtam.eu). Our workflow used the yellow and red warning values as a trigger for considering whether a forecasted night might have a migration peak.

2. **Regional and local forecasts** of wind speed, wind direction, rain, fog and low or high pressure systems published online (e.g. www.windy.com European Centre for Medium-Range Weather Forecasts (ECMWF) model based forecasts of rain and wind; www.buienradar.nl 7-day wind, pressure and precipitation forecasts). We considered the following criteria as favourable for high nightly bird densities in the Eemshaven wind farm:
   - Light winds (<8-10m/s) and no rain or storms at bird departure locations and along migratory routes, especially after several days of unfavourable weather conditions since migration is often more intense after successive nights with unsupportive weather conditions.
   - Tailwinds or light crosswinds at bird departure locations and along migratory routes, especially when generated by regional low-or-high pressure systems (Bauer et al., 2018, Karlsson et al., 2011).
   - Local rain, fog, low cloud cover and low visibility in Eemshaven that may cause migrating birds to fly at turbine altitudes or take off/land in Eemshaven.

Figures 2.1 and 2.2 show the favourable 24-hour forecast for the peak migration night 18 October 2019 as an example. A center of high pressure over the western side of the North Sea created calm conditions and favourable winds at bird departure locations in Scandinavia and along the migratory route to the Netherlands.

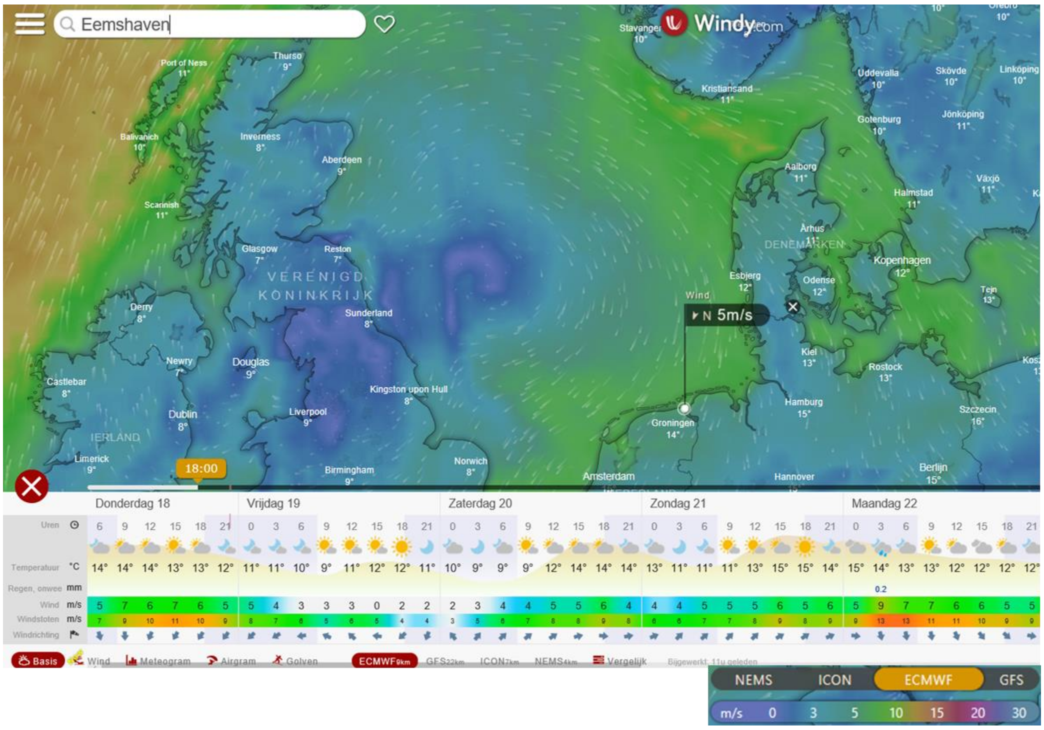


Figure 2.1. www.windy.com ECMWF-based 24-hour forecast of wind direction (arrows) and wind speed (color shading) for Eemshaven, bird departure locations and along migratory route for one of the peak migration nights, 18 October 2019. The forecast indicated very low wind speeds of less than 5 m/s, and tailwinds or crosswinds for birds departing Norway and Denmark. Actual weather conditions were similar to the 24- and 48-hour forecasts.

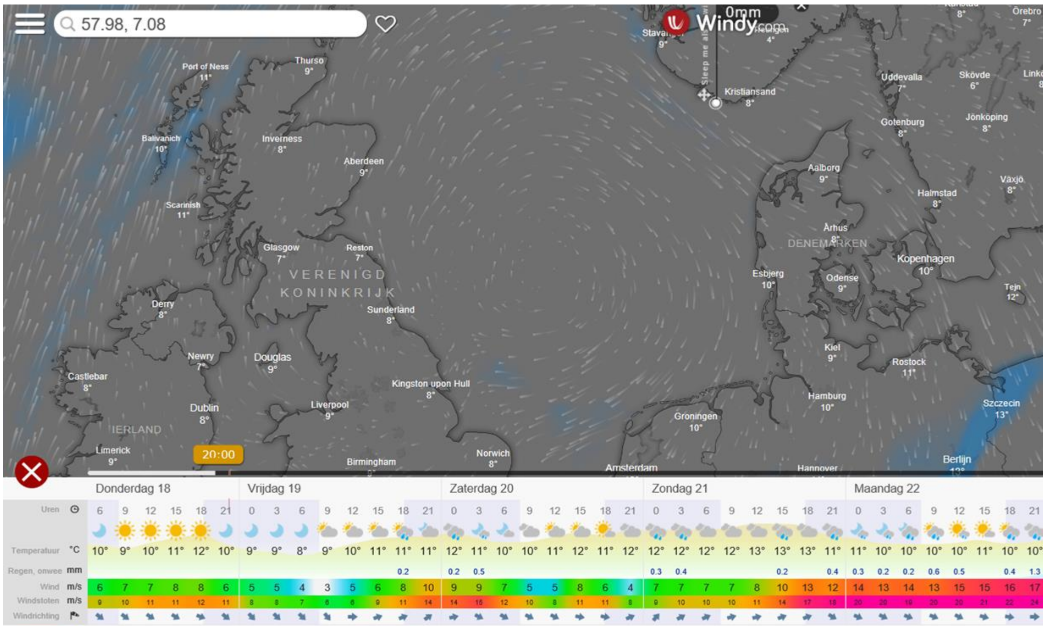


Figure 2.2. www.windy.com hourly ECMWF-based 24-hour forecast of rain intensity (color shading) for southern Norway and along migratory route for one of the peak migration nights, 18 October 2019. The forecast indicated no rain and no clouds for the entire night.

We looked at forecasts for the following locations, as seen in figures 2.1 and 2.2:

- Local weather forecasts for the Eemshaven area
- For the autumn season, forecasts for bird departure locations in southern Norway, Sweden and Denmark, along migratory routes from Scandinavia across the North Sea and the North Sea coast
- For the spring season, forecasts for bird departure locations in Belgium, northern France, northern Germany and the UK, and along migratory routes between the departure locations and the Netherlands

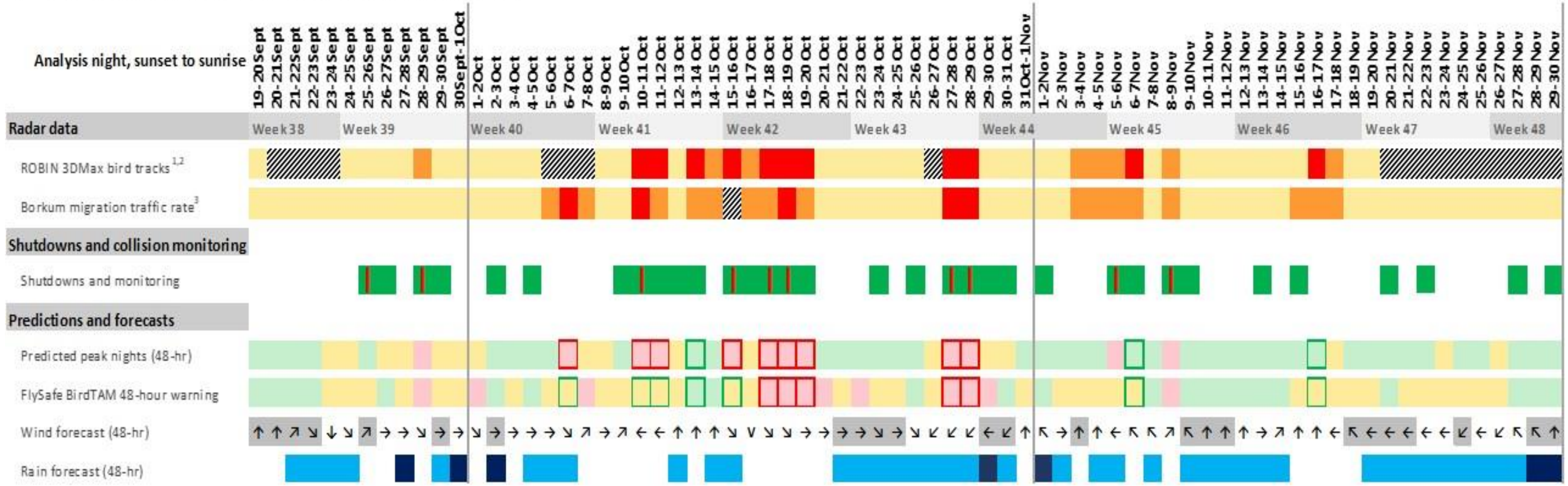
The UvA team checked the weather and migration forecasts based on the criteria described above every morning before noon during the autumn and spring seasons. If we determined that a high intensity migration night was likely to occur within the next 48-72 hours, we consulted with the consortium via a WhatsApp messaging group and confirmed that field crews were available to conduct the casualty searches in Eemshaven. If a shutdown experiment was also planned, we then informed the turbine operators that conditions were favourable for peak migration and requested the temporary shutdown approximately 48-72 hours in advance. In most cases, casualty search field crews were available and operators were able to shut down the turbine on nights when we predicted high intensity migration.

Temporary shutdown experiments and collision casualty searches - Autumn 2018

The project proposal planned for the autumn research field work season to span a 10-week period from 11 September 2018 to 15 November 2018, although routine casualty monitoring continued through 29 November. We began checking the forecasts and logging general observations about forecasted and actual conditions on 4 September and stopped on 29 November when the routine casualty monitoring was complete. Rain was forecasted and migration was low from 11 September until 18 September 2018, so that week is typically not included in analyses.

Nights with strong and moderate migration were predicted based on weather forecasts and expert knowledge of bird migration during the autumn season. Table 2.0 is a time line of the predicted peak migration nights that we determined based on forecasted information ('Predictions and forecasts'), the measured peaks in migration with the ROBIN 3D Max bird radar and the Borkum meteorological radar ('Radar data'), and shutdown nights and collision monitoring events ('Shutdowns and collision monitoring'). High nocturnal migration measured with either the ROBIN radar or the Borkum radar (shown in red in the 'Radar data' section of the table) was concentrated to 13 of 79 nights between 6 October and 17 November 2018. We were able to predict 9 of these high-density nights 48 hours in advance. Three of the high predicted nights had moderate measured densities because forecasts of rain around Eemshaven or the expected departure areas created uncertainty in the prediction. Three nights with high measured densities were not accurately predicted 48 hours in advance, while 3 nights were over-predicted.

Table 2.0: Time line for the autumn 2018 season of predicted peak migration nights, measured peaks, and timing of shutdowns and collision monitoring. High migration was predicted 48 hours in advance on 12 nights; high bird densities were measured on 9 of the predicted nights, and moderate densities were measured on 3 nights. Three nights with high measured densities were not accurately predicted 48 hours in advance, while 3 nights were over-predicted.



Legend

- low overnight migration
- moderate overnight migration
- high overnight migration
- data not available for more than 5 hours between 17:00 to 6:00 UTC
- days when monitoring was conducted
- nights when shutdowns were carried out
- predicted peak in migration occuring on night with high measured bird density
- night with high measured bird density that was not predicted
- high predicted nocturnal migration based on forecasts 48-hrs in advance
- high FlySafe BirdTAM warning for 48-hour forecast for North Netherlands (7-10)
- moderate predicted nocturnal migration based on forecasts 48-hrs in advance
- moderate FlySafe BirdTAM warning for 48-hour forecast for North Netherlands (5-7)
- low predicted nocturnal migration based on forecasts 48-hrs in advance
- low FlySafe BirdTAM warning for 48-hour forecast for North Netherlands (<5)

Notes

1: ROBIN 3DMax data classified as small birds and flocks.

2: ROBIN 3D Max bird radar maximum nightly migration rate:
yellow: < 800 birds/km/hr, orange: 800-1500 birds/km/hr; red: > 1500 birds/k/hr

3: Borkum meteorological radar maximum nightly migration traffic rate:
yellow: < 1500 birds/km/hr, orange: 1500-3000 birds/km/hr; red: > 3000 birds/k/hr

- → prevailing nighttime wind direction over migration route, 48-hour forecast (V=variable)
- forecasted regional nighttime wind speeds > 10m/s, 48-hour forecast
- heavy/consistent rain over Eemshaven and/or migration route, 48-hour forecast
- light/ spotty rain over Eemshaven and/or migration route, 48-hour forecast
- no rain over Eemshaven and/or migration route, 48-hour forecast

were measured with the ROBIN radar and/or Borkum radar. We aimed to schedule the 10 shutdowns on as many forecasted peak nights as possible, but we also tried to space them across the 10-week period to be able to capture temporal differences in bird mortality (e.g. different weather conditions that may cause birds to migrate at higher altitudes). The 25 September shutdown was scheduled on a night when light to moderate migration was predicted because we wanted to carry out 1-2 shutdowns during the month of September. Table 2.1 provides details regarding the timing and turbines used for the 10 shutdowns.

Table 2.1. Details of autumn 2018 temporary shutdown experiments at Eemshaven wind park

Shutdown	Start date-time of shutdown (UTC)	End date-time of shutdown (UTC)	Sunset (UTC)	Sunrise (UTC)	Bakker Bierum turbines	Growind turbines	Engie turbines
1	9/25/2019 18:00	9/26/2019 6:00	17:25	5:24	1, 3	1, 2, 6, 7, 8, 11, 19, 21	
2	9/28/2019 18:00	9/28/2019 6:00	17:18	5:29	1, 3	1, 2, 6, 8, 12, 19, 20, 21	
3	10/10/2019 18:00	10/11/2019 6:00	16:49	5:50	1, 3	1, 2, 6, 7, 11, 12, 20, 21	
4	10/15/2019 18:00	10/16/2019 6:00	16:38	6:00	1, 3	1, 2, 7, 8, 11, 12, 19, 20	
5	10/17/2019 18:00	10/18/2019 6:00	16:33	6:03	1, 3	1, 6, 7, 8, 11, 12, 19, 21	
6	10/18/2019 16:00	10/19/2019 6:00	16:31	6:05	1, 3	2, 6, 7, 8, 11, 12, 20, 21	
7	10/27/2019 16:00	10/28/2019 7:00	16:12	6:24		2, 6, 7, 12, 19, 20	3, 5, 6, 8
8	10/28/2019 16:00	10/29/2019 7:00	16:10	6:26		1, 6, 8, 11, 12, 19, 21	4, 7, 9
9	11/5/2019 15:00	11/6/2019 7:00	15:54	6:41	1	1, 2, 7, 11, 20	3, 5, 6, 8
10	11/8/2019 15:00	11/9/2019 7:00	16:49	7:46	3	1, 8, 11, 12, 19, 21	4, 7, 9

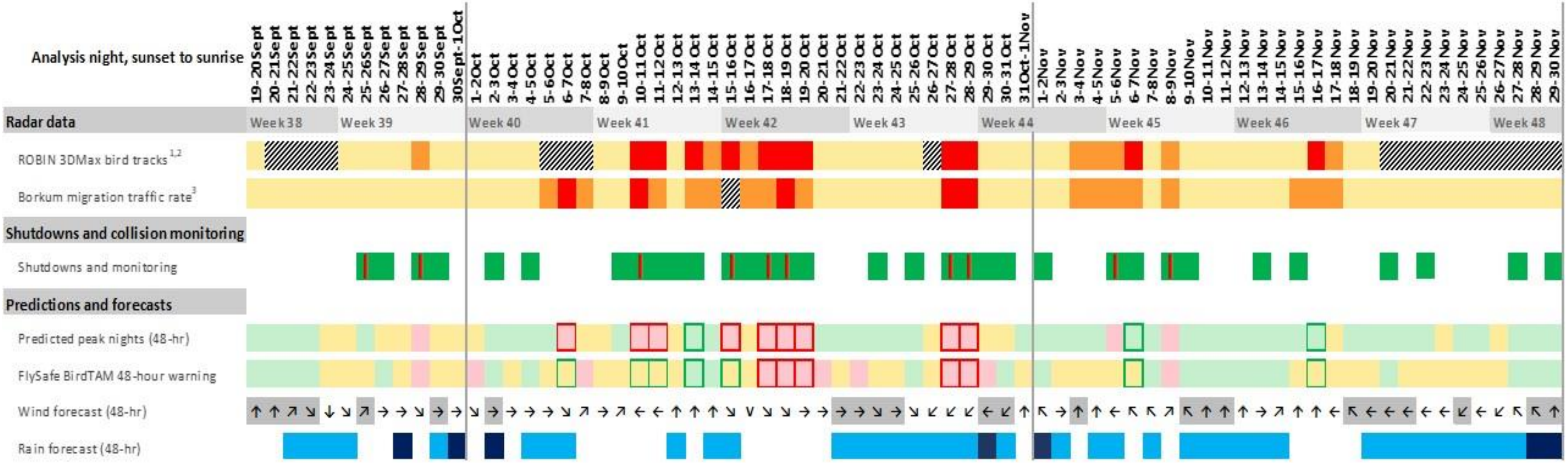
All times shown in Coordinated Universal Time zone (UTC). Eemshaven is in Central European Time zone (CET = UTC + 2 hours before daylight savings time (DST) ended on 28 October 2018; CET = UTC + 1 hour after DST change.

Collision casualty searches – Spring 2019

Spring field work was initially proposed for the period of 1 March to 30 April 2019, but we continued migration forecasting and casualty searches through 12 May due to heavy rains during the first 2 weeks of March that delayed the start of field operations. As shown in table 2.2, 21 collision monitoring searches were conducted between 4 March and 2 May 2019. No shutdown experiments were performed in spring 2019 because no collision casualties were found under shutdown turbines during the autumn 2018 experiments.

Table 2.2 is a time line of the predicted peak migration nights based on forecast information ('Predictions and forecasts'), measured peaks in migration ('Radar data'), and collision monitoring events ('Collision monitoring'). We were able to forecast all of the 13 nights with the highest migration densities 48 hours in advance except for 3 nights. On 5 nights we predicted high intensity migration when moderate or low migration was actually measured. Rain forecasted for Eemshaven or in the expected departure areas created more uncertainty in the migration forecasts.

Table 2.3: Time line for the autumn 2018 season of predicted peak migration nights, measured peaks, and timing of shutdowns and collision monitoring. High migration was predicted 48 hours in advance on 12 nights; high bird densities were measured on 9 of the predicted nights, and moderate densities were measured on 3 nights. Three nights with high measured densities were not accurately predicted 48 hours in advance, while 3 nights were over-predicted.



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3.0 Meteorological radar data access, storage and quality

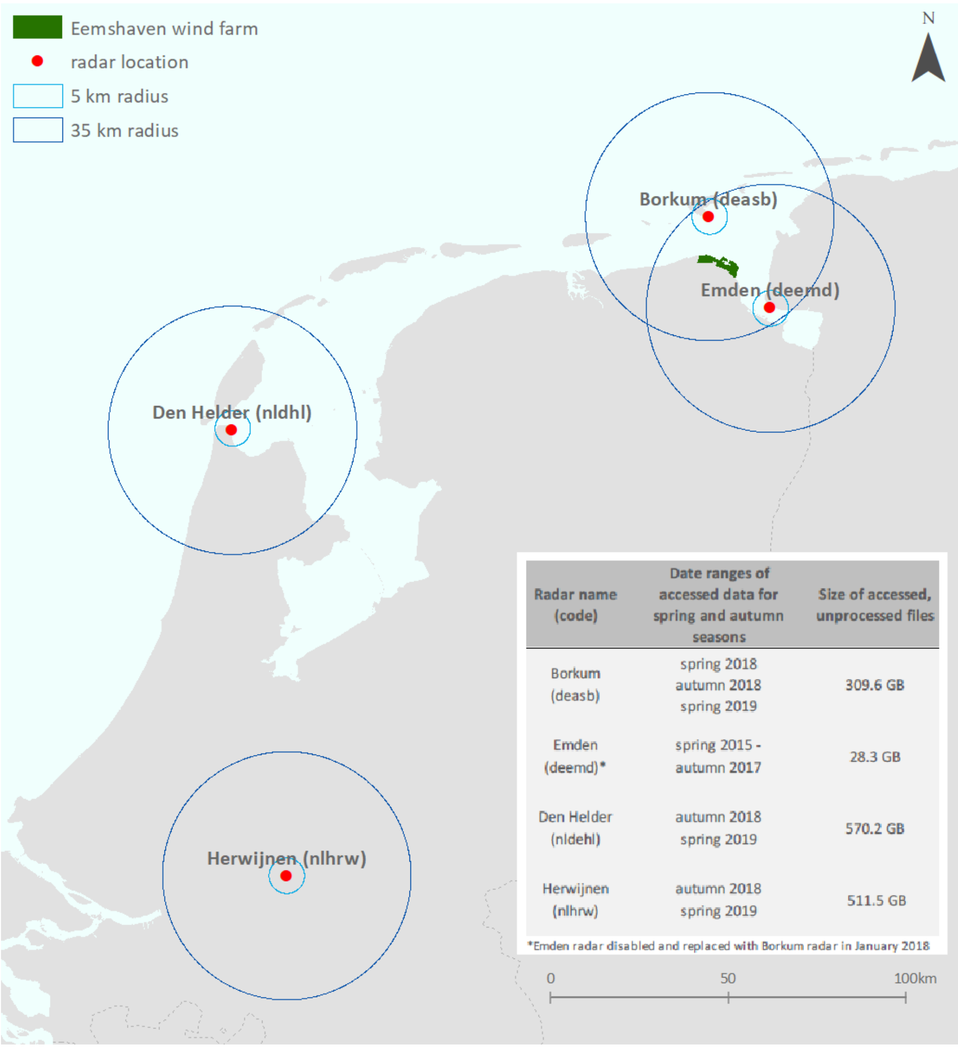
The German Weather Service (Deutscher Wetterdienst - DWD) and the Royal Dutch Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut - KNMI) operate a network of single- and dual-polarization weather radars that can be processed to extract local and regional biological signals (Shamoun-Baranes et al., 2014). Single-polarization radar data provides basic information on reflectivity and radial velocity from which we can calculate bird density, direction and speed (van Gasteren et al., 2008). Dual-polarization radars collect additional parameters that can be used to improve data processing, such as automated filtering of precipitation (Dokter et al., 2010). Meteorological radar data is typically available for multiple countries and going back multiple years, making it an ideal input for predictive models of bird migration especially when used in conjunction with more spatially and temporally specific data collected with a dedicated bird radar (Shamoun-Baranes et al., 2019, Nilsson et al., 2018).

Raw meteorological data is stored in HDF5 files called polar volumes which consist of multiple scans (datasets) of measured parameters like reflectivity and radial velocity. Each dataset is created as the radar rotates at different elevation angles while recording signals created by objects in the air. These two-dimensional datasets are packaged together into three-dimensional volume data. The raw files also provide metadata about the radar and the data (Stepanian et al., 2014).

DWD provided data for two single-polarization Doppler radars with current and historical coverage of the Eemshaven wind farm area. The Emden radar, located about 17 km southwest of Eemshaven, collected single-polarization (horizontal) data from 1994 until February 2018, when it was replaced with a temporary, single-polarization system in Borkum, located 13 km north of Eemshaven (figure 2.1). DWD expected to install a permanent, dual-polarization radar in Borkum in 2019, but it has been postponed until further notice. We obtained data for Emden for 2014-2018 and for Borkum for February 2018-May 2019 from DWD. We also obtained data from KNMI collected with dual-polarization radars located in Den Helder and Herwijnen in order to better understand regional migration fluxes (see sections 5 & 6 for analysis of processed results).

The primary objective of this project is to assess the feasibility of creating a future predictive model of bird migration in and around the Eemshaven wind farm. Meteorological radar data collected over multiple migration seasons will be essential to the development of the model, so a first step in this project was to access, store and assess the quality of raw data collected with weather radars in Germany and the Netherlands.

We have accessed and stored over 1.4 TB of raw files during the project, and the majority of the raw files have been processed to extract biological information using the vol2bird bird detection algorithm within the open source R package bioRad (Dokter et al., 2019). We focused on data for dates that overlap with the operation of the ROBIN 3DMax bird tracking radar (detailed in Kleyheeg-Hartman, J.C. & A. Potiek, 2020) during autumn 2018 and spring 2019 migration seasons. This task also provided experience and knowledge important to the future development of a national data infrastructure.



Radar name (code)	Date ranges of accessed data for spring and autumn seasons	Size of accessed, unprocessed files
Borkum (deasb)	spring 2018 autumn 2018 spring 2019	309.6 GB
Emden (deemd)*	spring 2015 - autumn 2017	28.3 GB
Den Helder (nldehl)	autumn 2018 spring 2019	570.2 GB
Herwijnen (nlhrw)	autumn 2018 spring 2019	511.5 GB

*Emden radar disabled and replaced with Borkum radar in January 2018

Figure 3.0. Location of the Eemshaven wind farm and the German and Dutch meteorological radars used in this study. Although the maximum range of detection of weather radars is approximately 180 km, processed data contains biological signals up to 50 km from the radar. At lower altitudes relevant to wind farms, accurate and specific information on bird movement can be extracted for a volume 5-35 km around the radar and up to 4000 meters in altitude, depending on the location of the reflected object within the radar volume. **Inset table:** Date ranges and file sizes of meteorological radar data accessed for this project.

The German radar data belonging to DWD was only available upon direct request and through a secure connection. We accessed data collected with Dutch radars with a different method because the Royal Dutch Meterological Institute has made their data publicly available. Raw files were accessed and stored as shown in figure 3.1, then processed using the vol2bird detection algorithm to extract biological signals from meteorological radar data (Dokter et al., 2019). See section 4 for details regarding the algorithm.

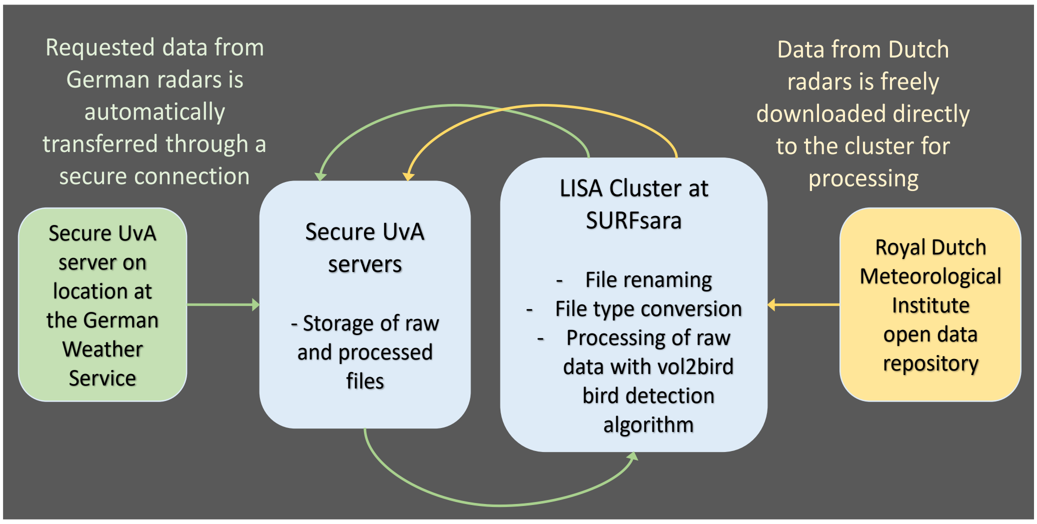


Figure 3.1. Workflow used to access, store and process German and Dutch meteorological radar data.

Although this task required large amounts of data storage and computing power, we were able to access and store the majority of the data needed for the feasibility study, investigation of regional migration and local patterns, and comparison with the ROBIN 3D Max bird tracking radar data. In addition, the quality of the data was sufficient for us to be able to process and visualize the desired biologically relevant information. Data quality for the Borkum radar was high during autumn 2018 with only one outage in mid-October and very little rain clutter. Data quality in spring 2019 was lower with several short outages throughout the season and several periods of clutter caused by rain, but quality was still high enough to measure biological signals and discern patterns in 3D movement.

Static and dynamic clutter

Signals of bird movement may be masked by static clutter created by wind turbines, urban areas, and ships, especially at lower altitudes below 200 m amsl. Majority of the reflectivity due to static clutter is removed by the meteorological data provider using clutter filters, but it is important to understand how much of the radar area is being

masked by static clutter and where the areas are located relative to the areas and flight paths being used by the birds.
Static clutter is best visualized on plan position indicator maps which show parameters from the raw radar files plotted over a background map prior to processing with the bird detection algorithm (figure 3.2). Clutter correction (ccor) values indicate whether the data provider has detected static clutter. Pink areas on ccor images indicate a zero value and therefore have no detected clutter. Non-zero values indicate where the data provider has detected static clutter that will be removed from total reflectivity (DBZ) values that will be processed with the bird detection algorithm to calculate bird densities. A plot of total reflectivity (DBZ) values shows bird and precipitation signals overlaid on a background map with areas of static clutter removed.

As seen in figure 3.2, Eemshaven and nearby coastal areas have wind farms and other structures that consistently create static clutter detected by the radar. Because the static clutter masks biological signals, birds flying at low altitudes in areas with wind farms or other static clutter are not detected or included in calculations of bird densities.

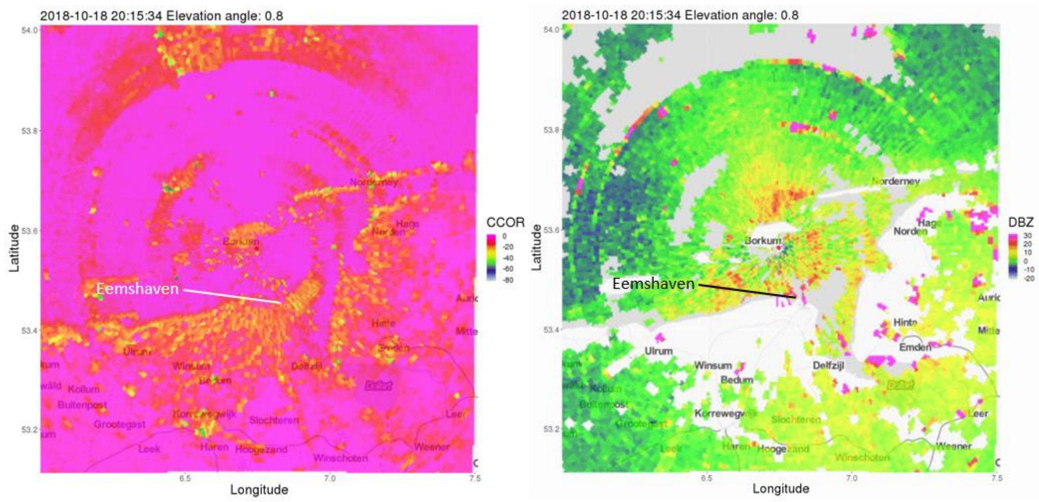


Figure 3.2. Plan position indicator plots of the Borkum radar data collected on 10 October 2018 at 20:15 UTC for the lowest elevation angle (0.8). Left image: map of clutter correction (ccor) values; non-zero values indicate where the data provider has detected static clutter that will be removed from total reflectivity (DBZ) values. Right image: Total reflectivity (DBZ) values show bird and precipitation signals overlaid on a background map. Reflectivity values in areas of static clutter removed. As a result, birds flying at low altitudes in areas with wind farms or other static clutter are not detected or included in calculations of bird densities.

Dynamic clutter changes over time and space and is usually caused by precipitation moving through the radar volume. Rain contamination covers bird signals that might have otherwise been recorded by the radar and is usually visualized as very high reflectivity (pink) on plots of raw reflectivity data, as seen in figure 3.3.

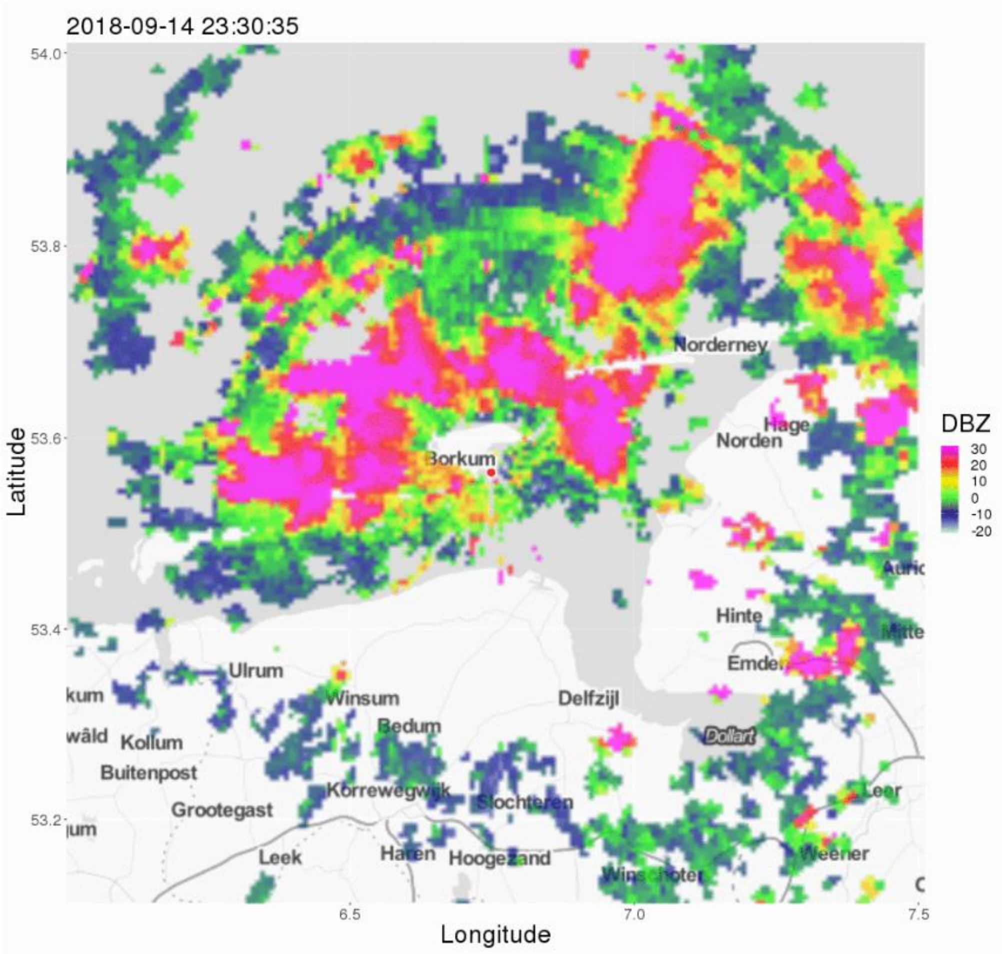


Figure 3.3. Plan position indicator map of total reflectivity (DBZ) measured at the lowest elevation with the Borkum meteorological radar at 23:30 UTC on 14 September 2018. Large areas of high reflectivity to the north of Borkum which appear pink in the image are areas of rain which mask bird signals and are removed from the dataset by the bird detection algorithm.

Vol2bird, the bird detection algorithm used to extract biological signals from the raw meteorological data, is able to remove reflectivity values identified as rain from the dataset. As seen on the night of 6-7 October (figure A.3 of the appendix to this report), areas at a specific altitude and time stamp where rain was detected will be shaded grey or appear blank on the volume bird density graphs indicating zero or null values for the bird density value. In addition, the algorithm is usually not able to detect bird movements at altitudes above and below where the rain was detected, although small birds like nocturnal passerines are unlikely to migrate during long or intense rain events (Nilsson et al., 2019). As seen on the night of 24-25 April (figure A.4 of the appendix to this report), sometimes small areas of high density at the leading or trailing edge of a precipitation event are not filtered out and cause a high, thin peak in migration traffic rate. It is important that these peaks are not mistaken for peaks in bird movement.

4.0 Extracting spatial information on bird movement within the domain of a weather radar

Meteorological radar data capture biological signals that can be extracted separately from non-biological information, like precipitation and ground clutter. To accomplish this, we apply an automated bird detection algorithm called vol2bird using the open source R package bioRad that has been developed and improved upon over the past 10 years (Dokter et al., 2010, Dokter et al., 2019).

Section 5 presents visualizations of these processed results, showing daily rhythms, altitude patterns and occurrence of peaks in migration intensity. The existing bird detection algorithm allows us to detect mean density, mean speed and mean direction of birds at different altitudes within the volume, ranging from distances 5-35 km from the radar and altitudes from ground level to 4000 m. However, the radar covers a much larger area. The data also contains more spatially explicit information that is relevant to understanding movement patterns within the smaller wind farm area and at lower altitudes relevant to calculating collision risk.

A technical challenge during the course of this project was to improve the methodologies we use to process the radar data, specifically within the context of future development of a predictive model of migration specific to the Eemshaven wind farm. To predict nights of high intensity migration in Eemshaven, we must also have a clear understanding of regional patterns of nocturnal migration across northwest Europe.

To this end, we have started to develop a method that is able to integrate reflectivity data of up to 20 meteorological radars into a single composite map for particular time stamps (Kranstauber et al., 2020). The maps also integrate the data over the entire altitudinal range using data from all the radar scans measured at different elevations, as shown in figure 4.0.

This figure also illustrates how the radars, some of which can collect data in a radius up to 100 km from the radar, are not distributed on a regular grid. The method must account for this variation in the geographic overlap across the datasets, as well as differences in the airspaces sampled with each elevation scan and at different distances from the radar. We have successfully applied this method to historical data from 2017 that could be used for model development in the future to be able to visualize spatial-temporal patterns in bird migration across the region. Continued refinement of the method will be necessary to remove non-biological clutter such as rain, as seen by the pink areas in the figure located north of the Netherlands, and wind parks, as seen along the IJsselmeer coast at

Urk. A movie of the Dutch and Belgian radars clearly shows that there are almost no birds during rainy nights (1-2 October 2016) but increasing migration in the nights from 2-3 October to 4-5 October 2016). The movie can be found here: https://surfdrive.surf.nl/files/index.php/s/s4R9A3ABsS01KOI

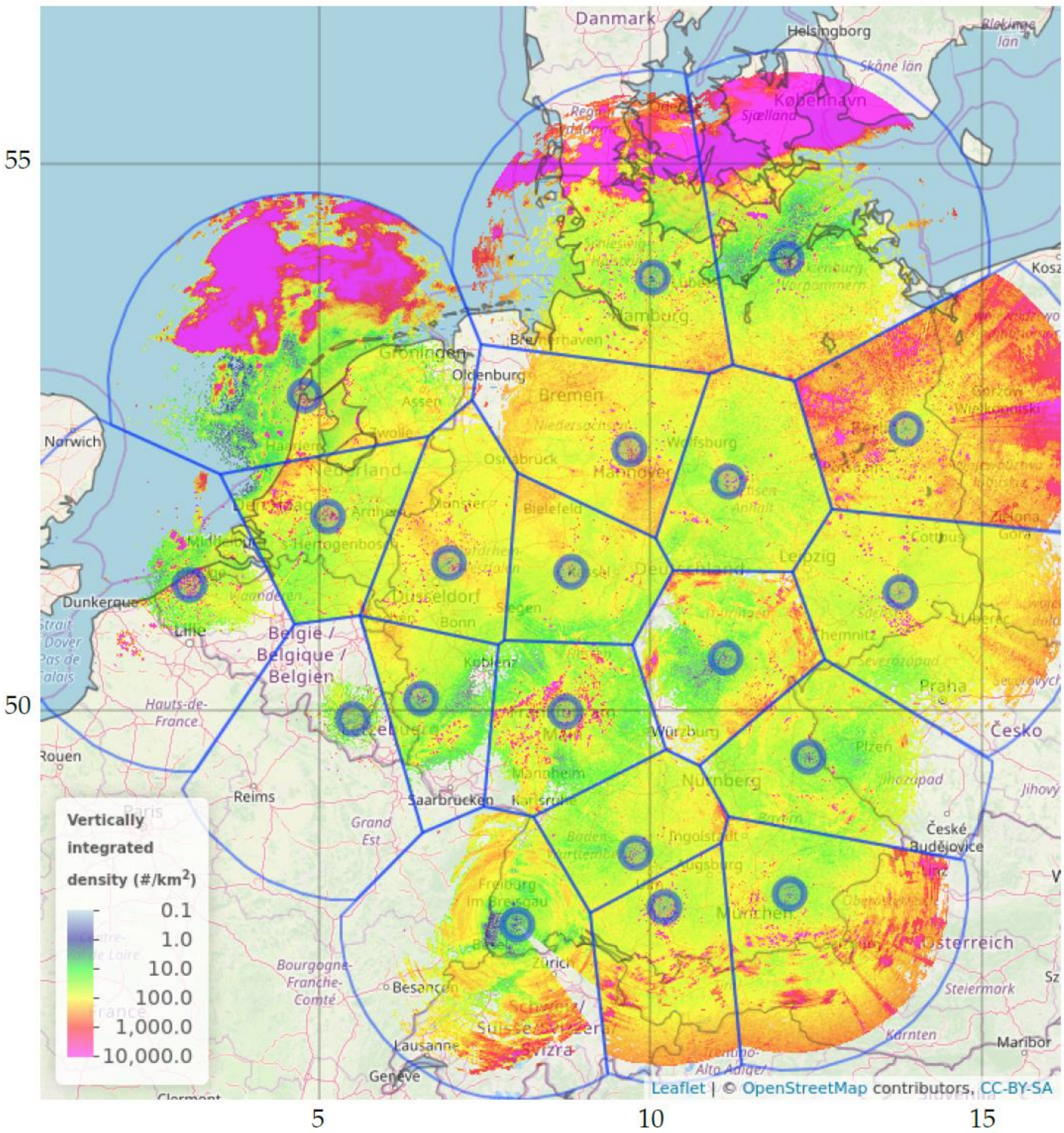


Figure 4.0. A composite map of reflectivity data compiled using data from 20 radars in northwest Europe for 18 October 2017 at 21:00. The reflectivity data is vertically integrated across all of the measured volume and converted to volume bird density. Looking at composites on regular time intervals allows for an overview of regional patterns of migration, including movement from the northeast towards the southwest throughout the night.

5.0 Measurement of bird movements using meteorological radar data

Future development of a predictive model capable of initiating temporary turbine shutdown operations will require a thorough understanding of 3D bird movement in and around the Eemshaven wind farm. As detailed in sections 3 and 4, we have accessed, stored, and processed the data from the single-polarization meteorological radar located 13 km north of Eemshaven in Borkum, Germany for autumn 2018 and spring 2019 migration seasons.

The Borkum radar collects data for multiple parameters every 5-15 minutes within a 70-km radius from ground level up to 4000 meter above mean sea level (amsl). Close to the radar (<5 km), data are not included in analyses as there is too much clutter. At far distances, the data close to the earth's surface are missing due to curvature of the earth. At lower altitudes relevant to wind farms, accurate and specific information on bird movement can be extracted for a volume 5-35 km around the radar, although in that area data quality is usually poor below 200 m amsl due to ground clutter caused by wind turbines, ships and stationary structures.

We processed the raw radar data using the vol2bird bird detection algorithm as described in sections 3 and 4 for the autumn 2018 and spring 2019 migration seasons to calculate and visualize migration traffic rates, density profiles, flight speed, fight direction, and other measures of bird movement.

Results - Autumn 2018

Figure 5.0 shows migration traffic rates recorded with the Borkum radar from 9 October to 9 November when the majority of high intensity migration occurred. Temporal patterns of migration within the radar volume, including the number and timing of high intensity migration nights over the season, can be discerned from this figure. High intensity migration traffic rates (above 3000 birds/km/hour) were calculated with the Borkum radar data on 4 nights: 10-11 October, 18-19 October, 27-28 October, 28-29 October. Weather conditions in the Netherlands and the North Sea region on those four nights were highly favourable to migration, with no rain and wind speeds around 5.0 m/s. Wind directions on peak migration nights were generally out of the east and southeast, which is the prevailing regional wind direction during autumn. Several nights with moderate traffic rates were measured starting on 5 October through mid-November, and these moderate intensities were also on nights when there was no rain and light winds. These results indicate that adult and juvenile birds at nesting grounds and/or stopover areas in Norway, Sweden, and Denmark chose to depart at sunset in large numbers when weather conditions were favourable, especially after several days of unfavourable weather conditions, arriving at Eemshaven later in the night after crossing the North Sea.

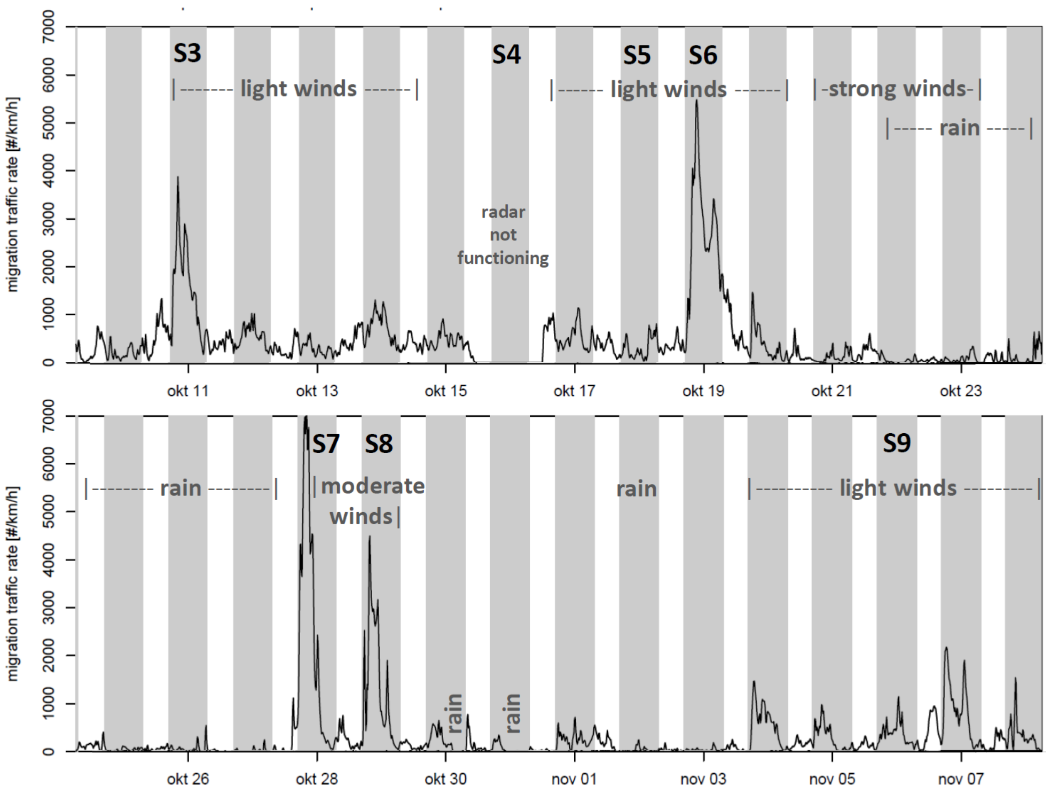


Figure 5.0. Migration traffic rate in number of birds passing over a over a transect of one kilometer in one hour summed over all altitudes as measured with Borkum radar during the 2 weeks when the highest activity was measured during the autumn 2018 migration season. "S#" indicates nights when temporary shutdowns were conducted; other labels indicate weather conditions recorded at a nearby weather station. See appendix for a figure of the entire autumn season.

Vertical profiles of bird densities from ground level up to 4000 meters above mean sea level (amsl) provide additional information about daily flight patterns, high density flow, flight altitude and flight direction, as shown in figure 5.1 for the nights of 10-11 October 2018 and 27-28 October 2018. Temporary shutdowns were carried out on these two nights, and some of the highest bird densities of the season were also measured, especially between sunset and 00:00 UTC. The peak in bird movement right after sunset may indicate that nocturnal passerines were taking off within the radar volume. Peaks around midnight may indicate the arrival of migrants that took off at sunset in Scandinavia. It is also typical to see a small peak around sunrise when nocturnal migrants may be landing. Measured flight directions on high intensity nights were mainly from the northeast and east, as indicated by the black barbs laid over the volume density graphs.

Most bird movement on peak migration nights was measured below 2000 meters amsl, and the highest densities were measured below 1000 amsl meters which indicates that a significant portion of autumn migration could be occurring at altitudes relevant to the Eemshaven wind farm. On the night of 10-11 October, most movement was measured below 500 meters amsl.

Certain atmospheric conditions, such as crosswinds or headwinds, may cause the birds to choose to land, and birds that are landing or taking off in or near the wind farm may be more likely to fly at turbine rotor heights. When these results are compared to measurements from spring 2019, it appears that during autumn migration birds consistently fly at lower altitudes, possibly due to unfavourable headwinds.

Results - Spring 2019

Figure 5.2 shows average migration traffic rates recorded with the Borkum radar from 24 March through 28 April when most of the highest migration traffic rates were measured. Bird migration traffic rates measured in spring 2019 were consistently lower than those measured in autumn 2018, with the highest migration traffic rates recorded above 2000 birds/km/hour. Rates were rarely higher than 3000 birds/km/hour which is well below high intensity migration rates measured in the autumn. This may have been caused by a lower overall number of migrants during the spring season caused by mortality of juveniles at wintering grounds.

The first high density night was 19 March, and migration decreased after the night of 23-24 April, indicating that the spring peak season was slightly longer than in the autumn. There were 10 nights in the spring when migration traffic rates calculated with data from the Borkum radar were higher than other nights in the same season, even though rates were consistently lower than in the spring. Less intense migration observed in the Netherlands and western Germany in spring may be a result of migration patterns that are more temporally and spatially diffuse than in autumn as birds depart each night at sunset from multiple stopover areas in Belgium, the Netherlands, France and Germany. In addition, frequent tailwinds in the spring allow birds to be less selective about when they choose to fly, in contrast to the autumn when headwinds predominate throughout the season.

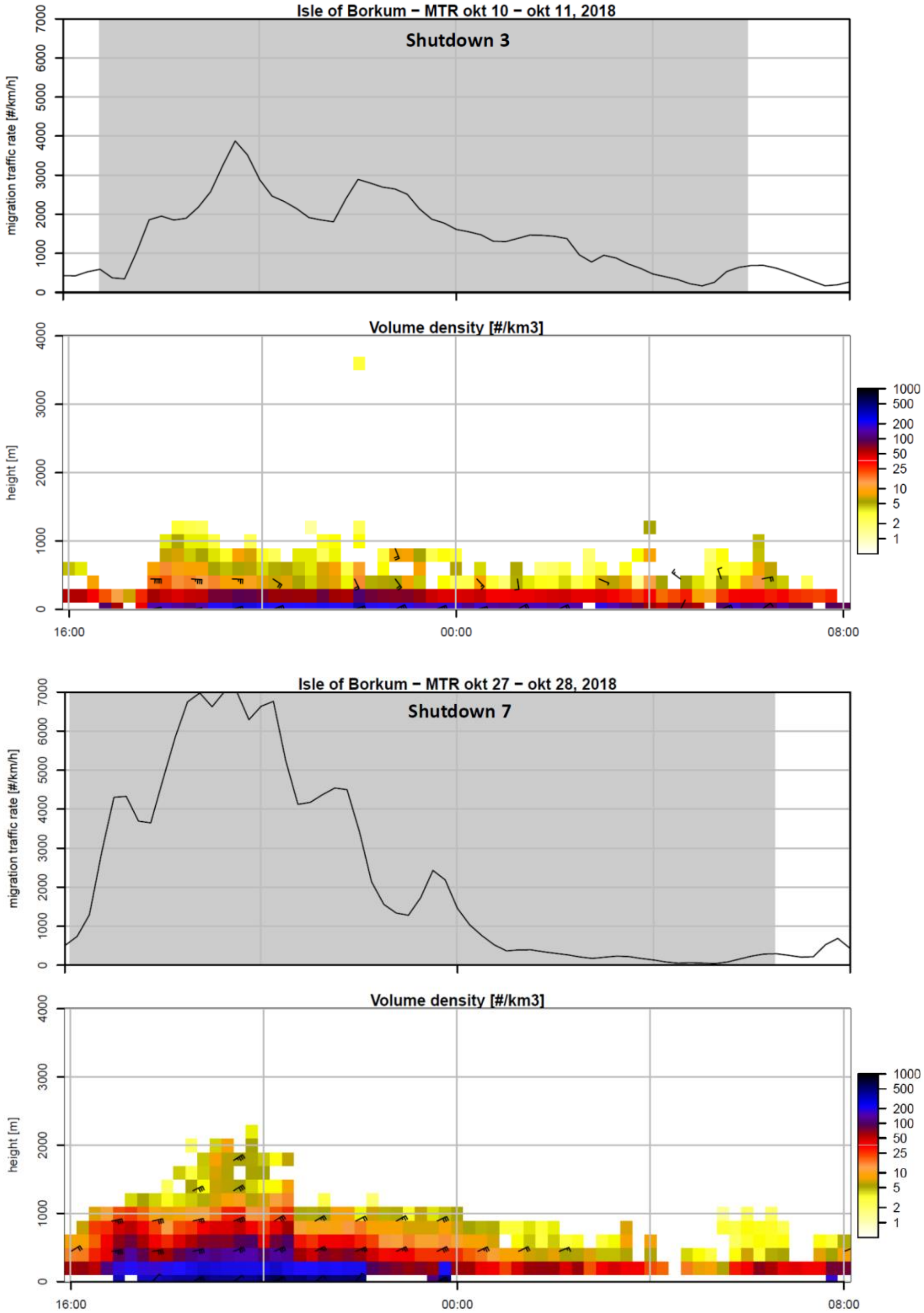


Figure 5.1. Nightly migration traffic rates and bird volume densities measured with Borkum radar on the nights of 10-11 October 2018 and 27-28 October 2018. Temporary shutdowns were carried out on these nights, and high bird densities were measured at low altitudes between sunset and 00:00 UTC. See appendix for figures for other shutdown nights. Times are in UTC.

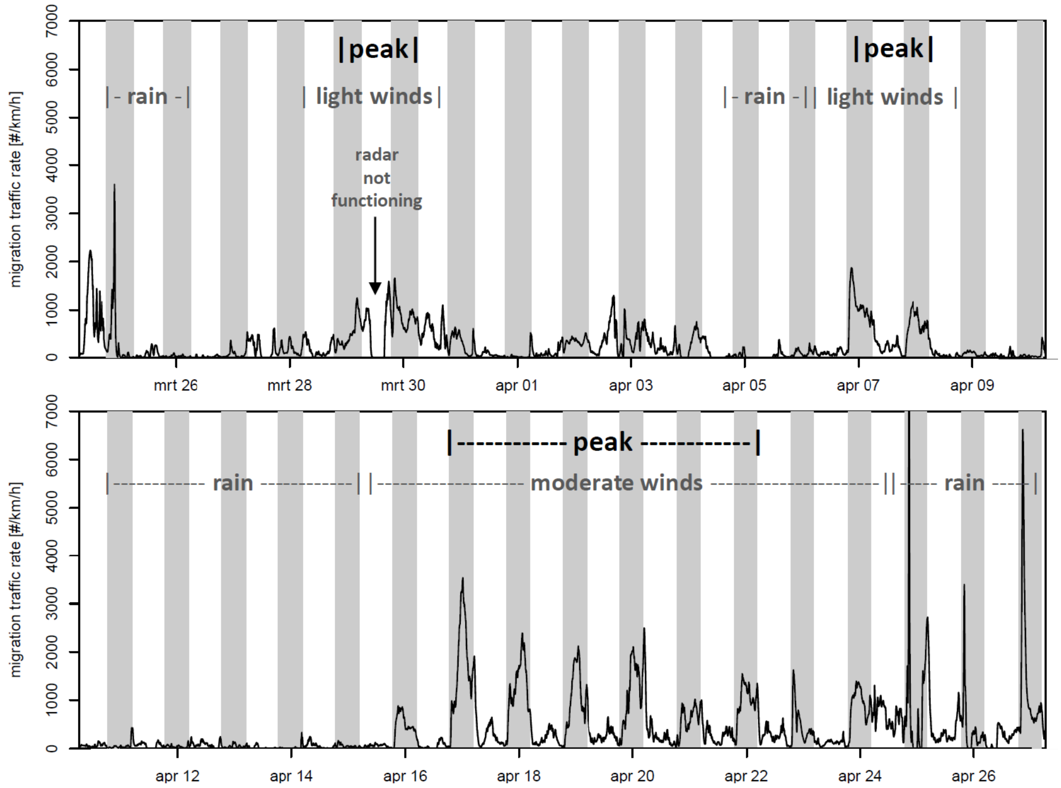


Figure 5.2. Migration traffic rate in number of birds passing over a transect of one kilometer in one hour summed over all altitudes as measured with Borkum radar during the 2 weeks when the highest "peak" activity was measured during the spring 2019 migration season. Labels indicate rain and wind conditions recorded at a nearby weather station. See appendix for a figure of the entire spring season.

Figure 5.4 presents the vertical profile of volume bird density for 16-17 April, the spring night with the highest migration traffic rate. Flight altitudes on peak nights at the end of March and in April were much higher than in autumn, extending up to 3000 meters amsl and with high density flows observed between 2000-3000 meters amsl. Flight altitudes for the measured densities for the first 3 peak nights in March were below 2000 meters amsl, with the highest densities occurring below 1000 amsl meters. Wind directions on peak migration nights were generally light and out of the south, meaning that migrants were mostly encountering tailwinds.

The vertical profile graphs also show daily patterns in bird movement, with higher density peaks visible around sunrise and/or sunset when nocturnal passerines are likely to be taking off or landing within the measured volume. Vertical profiles also indicate high intensity flows at higher altitudes (around 2000 meters amsl) that are indicative of large numbers of migrants passing through the radar space during the night. Measured flight directions on high intensity nights were from the south, southwest and west.

Some areas of very dense migration appear blank on the graphs for 6-7 April, 16-17 April, 17-18 April, 18-19 April and 19-20 April due to the bird detection algorithm misclassifying those areas as rain, as seen in figure 5.4. These gaps may occur more frequently in the spring because the birds are flying with a tailwind and therefore moving at the same velocity as the wind, causing the algorithm to classify them as rain particles which, unlike birds, passively move with the wind. We are working to solve these types of misclassification problems that occasionally occur.

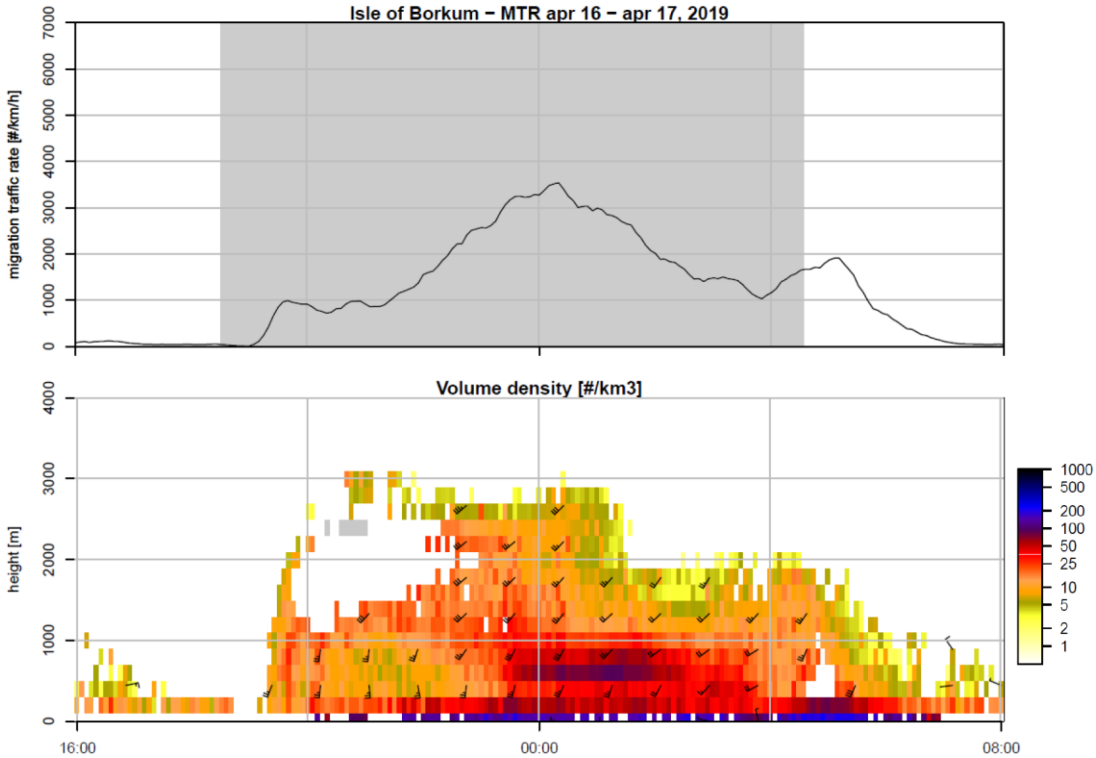


Figure 5.4. Nightly migration traffic rates and bird volume densities measured with Borkum radar on the night of 16-17 April 2019. Migration traffic rates were high, and high bird densities were measured at low altitudes between 00:00 UTC and sunrise. See appendix for figures of additional peak nights. Times are in UTC.

The appendix to this report includes figures A.1 and A.3 showing migration traffic rates for the autumn and spring seasons. Migration traffic rate is a measure of the total number of birds moving over a transect of one kilometer over one hour summed over the entire altitudinal radar range, so this measure allows us to quickly discern peak nights when bird densities were highest. We have indicated on the graphs the ten nights when operational shutdowns were carried out and/or nights when peak migration was observed. We have also indicated periods when rain or light/moderate wind speeds were measured at the KNMI Lauwersoog weather station located on the Dutch coast approximately 40 km to the southwest of Borkum.

Figures A.2 and A.4 are visualizations of volume bird densities for nights when shutdowns were conducted in autumn 2018 and high traffic rates were observed in spring 2019. The densities are shown as a time series in 5- or 15-minute increments and as a function of altitude in 200-meter increments. Direction of bird movement in high density flows is also shown as black barbs laid over the volume bird density graphs. As part of a comparative analysis across multiple radars detailed in section 6, the volume bird densities for every night of both seasons are visualized for the Borkum radar (figures A.5 and A.6 of the appendix).

6.0 Regional differences in migration measured with meteorological radars

As passerines migrate in the spring and autumn, they follow the East-Atlantic flyway, a major migratory route that passes through Scandinavia, the United Kingdom and western Europe. By looking at data gathered with multiple meteorological radars located around Eemshaven, we can better understand regional movement as well as patterns that are unique to Eemshaven.

We compared bird movement data collected with meteorological radars at Borkum, Herwijnen, and Den Helder for the autumn 2018 and spring 2019 migration seasons (see figure 2.1 for radar locations). These data were generated from raw weather radar data described in section 3 using the automated bird detection algorithm called vol2bird as described in section 4. Data for all 3 radars for the entire season are visualized in figures A.5 and A.6 of the appendix which present volume bird densities from ground level up to 4000 meters above mean sea level (amsl) for the 3 radars on the top three graphs. Fine-scale differences in data visualization can be observed on the top three graphs which are due to differences between Dutch and German radar equipment that cause slight variability in data quality. The bottom graph on each page shows migration traffic rates for all 3 radars. Migration traffic rate is a measure of total bird traffic moving over a transect of one kilometer in one hour summed over the entire altitudinal radar range.

We have indicated on the graphs the ten nights when operational shutdowns were carried out and/or nights when peak migration was observed. We have also indicated periods when rain or light/moderate wind speeds were measured at the KNMI Lauwersoog weather station located on the Dutch coast approximately 40 km to the southwest of Borkum. This weather information is useful because rain interferes with data quality. In addition, lower wind speeds appear to coincide with peaks in migration especially in the autumn when headwinds are more prevalent.

Comparison of bird movement patterns measured at Den Helder, Herwijnen and Borkum – Autumn 2018

Intensity patterns of nocturnal migration

During the autumn 2018 season, high intensity migration traffic rates (above 3000 birds/km/hour) were measured at all 3 radars on 4 nights: 10-11 October, 18-19 October, 27-28 October, 28-29 October (see figure A.5 of the appendix). This indicates that pulses of intense mass migration were occurring on a regional or national scale on those 4 nights. Moderate migration (1500-3000 birds/km/hour) was measured at 2 of the radars (typically Borkum and Herwijnen) on 6 nights: 6-7 October, 17-18 October, 19-20 October, 4-5 November, 15-16 November and 16-17 November.

Timing of nocturnal bird movements

Patterns measured at Herwijnen indicate that nocturnal movements began earlier in the season there at the end of September as compared to Borkum and Den Helder where densities began to increase on 5 October. Densities at Borkum were slightly higher than those measured at the Dutch radars in November. Daily patterns of intensity appeared similar on peak nights at the 3 radars, with higher densities observed around sunrise and/or sunset.

As shown in figure A.5, higher nocturnal bird intensities occurred more frequently in autumn 2018 at Herwijnen while migration at Den Helder was consistently lower than the other 2 radars. There were several nights when high densities were only measured with the Herwijnen radar (eg. 24-25 and 28-29 September, 17-18 October, 22-23 October, 14-15 November) indicating that migration was more localized or more concentrated in inland areas on those nights.

Altitudinal and directional patterns

Altitudinal profiles show that flight altitudes were generally within the same range at all 3 radars, with most bird movement occurring below 2000 meters amsl and the highest densities occurring below 1000 amsl meters except for the night of 10-11 October when most movement was measured below 500 meters amsl.

Measured flight directions on high intensity nights were mainly from the north and northeast for all 3 radars, as indicated by the black barbs laid over the volume density graphs. On some high intensity nights, flight directions in Herwijnen were from the east which may be indicative of birds flying to the United Kingdom.

Comparison of bird movement patterns measured at Den Helder, Herwijnen and Borkum – Spring 2019

Data for Borkum, Herwijnen, and Den Helder radars for the spring 2019 migration season are visualized in figure A.6 of the appendix.

Intensity patterns of nocturnal migration

Bird migration traffic rates measured in spring 2019 were consistently lower than those measured in autumn 2018. At Herwijnen and Borkum, the highest migration traffic rates were recorded above 2000 birds/km/hour, and rates were never higher than 4000 birds/km/hour which is well below high intensity migration rates measured in the autumn. Rates at Den Helder were consistently under 1000 birds/km/hour except for 22-

23 April and 24-25 April when intensities at all 3 radars fell into a similar moderate range. These lower rates at all 3 radars may be due to a lower overall number of migrants during the spring season for the entire East Atlantic Flyway caused by mortality of juveniles at wintering grounds. Less intense migration observed in the Netherlands and western Germany may also be a result of spring migration patterns that are more temporally and spatially diffuse than in autumn.

Timing of nocturnal bird movements

Migration intensity in Herwijnen started to increase after 11 March, but in Borkum and Den Helder intensities remained low until 19 March indicating that nocturnal movements in spring also begin earlier in Herwijnen. Migration rates dropped at all 3 radars after 23 April.

As shown in figure A.6, higher nocturnal bird densities were measured more frequently at Herwijnen while densities at Den Helder were consistently lower than the other 2 radars. High intensity migration was measured at Herwijnen on 5 nights over the season when rates at the other 2 radars when moderate or low. During the spring season, high intensity nocturnal migration (above 2000 birds/km/hour) was not observed at all 3 radars on a single night. There were 3 peak nights in common at Borkum and Herwijnen: 16-17 April, 17-18 April and 19-20 April and 3 nights when Borkum had high measured migration when rates for the other 2 radars were moderate or low (19-20 March, 18-19 April, 24-25 April). These results indicate that flow patterns are more spread out spatially and temporally in the spring.

Altitudinal and directional patterns

Vertical profiles of volume bird density (figure A.6) show that flight altitudes during peak migration in March were below 2000 meters amslat all radars, with the highest densities occurring below 1000 amsl meters. In April, the vertical density profiles on high intensity migration nights were much higher than in the autumn, with high density flows observed between 2000-3000 meters amsl.

Daily patterns also appeared similar on peak nights at the 3 radars, with higher densities observed at lower altitudes around sunrise and/or sunset when nocturnal passerines are likely to be taking off or landing within the measured volume. Vertical profiles for all 3 radars also indicate high intensity flows at higher altitudes (around 2000 meters amsl) that are indicative of large numbers of migrants passing through the radar space during the night.

Measured flight directions on high intensity nights were from the south and southwest for all 3 radars, as indicated by the black barbs laid over the volume density graphs.

7.0 Evaluation of ability of Air Force FlySafe Bird Avoidance Model to predict migration in Eemshaven

When assessing the feasibility of developing a model to predict peaks in migration, it is useful to understand similar models and assess whether models developed for other areas and purposes can provide information about expected bird densities in Eemshaven. Migratory bird movement follows temporal and spatial patterns that are seasonally driven by local and regional weather conditions, but we need a better understanding of how spatially and temporally specific a model should be in order to effectively support temporary shutdown operations at a wind farm.

UvA has worked in the past as part of a team developing a predictive model for the Royal Dutch Air Force (RNLAF) and Belgian Air Force (BAF) for the purpose of improving flight safety and preventing bird strikes with military aircraft. The Air Force FlySafe Bird Avoidance Model (FlySafe-BAM) uses forecasts of atmospheric conditions to generate hourly warning levels for Air Force training operations up to 72 hours in advance for four different locations in the Netherlands and Belgium (http://www.flysafe-birdtam.eu). The results of this model are integrated over 0-4000 altitude layers because it is designed to improve flight safety (van Belle at al. 2007).

During autumn 2018 and spring 2019 field work in Eemshaven, we used FlySafe-BAM's migration forecasts for Netherlands and Belgian locations in spring to help identify peak migration nights on a regional scale, as described in section 2. However, this task aims to characterise the differences between bird densities forecasted with the FlySafe-BAM model and actual bird densities measured with the Borkum meteorological radar and the ROBIN 3D Max bird radar for each season.

Comparison of Borkum measurements with FlySafe-BAM Netherlands model predictions – Autumn 2018

The regional Flysafe-BAM model for the Netherlands was able to predict 5 nights out of the 13 total nights when high intensity migration was measured with one or both radars, but overall the model did not perform as well as the consortium's Eemshaven-specific forecasts (Table 7.0, also Table 2.0 in section 2). The model failed to predict 7 nights when high intensity migration was measured with one or both radars and a temporary shutdown could have been implemented. In addition, there were 7 nights when Flysafe-BAM would have triggered a temporary shutdown, but high intensity migration was not measured in Eemshaven. Figure 7.0 presents hourly predictions of bird migration intensity and migration traffic rates measured with the Borkum radar during the same season.

Migration traffic rate is a measure of total bird traffic moving over any given kilometer in the radar volume in one hour summed over the entire altitudinal radar range.

Table 7.0: Summary of autumn 2018 migration forecasts

Autumn 2018 migration season forecasts	Flysafe-BAM model (North NL)	Consortium
measured high migration nights that were forecasted to be high	5	9
measured high migration nights that were not forecasted to be high	7	3
measured low to moderate migration nights that were forecasted to be high	7	3
measured low migration nights that were forecasted to be low	28	46

(12 high nights in total)

Positive identification (model predicted well): 5 nights with high intensity migration, 3 nights with moderate migration

For the autumn 2018 migration season, FlySafe-BAM accurately predicted high bird densities for 5 nights when high intensity migration was measured with one or both of the radars (17-18 Oct, 18-19 Oct, 19-20 Oct, 27-28 Oct, 28-29 Oct). The consortium was also able to accurately predict these migration events. There were three nights (28-29 Sept, 7-8 Oct, 8-9 Nov) when FlySafe-BAM predicted high bird densities and moderate migration was measured.

False negatives (model failed to predict): 7 nights

The FlySafe-BAM model predicted low to moderate bird densities for 7 nights when high intensity migration was in fact measured with one or both of the radars (6-7 Oct, 10-11 Oct, 11-12 Oct, 13-14 Oct, 15-16 Oct, 6-7 Nov, 16-17 Nov). The project consortium was able to predict 4 of these high nights based on weather conditions (6-7 Oct, 10-11 Oct, 11-12 Oct, 15-16 Oct), and it should be noted that migration traffic rates on 6-7 Oct and 10-11 Oct were among the highest recorded during the season. Three nights (13-14 Oct, 6-7 Nov, 16-17 Nov) were not predicted to be high with FlySafe-BAM or by the consortium.

False positives (model over-predicted): 7 nights

The FlySafe-BAM model predicted high bird densities for 7 nights when low to moderate migration was in fact measured with one or both of the radars (28-29 Sept, 1-2 Oct, 7-8 Oct, 20-21 Oct, 22-23 Oct, 29-30 Oct, 8-9 Nov). The consortium also predicted high intensity migration on 2 of these nights.

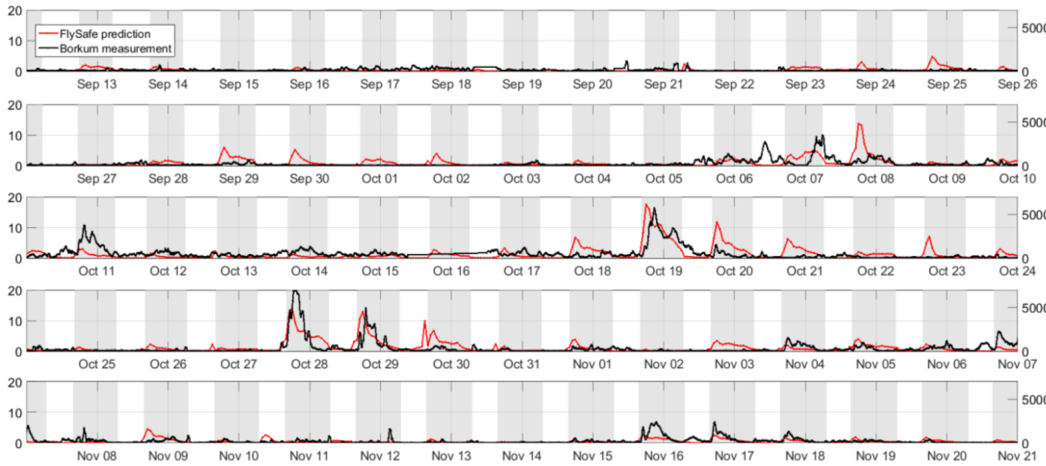


Figure 7.0. Comparison of migration traffic rates measured with the Borkum radar with bird densities forecasted with the FlySafe-BAM model for the southeast Wier area located approximately 100 km west of Eemshaven for each night of the autumn 2018 season. FlySafe bird density forecasts were calculated by taking the hourly mean of multiple density forecasts generated every 12 hours for 3 days.

Comparison of Borkum measurements with FlySafe-BAM Belgian model predictions – Spring 2019

For the spring migration season, we consulted the Belgian FlySafe-BAM model forecasts in lieu of the Netherlands forecasts because migrating passerines arriving from Africa and southern Europe likely fly over or stop in Belgium on their way to Eemshaven. Therefore, this model comparison is based on the predictions made for the northwest Glons area in Belgium. To verify that the Netherlands model predictions were less relevant, we performed a brief comparison of the southeast and northwest Wier predictions with the spring 2019 Borkum measurements and found that those predictions did not predict any nights when high intensity migration was measured with the radars (results not shown here).

The regional Flysafe-BAM model for the northwest Glons area in Belgium was able to predict 10 nights out of 11 total nights when high intensity migration was measured with one or both radars, but the model also greatly over-predicted high intensity migration nights (Table 7.1 and Table 2.2 in section 2). The model did not fail to predict any nights when high intensity migration was measured. However, on 22 nights, Flysafe-BAM indicated high regional migration, but high intensity migration was not measured in Eemshaven. Figure 7.1 presents hourly predictions and measured migration traffic rates.

Table 7.1: Summary of spring 2019 migration forecasts

Spring 2019 migration season forecasts	Flysafe-BAM model (North NL)	Consortium
measured high migration nights that were forecasted to be high	10	10
measured high migration nights that were not forecasted to be high	3	3
measured low to moderate migration nights that were forecasted to be high	11	5
measured low migration nights that were forecasted to be low	13	24

(13 high nights in total)

Positive identification (model predicted well): 10 nights with high intensity migration

For the spring 2018 migration season, the FlySafe-BAM model accurately predicted high bird densities for 10 nights when high intensity migration was measured with one or both of the radars (19-20 Mar, 20-21 Mar, 22-23 Mar, 28-29 Mar, 29-30 Mar, 16-17 Apr, 17-18 Apr, 18-19 Apr, 19-20 Apr, 23-24 Apr, 1-2 May). The consortium was also able to accurately predict these migration events. There were 11 nights when the FlySafe-BAM Model predicted high bird densities and moderate or low migration was measured.

False positives (model over-predicted): 11 nights

The FlySafe-BAM model predicted high bird densities for 11 nights when low to moderate migration was in fact measured with one or both of the radars; the consortium also predicted high intensity migration on 5 of these nights.

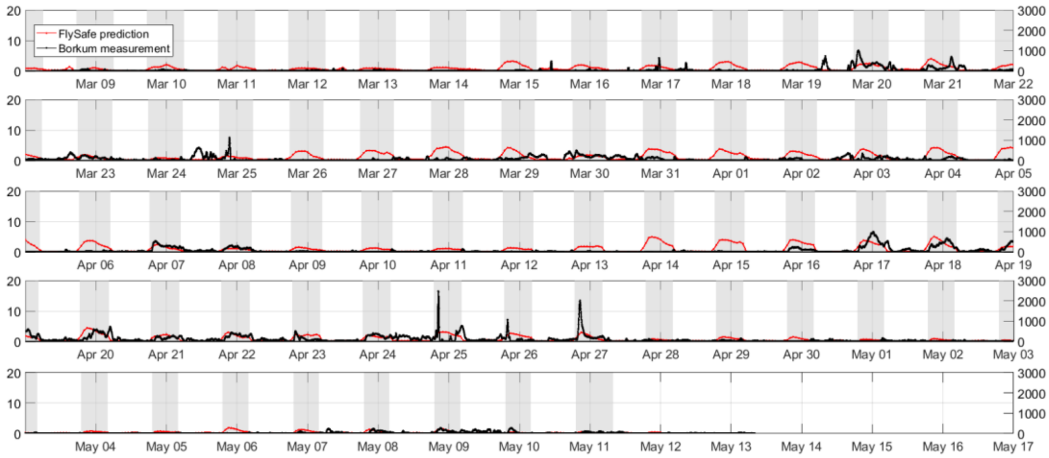


Figure 7.1. Comparison of migration traffic rates measured with the Borkum radar with bird densities forecasted with the FlySafe-BAM model for the southeast Wier area located approximately 100 km west of Eemshaven for each night of the spring 2019 season. FlySafe bird density forecasts were calculated by taking the hourly mean of multiple density forecasts generated every 12 hours for 3 days.

8.0 Conclusions

We make the following conclusions based on the work conducted during this project using the meteorological radar data and other sources of information used to predict and study spatial-temporal patterns of nocturnal passerine migration in the Eemshaven wind farm:

- We were able to access and process data from multiple meteorological radars for 2018 and 2019, data that would be essential in the future to the development of a predictive model of migration. More importantly, we made improvements to the algorithm that allow for a clearer view of local bird movement at altitudes relevant to the wind farm as well as large-scale regional patterns in northwest Europe.

- Detailed comparison of nocturnal migration measured in Borkum, Germany with radars in the Netherlands show that peaks in high intensity migration often co-occur on the same nights, indicative of broad front migration, although fine-scale local differences exist. For example, measured migration intensity along the coast of the Netherlands is often lower than in inland areas, especially in spring 2019.

- The consortium had enough information and expertise to accurately forecast migration within the Eemshaven area, especially nights when the highest migration intensities were measured with the weather radar at Borkum and the dedicated bird radar operated within the wind farm. The same information and expertise could be used to create a model able to forecast peak migration nights with a lead time of 48 hours designed to support temporary shutdowns to be operationally implemented by turbine operators as a mitigation measure.

Acknowledgements

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Appendix

Figure A.1. Migration traffic rate in number of birds passing over a given kilometer in one hour summed over all altitudes as measured with Borkum radar during autumn 2018 migration season. "S#" indicates nights when temporary shutdowns were conducted; other labels indicate weather conditions recorded at a nearby weather station.

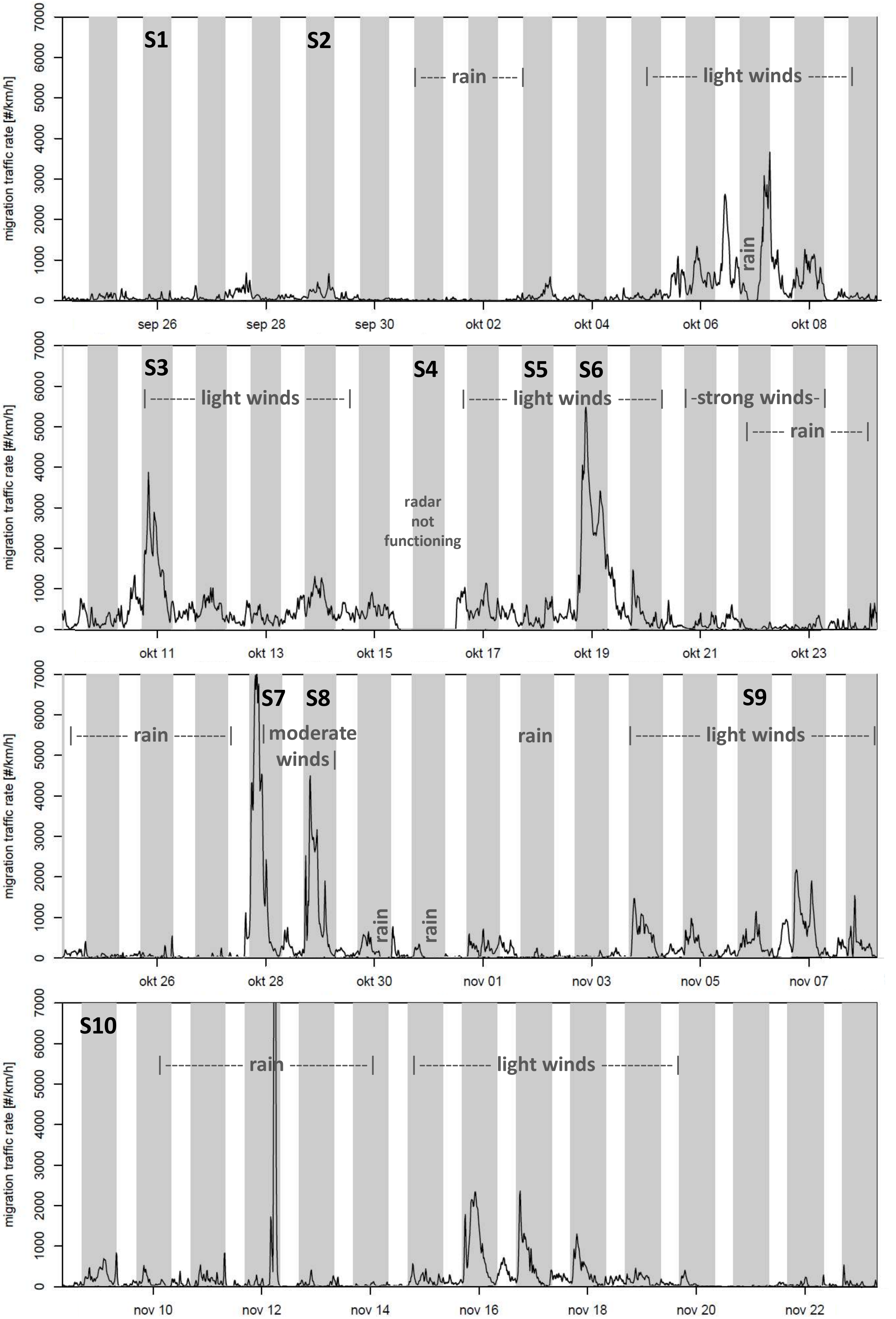
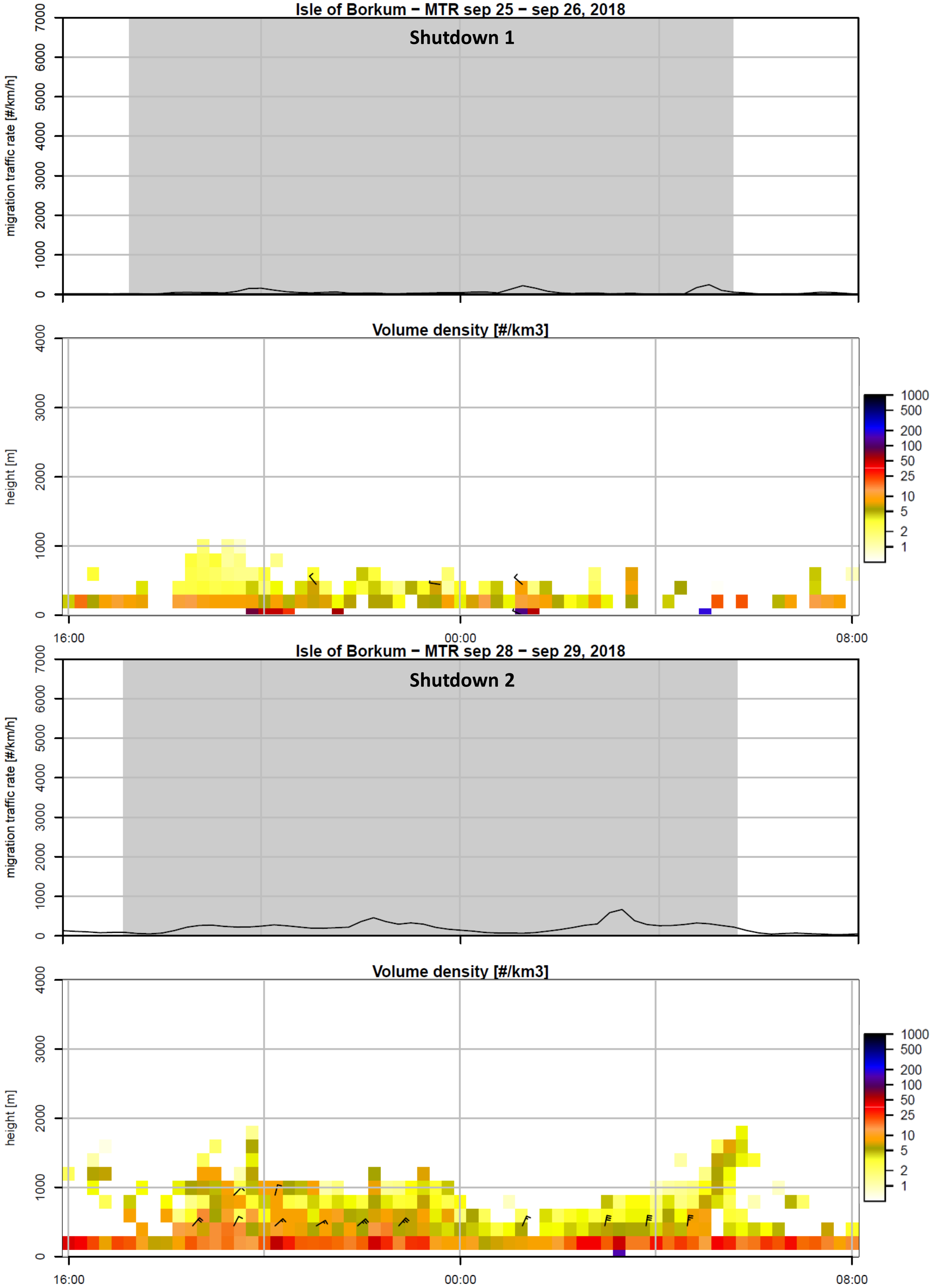
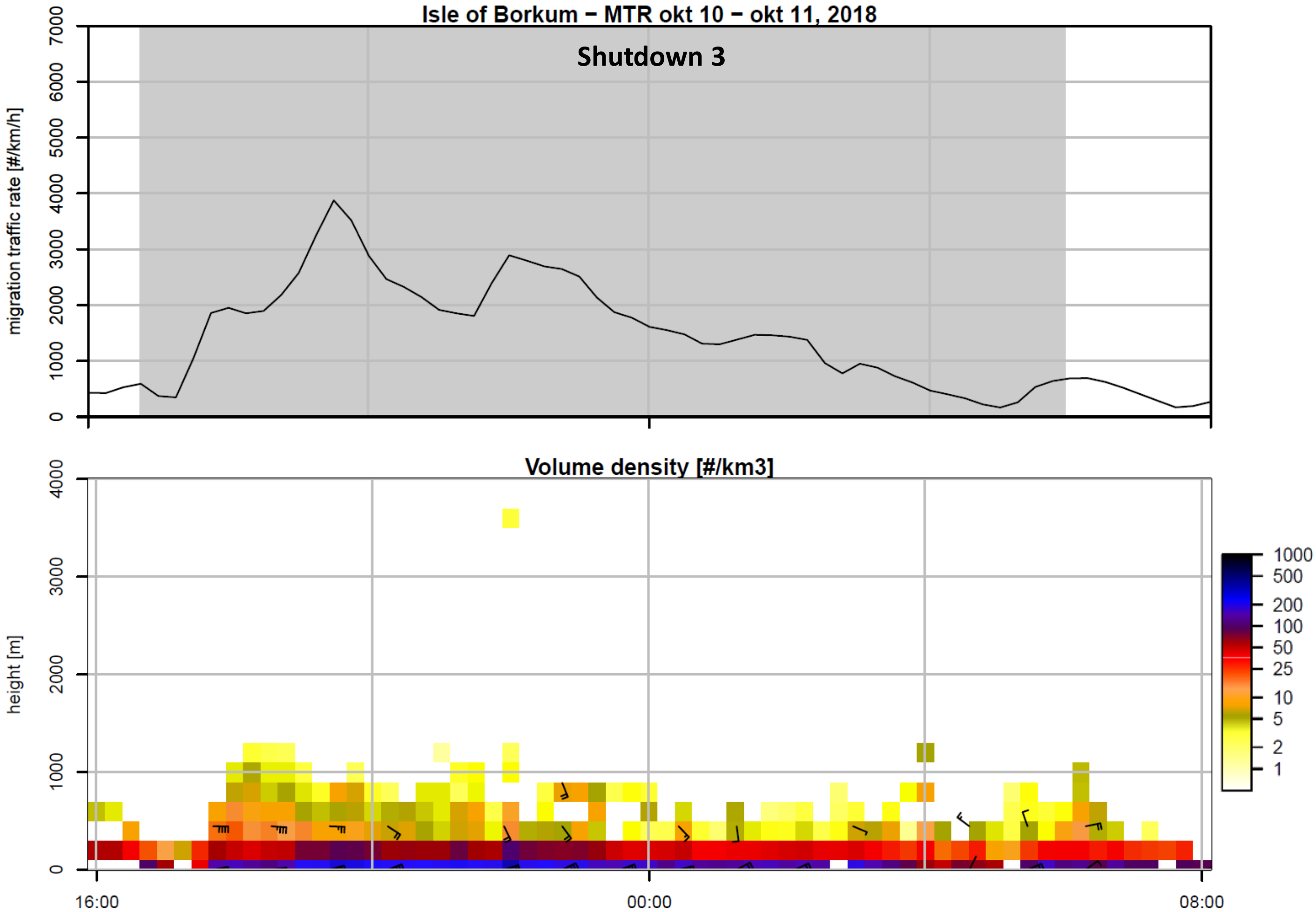
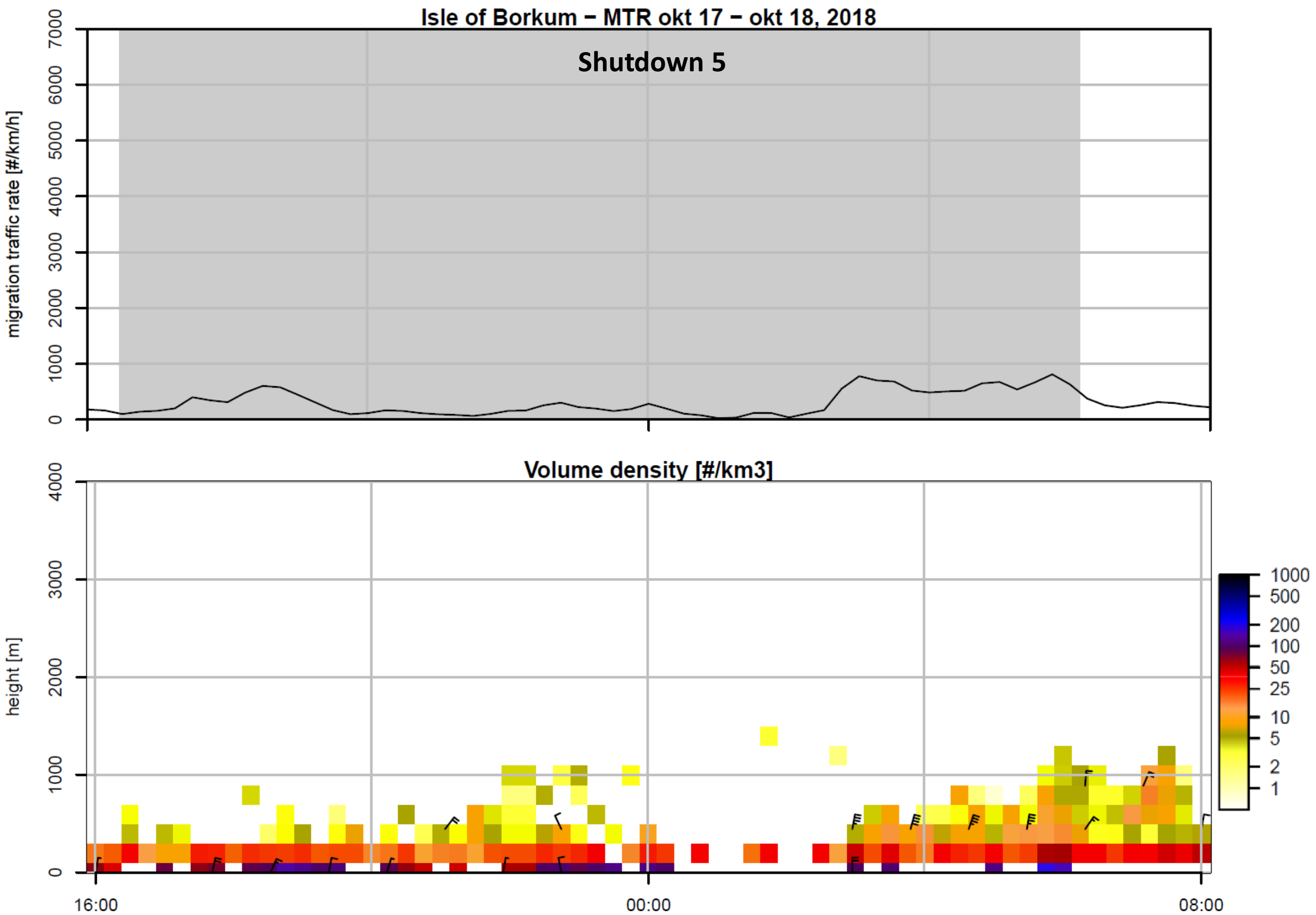


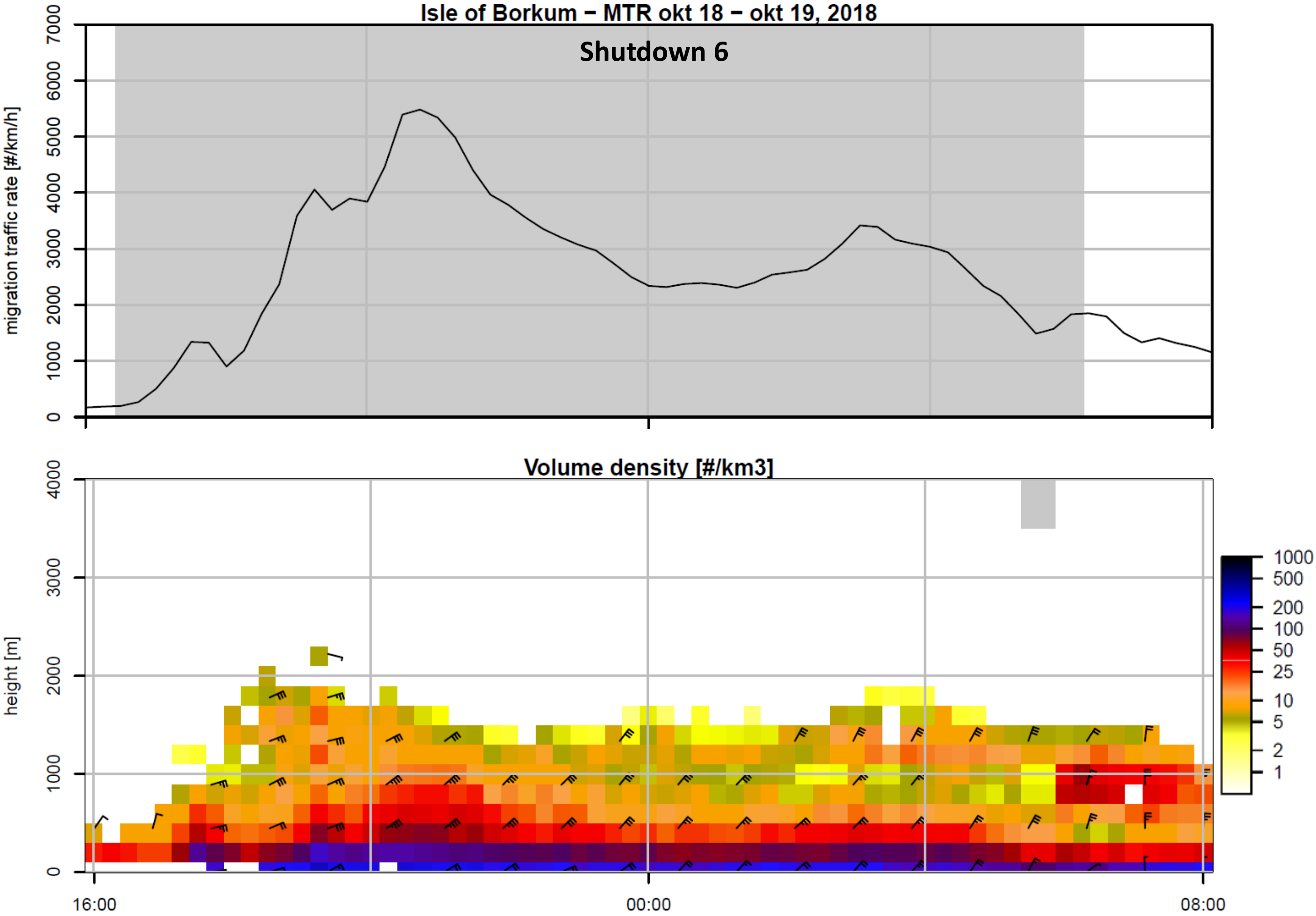
Figure A.2: Nightly migration traffic rate and bird densities measured with Borkum radar during autumn 2018 migratory season on nights when temporary shutdowns were conducted. Times are in UTC.

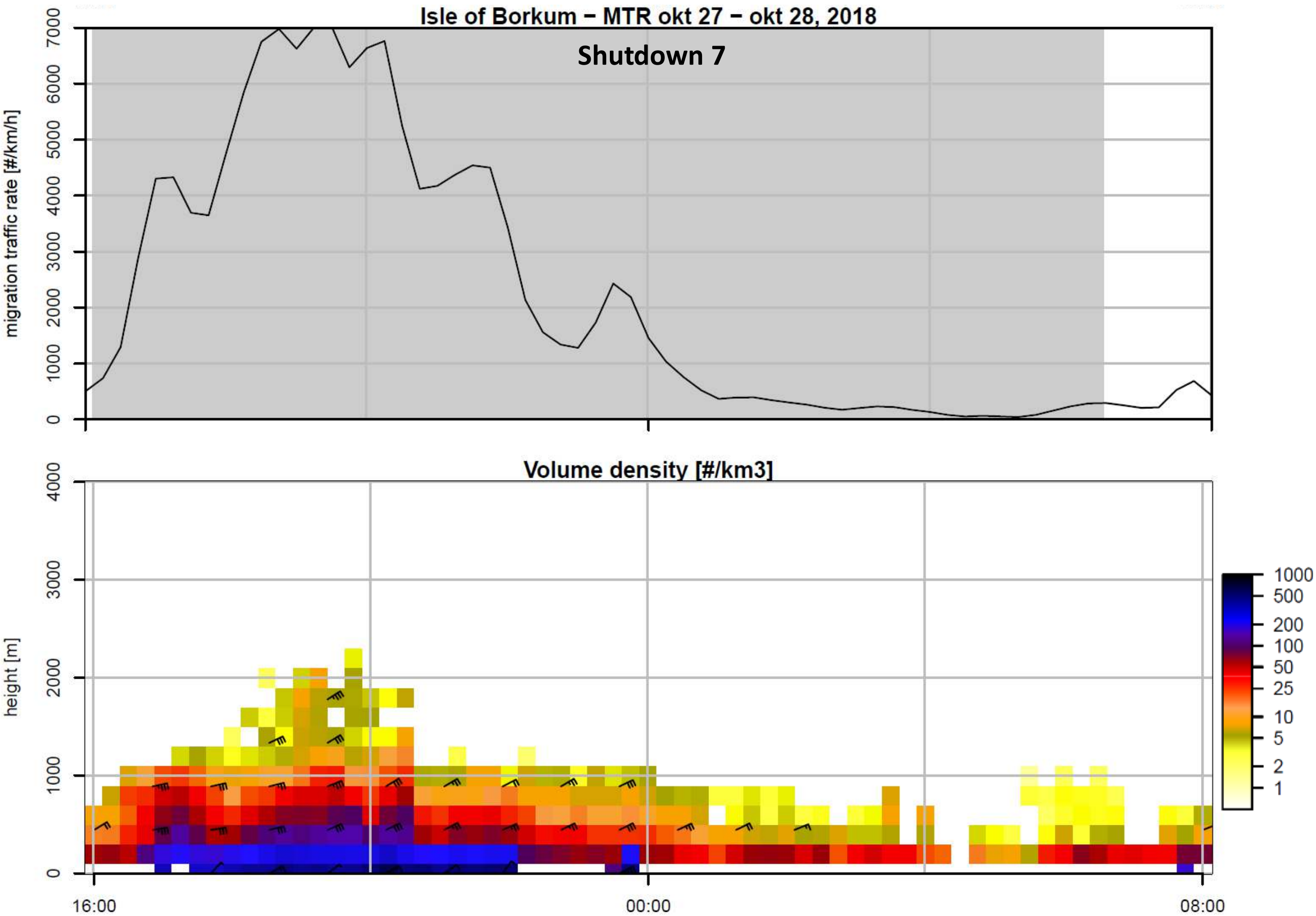


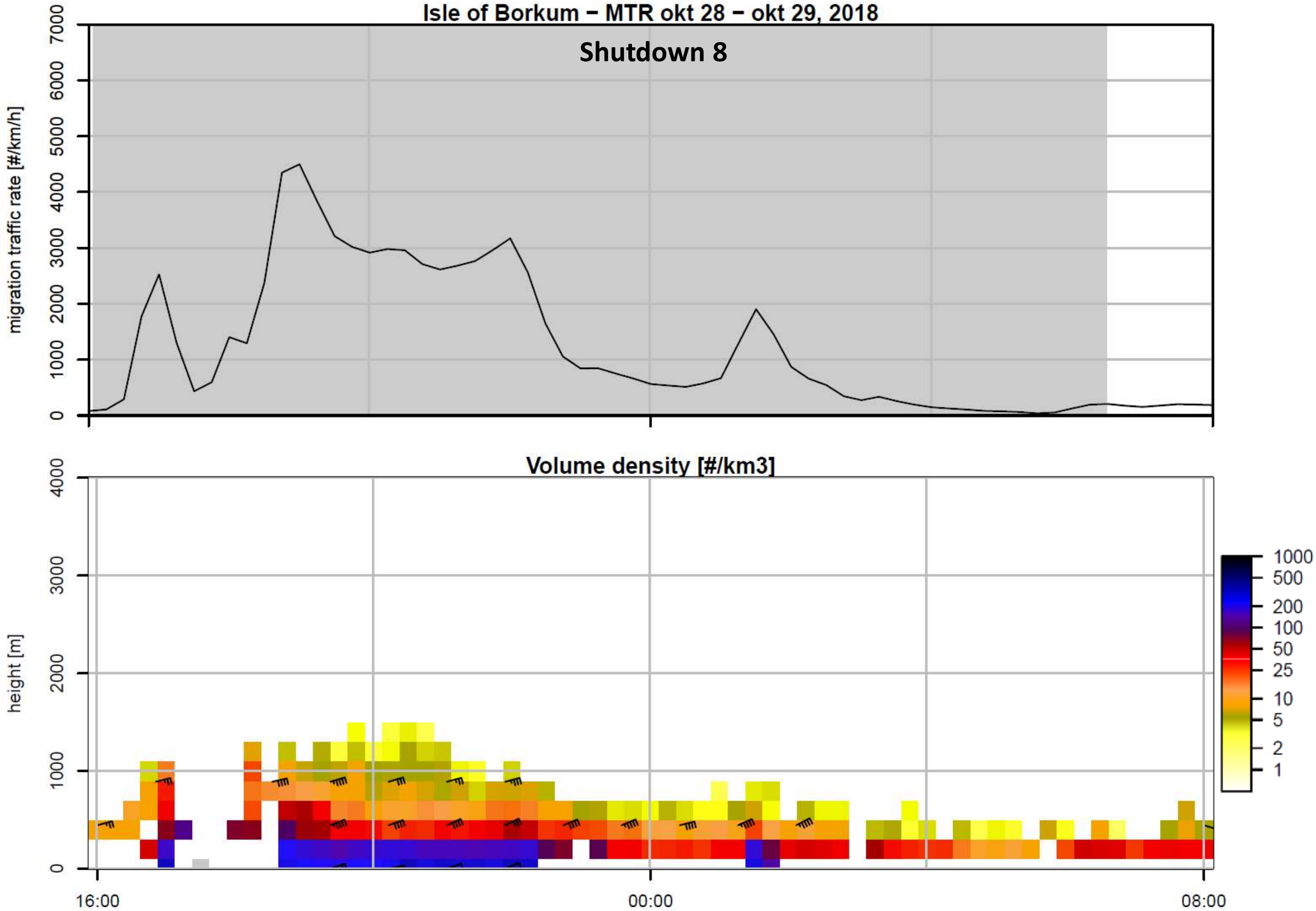


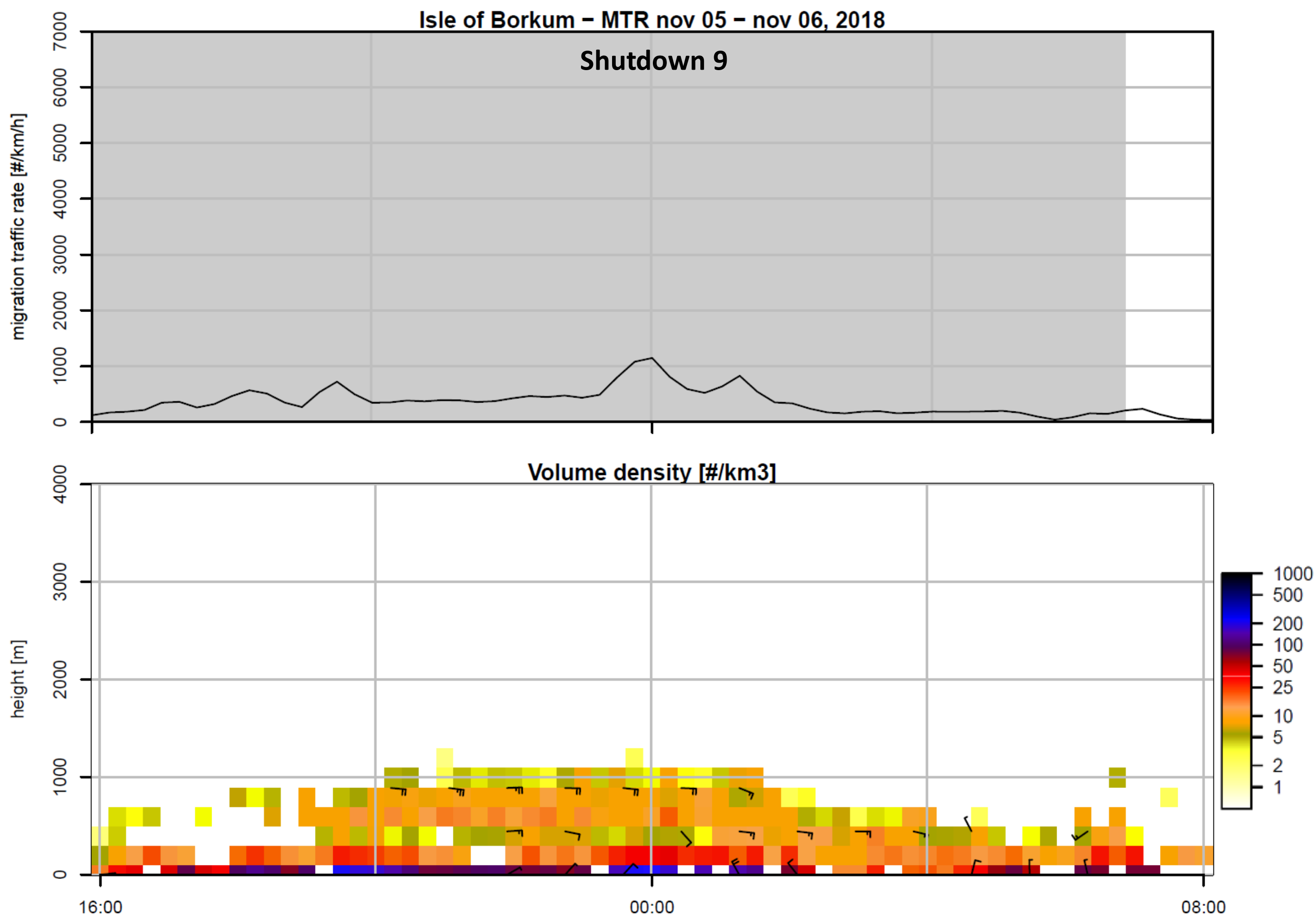


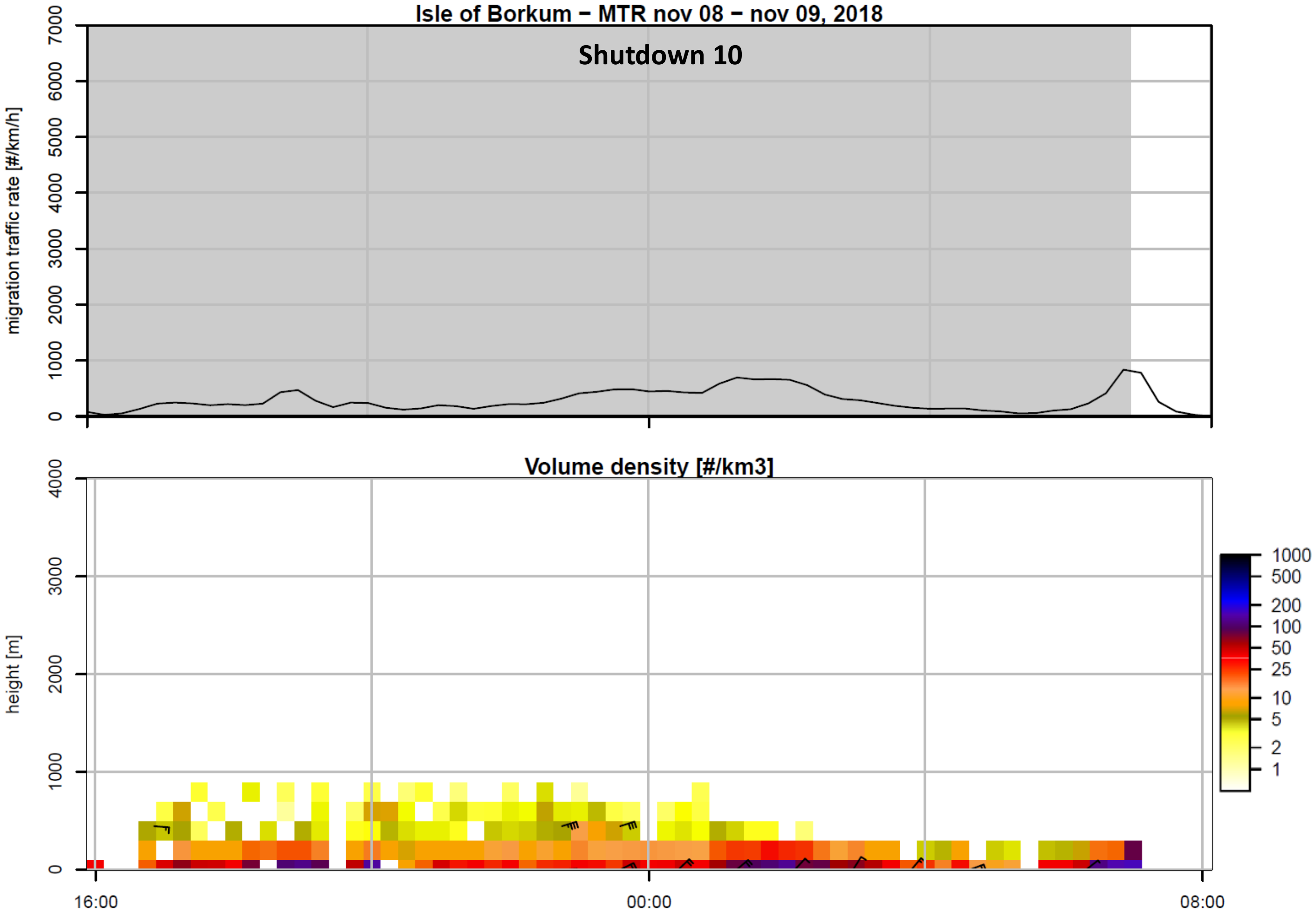
Note: Borkum radar was not functioning on 15-16 October when shutdown 4 was conducted.


Isle of Borkum – MTR okt 18 – okt 19, 2018
Shutdown 6
migration traffic rate [#/km/h]
Volume density [#/km3]
height [m]
16:00
00:00
08:00


Isle of Borkum – MTR okt 27 – okt 28, 2018
Shutdown 7
migration traffic rate [#/km/h]
Volume density [#/km3]
height [m]
16:00
00:00
08:00


Isle of Borkum − MTR okt 28 − okt 29, 2018
Shutdown 8
migration traffic rate [#/km/h]
Volume density [#/km3]
height [m]
16:00
00:00
08:00


Isle of Borkum − MTR nov 05 − nov 06, 2018
Shutdown 9
migration traffic rate [#/km/h]
Volume density [#/km3]
height [m]
16:00
00:00
08:00



Isle of Borkum − MTR nov 08 − nov 09, 2018
Shutdown 10
migration traffic rate [#/km/h]
0
1000
2000
3000
4000
5000
6000
7000
Volume density [#/km3]
height [m]
0
1000
2000
3000
4000
16:00
00:00
08:00
1000
500
200
100
50
25
10
5
2
1

Figure A.3. Migration traffic rate in number of birds passing over a given kilometer in one hour summed over all altitudes as measured with Borkum radar during spring 2019 migration season. "S#" indicates nights when temporary shutdowns were conducted; other labels indicate weather conditions recorded at a nearby weather station.

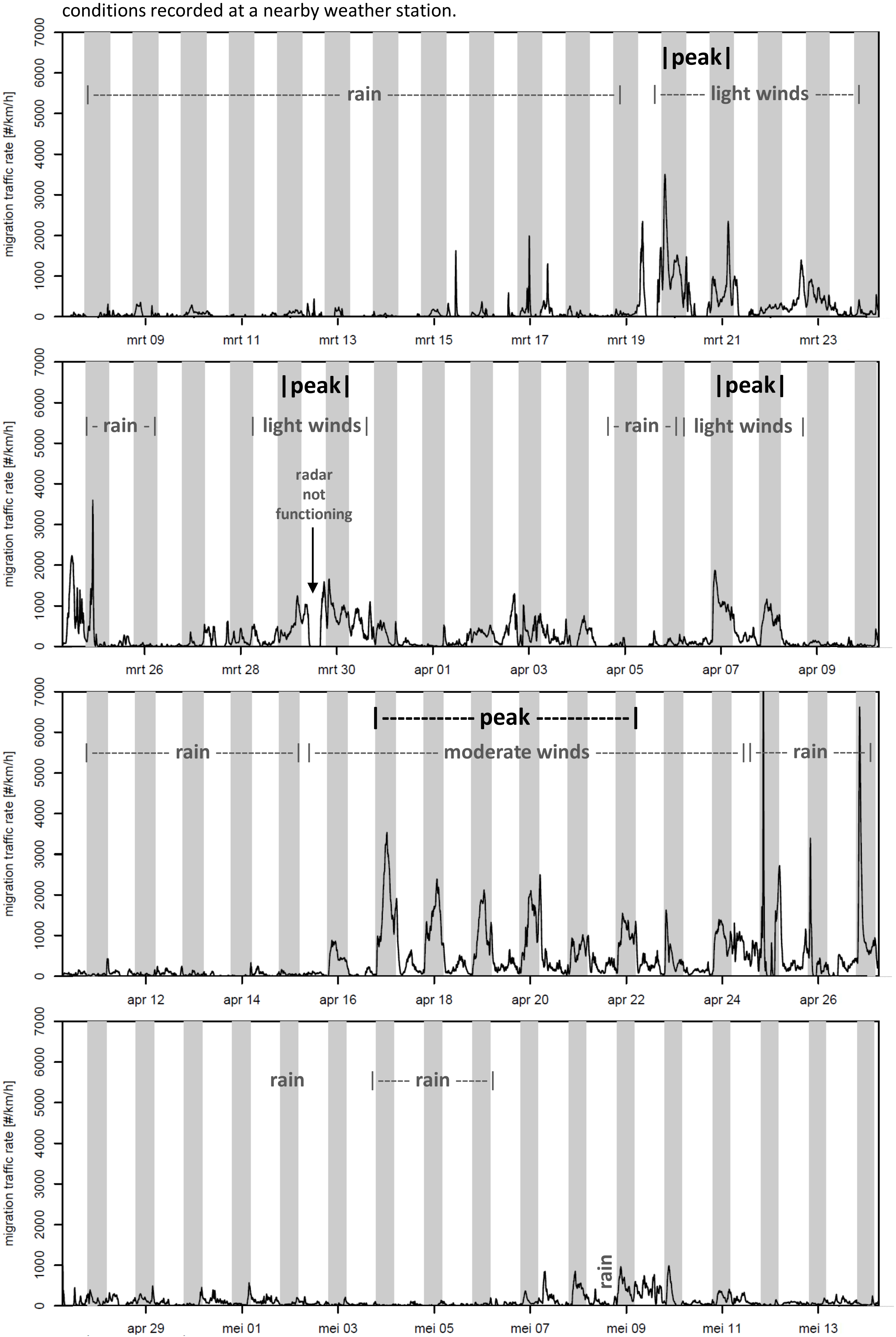
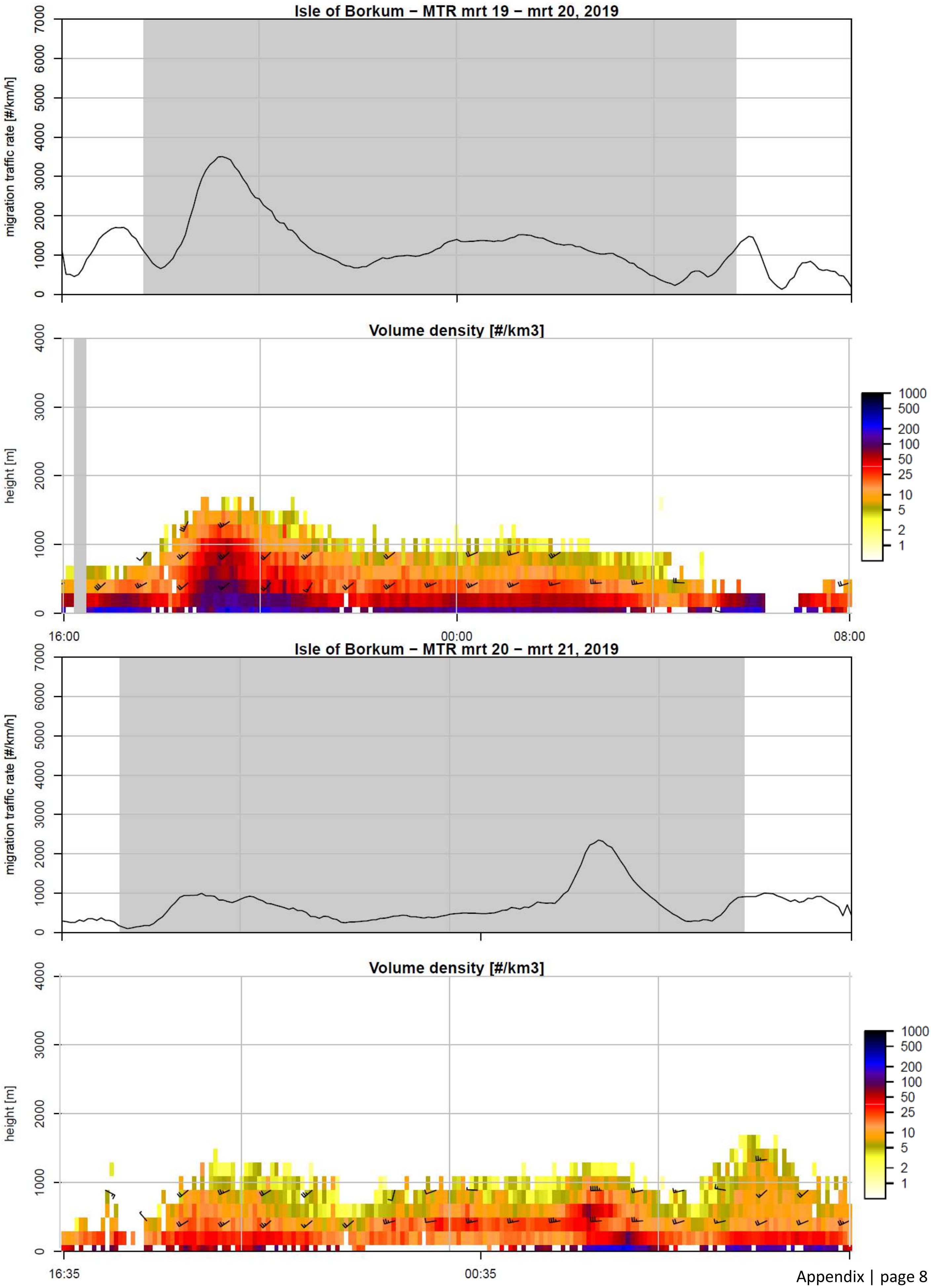
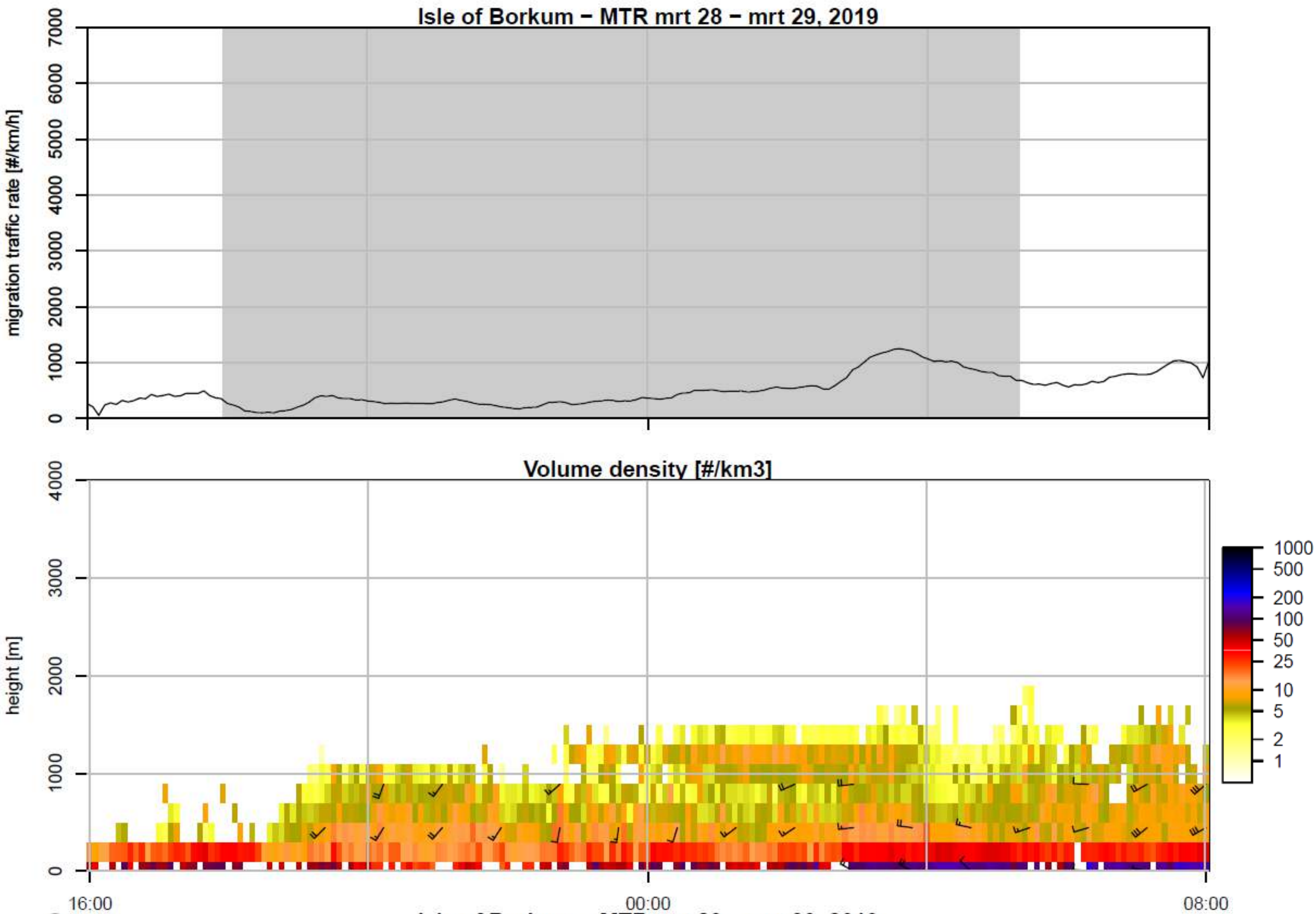
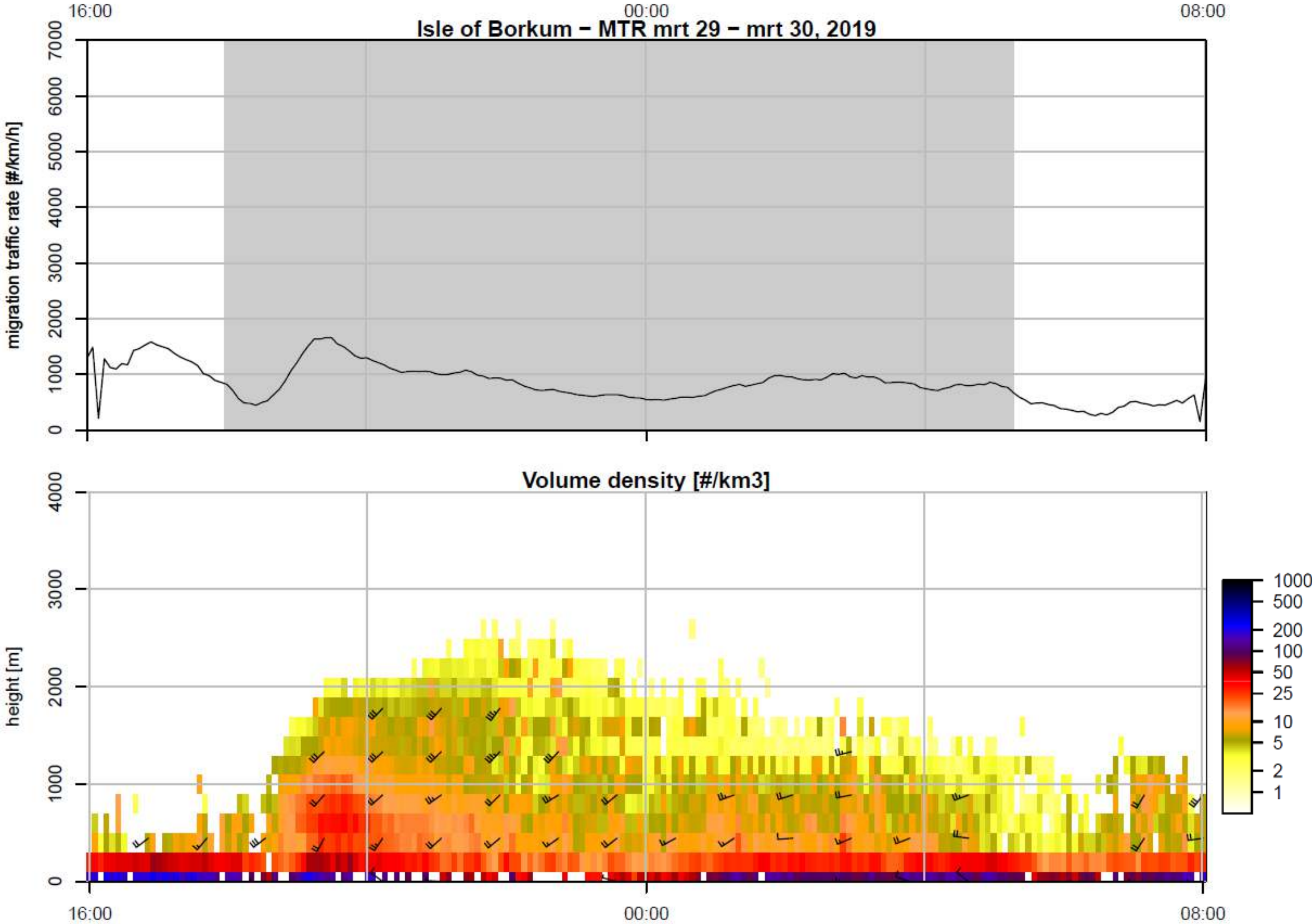
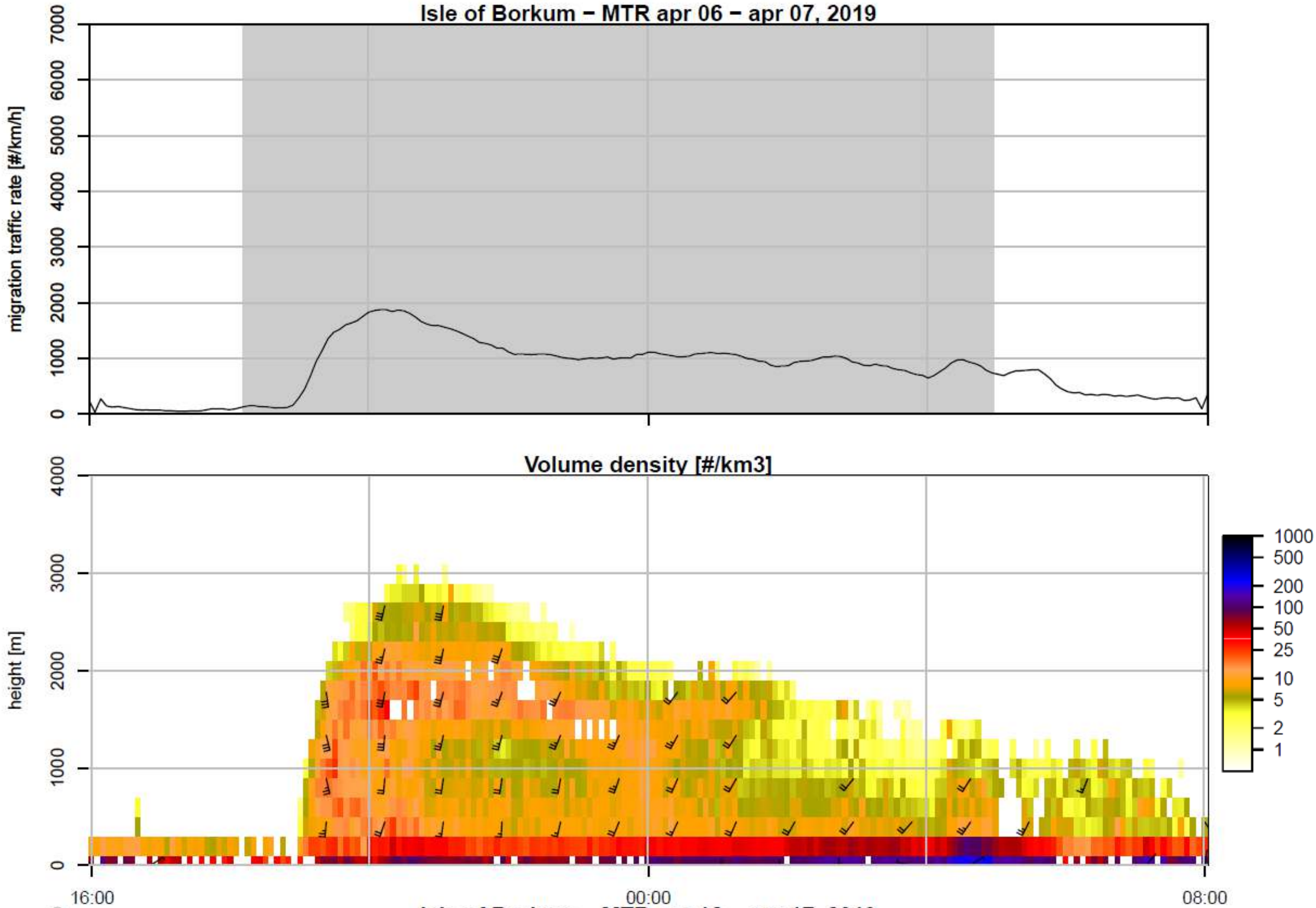


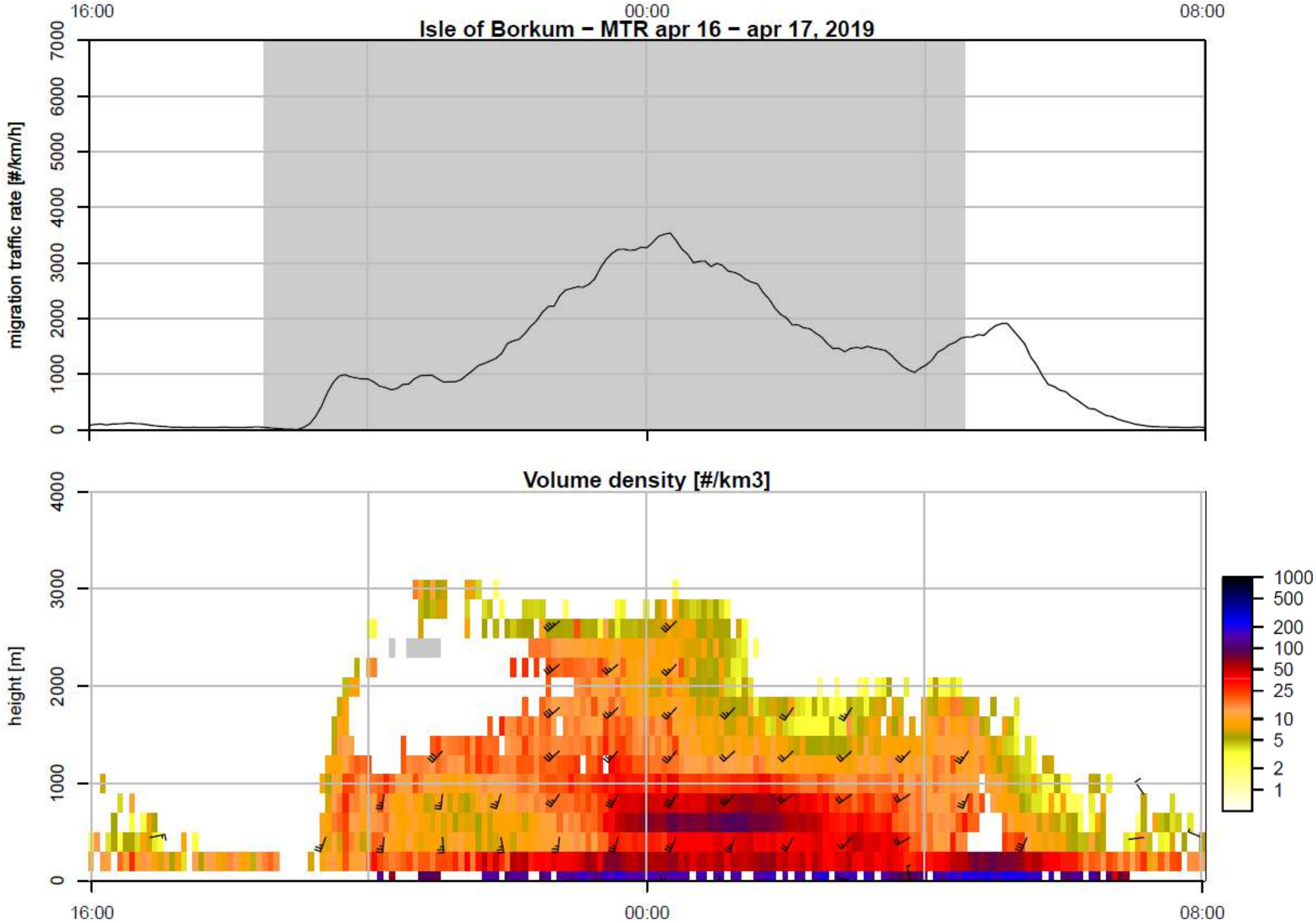
Figure A.4: Nightly migration traffic rate and bird densities measured with Borkum radar during spring 2019 migratory season on nights when temporary shutdowns were conducted. Times are in UTC.

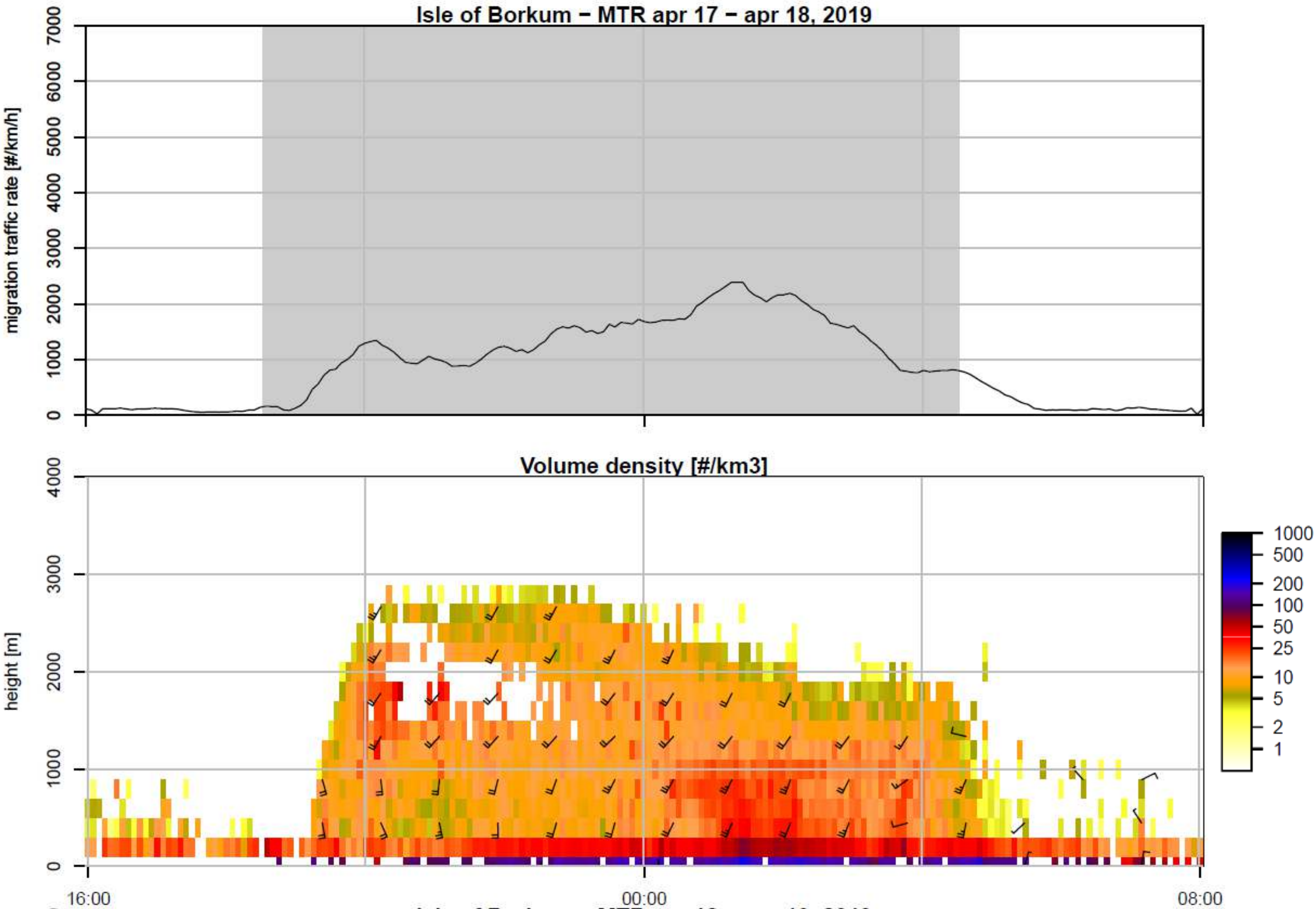


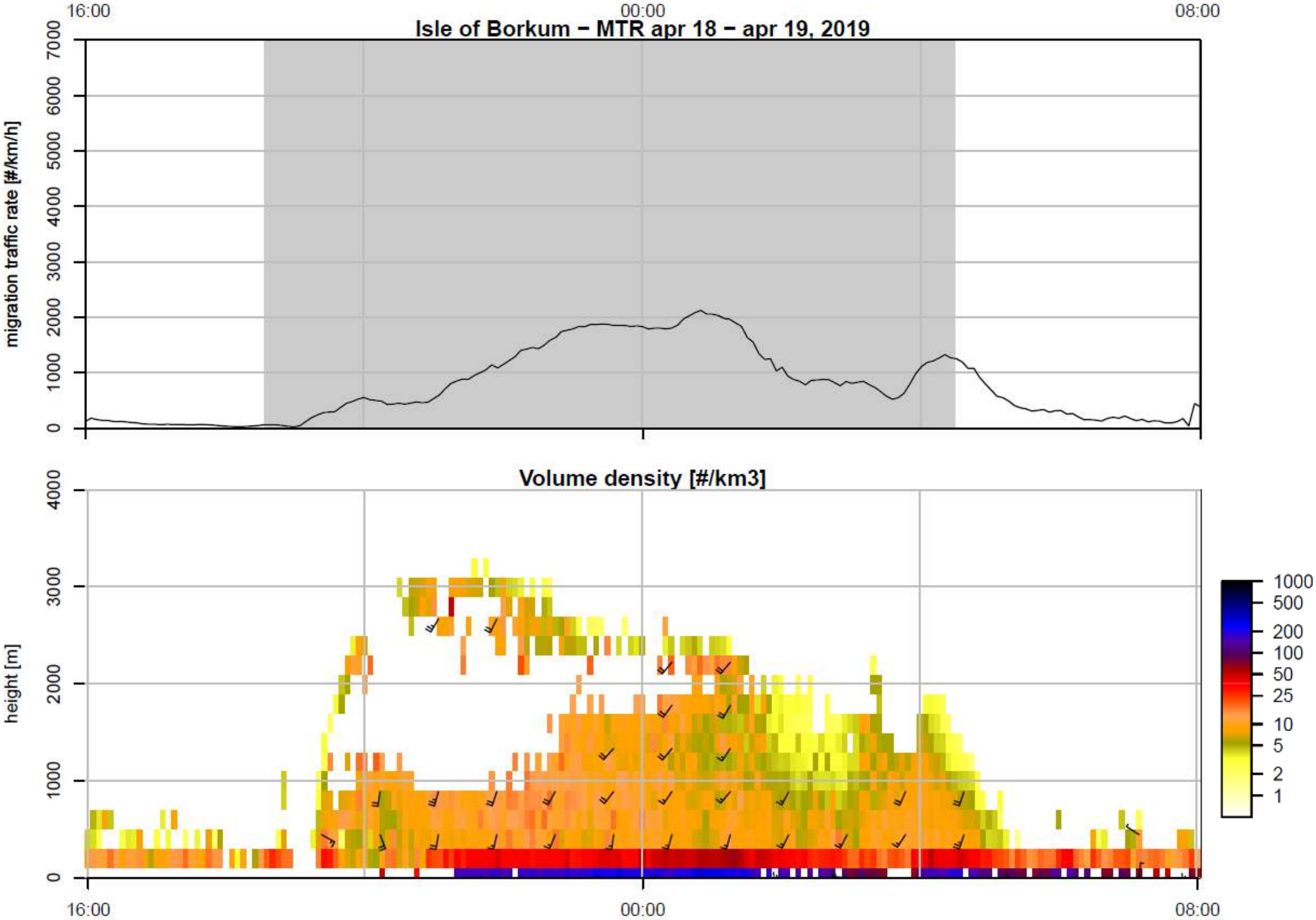

Isle of Borkum - MTR mrt 28 - mrt 29, 2019
migration traffic rate [#/km/h]
0
1000
2000
3000
4000
5000
6000
7000
Volume density [#/km3]
height [m]
0
1000
2000
3000
4000
1000
500
200
100
50
25
10
5
2
1
16:00
00:00
08:00


Isle of Borkum - MTR mrt 29 - mrt 30, 2019
migration traffic rate [#/km/h]
0
1000
2000
3000
4000
5000
6000
7000
Volume density [#/km3]
height [m]
0
1000
2000
3000
4000
1000
500
200
100
50
25
10
5
2
1
16:00
00:00
08:00


Isle of Borkum – MTR apr 06 – apr 07, 2019
migration traffic rate [#/km/h]
Volume density [#/km3]
height [m]
16:00
00:00
08:00


Isle of Borkum – MTR apr 16 – apr 17, 2019
migration traffic rate [#/km/h]
Volume density [#/km3]
height [m]
16:00
00:00
08:00


Isle of Borkum – MTR apr 17 – apr 18, 2019
migration traffic rate [#/km/h]
0
1000
2000
3000
4000
5000
6000
7000
Volume density [#/km3]
height [m]
0
1000
2000
3000
4000
16:00
00:00
08:00
1000
500
200
100
50
25
10
5
2
1


Isle of Borkum – MTR apr 18 – apr 19, 2019
migration traffic rate [#/km/h]
0
1000
2000
3000
4000
5000
6000
7000
Volume density [#/km3]
height [m]
0
1000
2000
3000
4000
16:00
00:00
08:00
1000
500
200
100
50
25
10
5
2
1

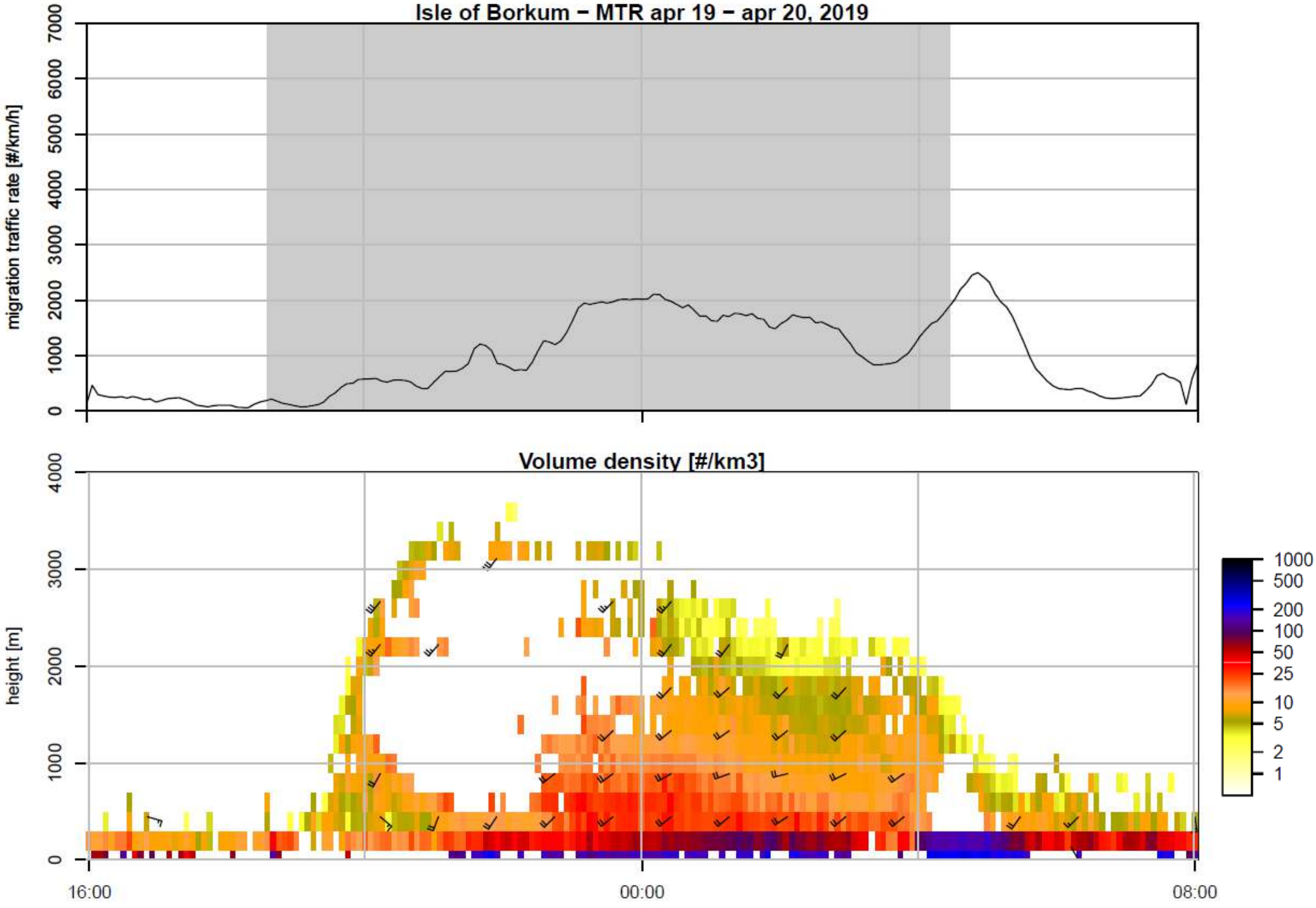
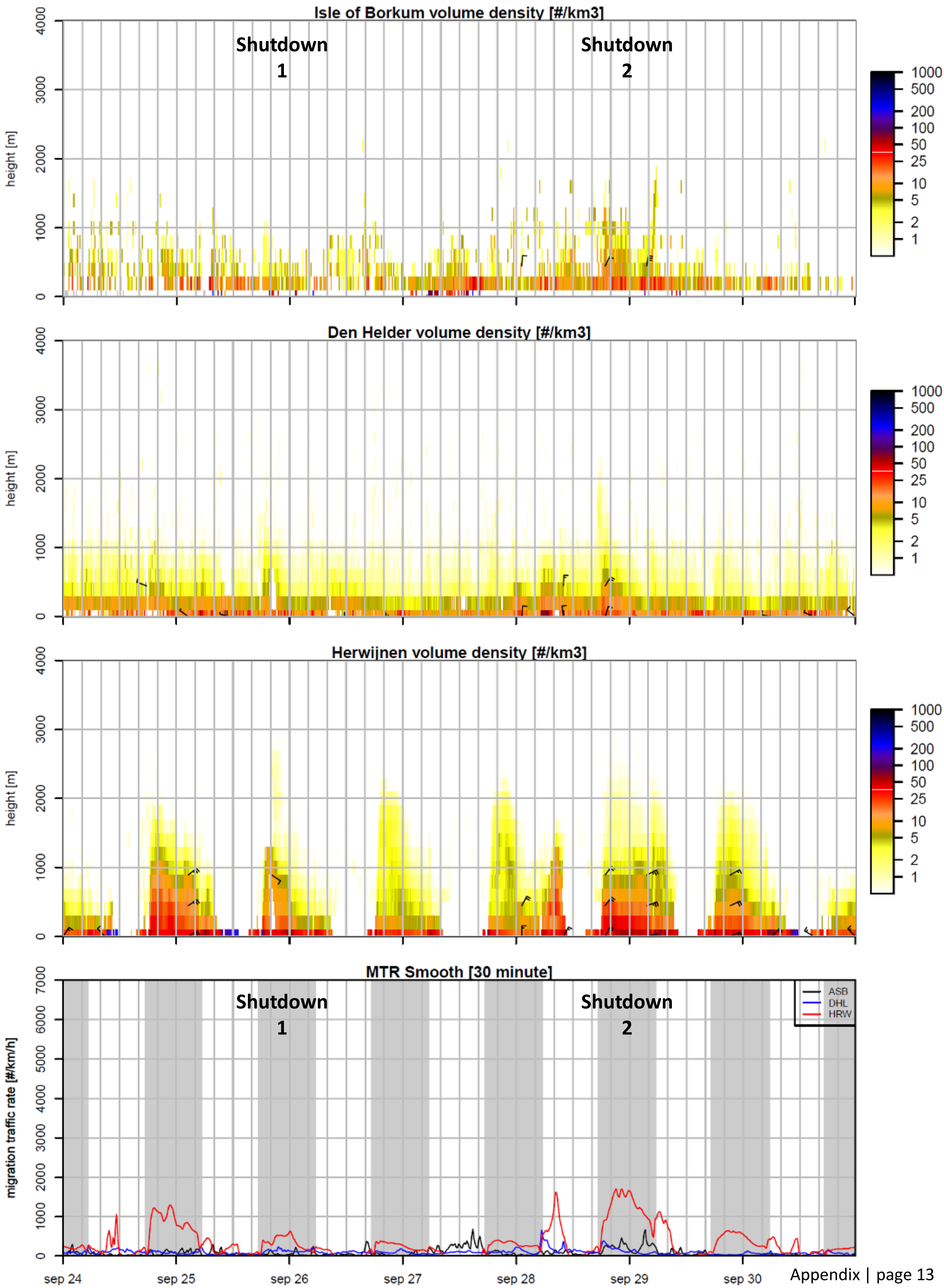
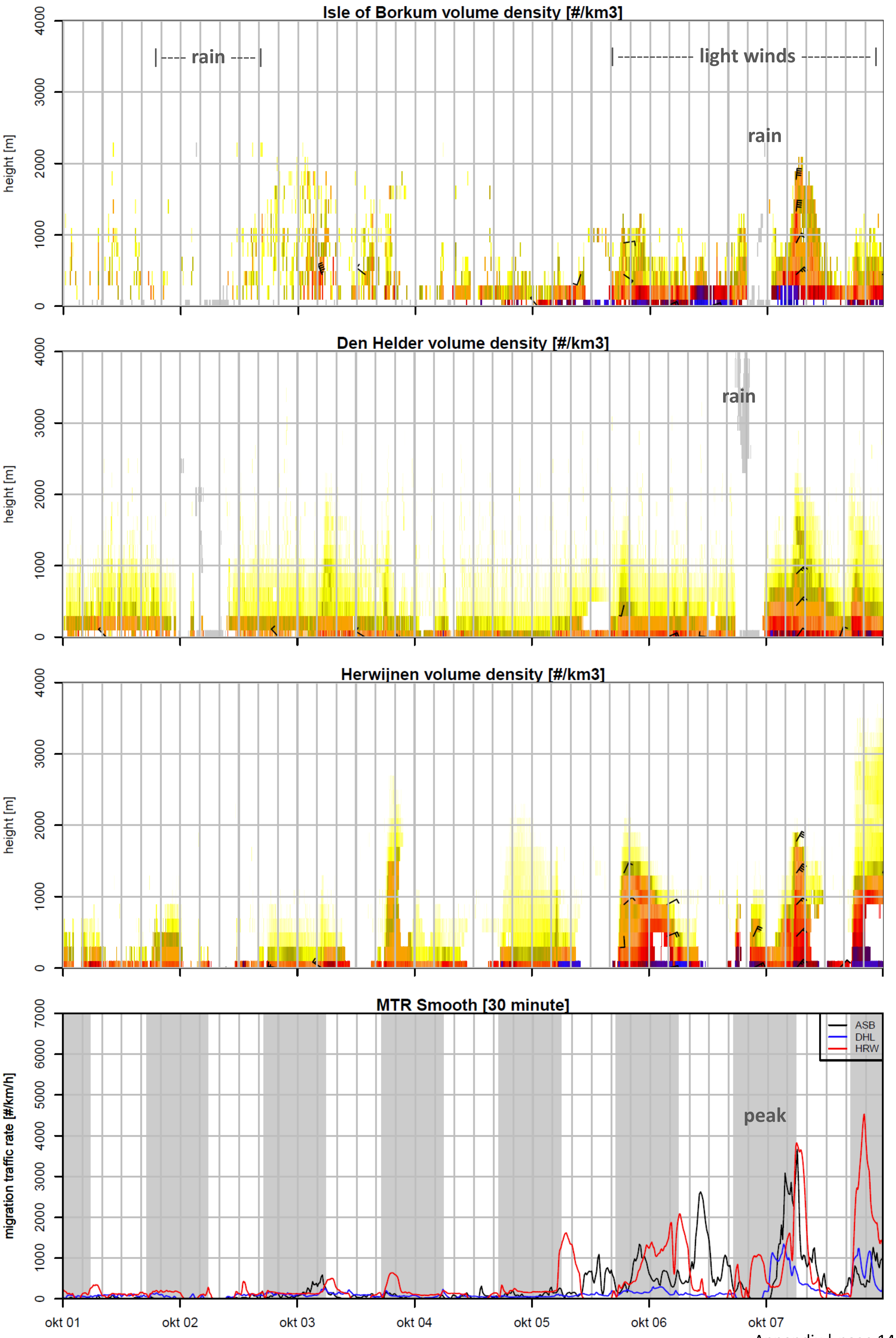
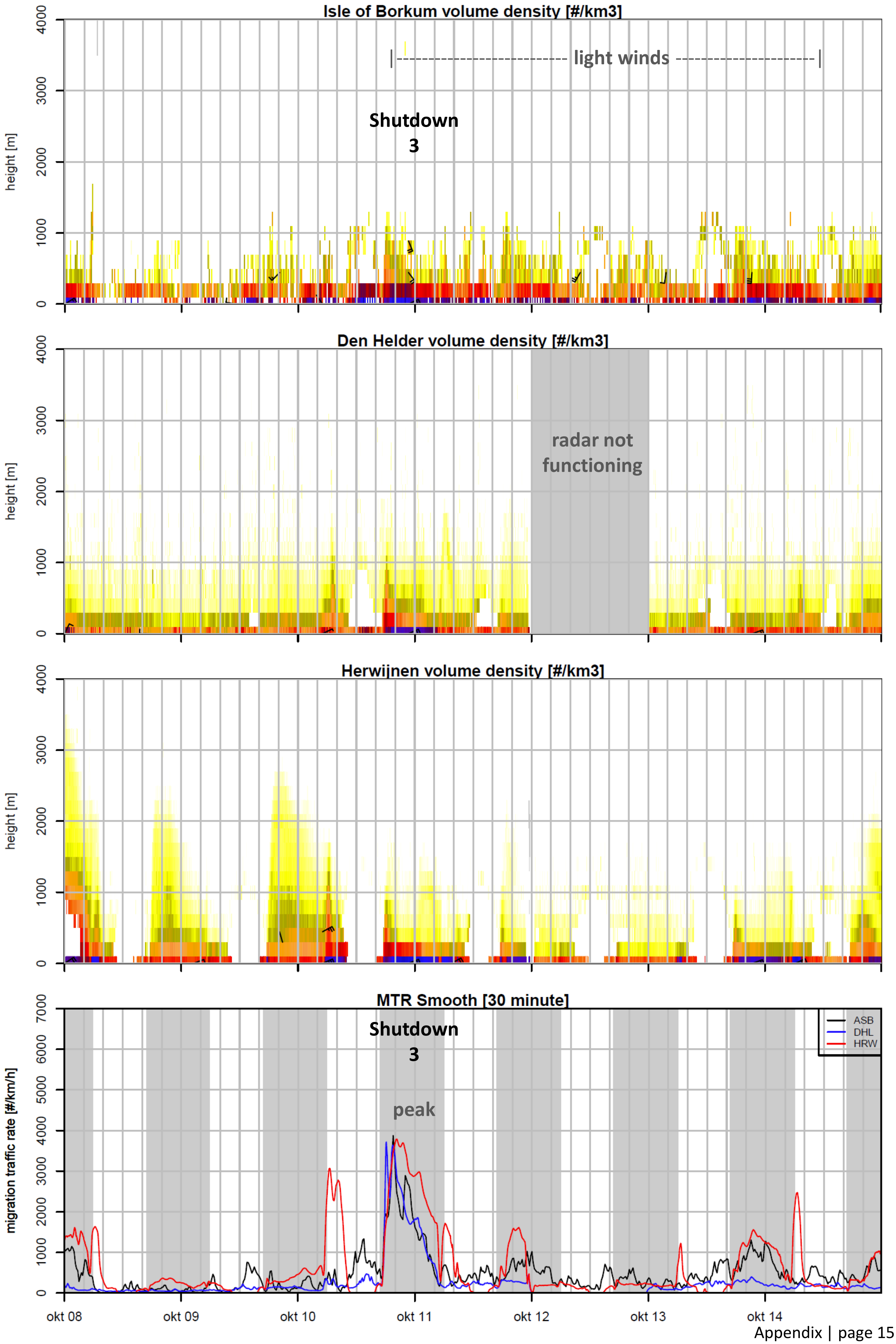
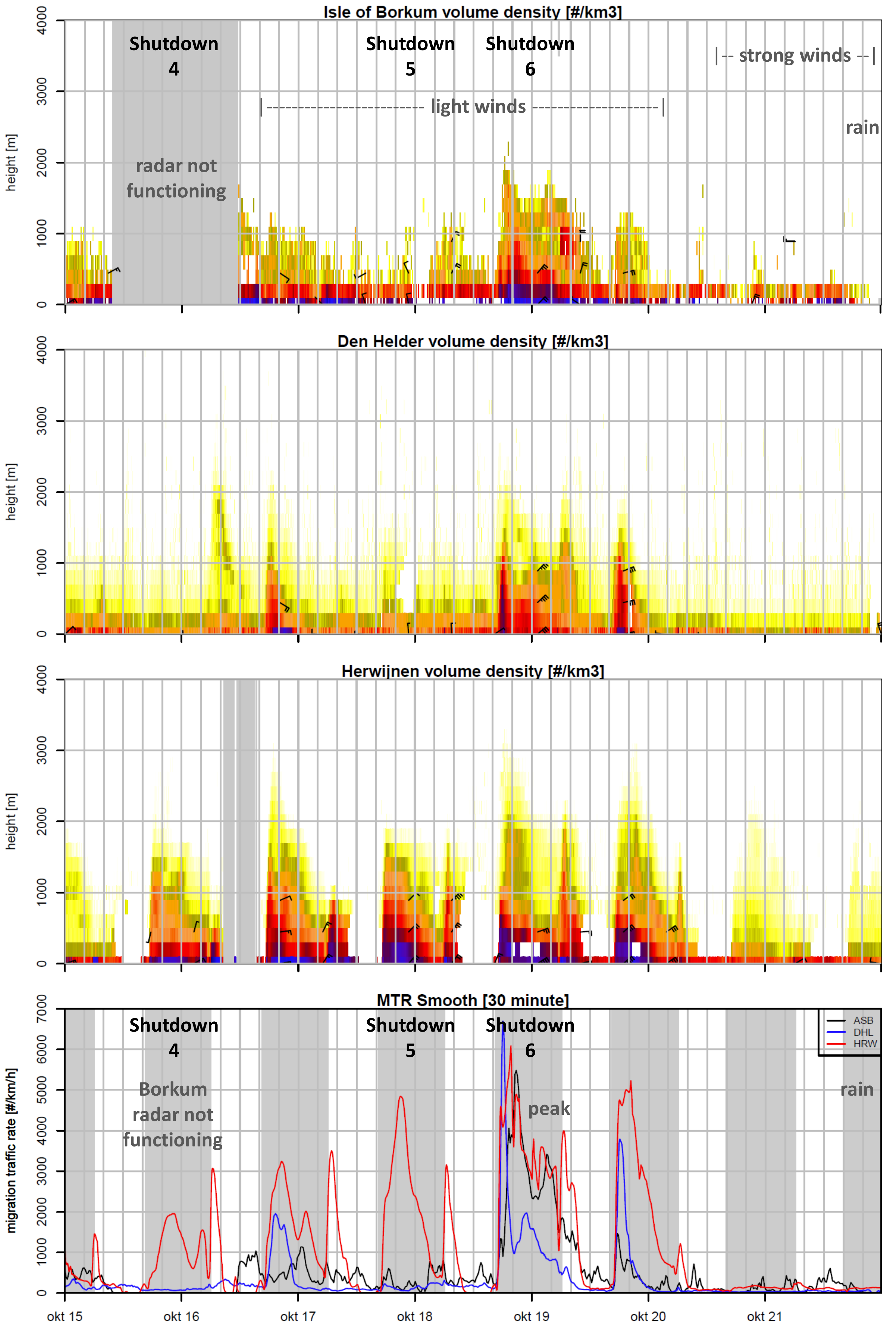

Isle of Borkum – MTR apr 19 – apr 20, 2019
migration traffic rate [#/km/h]
0
1000
2000
3000
4000
5000
6000
7000
Volume density [#/km3]
height [m]
0
1000
2000
3000
4000
16:00
00:00
08:00
1000
500
200
100
50
25
10
5
2
1

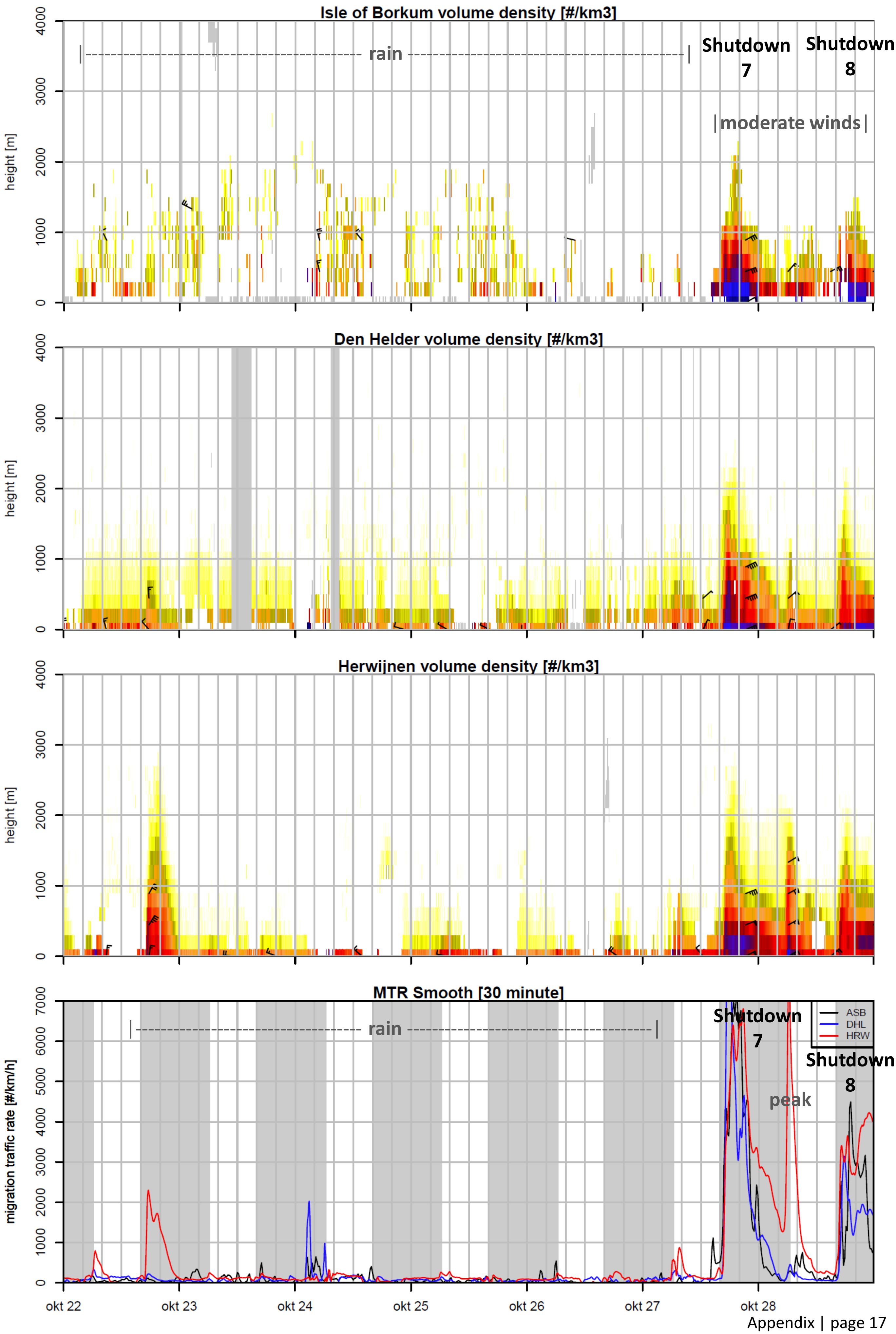
Figure A.5: Biological signals measured with Borkum (Germany), Den Helder and Herwijnen (Netherlands) radars for each week of the autumn 2018 migration season. Top three graphs show vertical profiles of volume bird densities and flight directions are indicated using black barbs laid over high density areas. Bottom graph shows average migration traffic rate, which is a measure of total bird traffic per hour summed over the entire vertical profile.

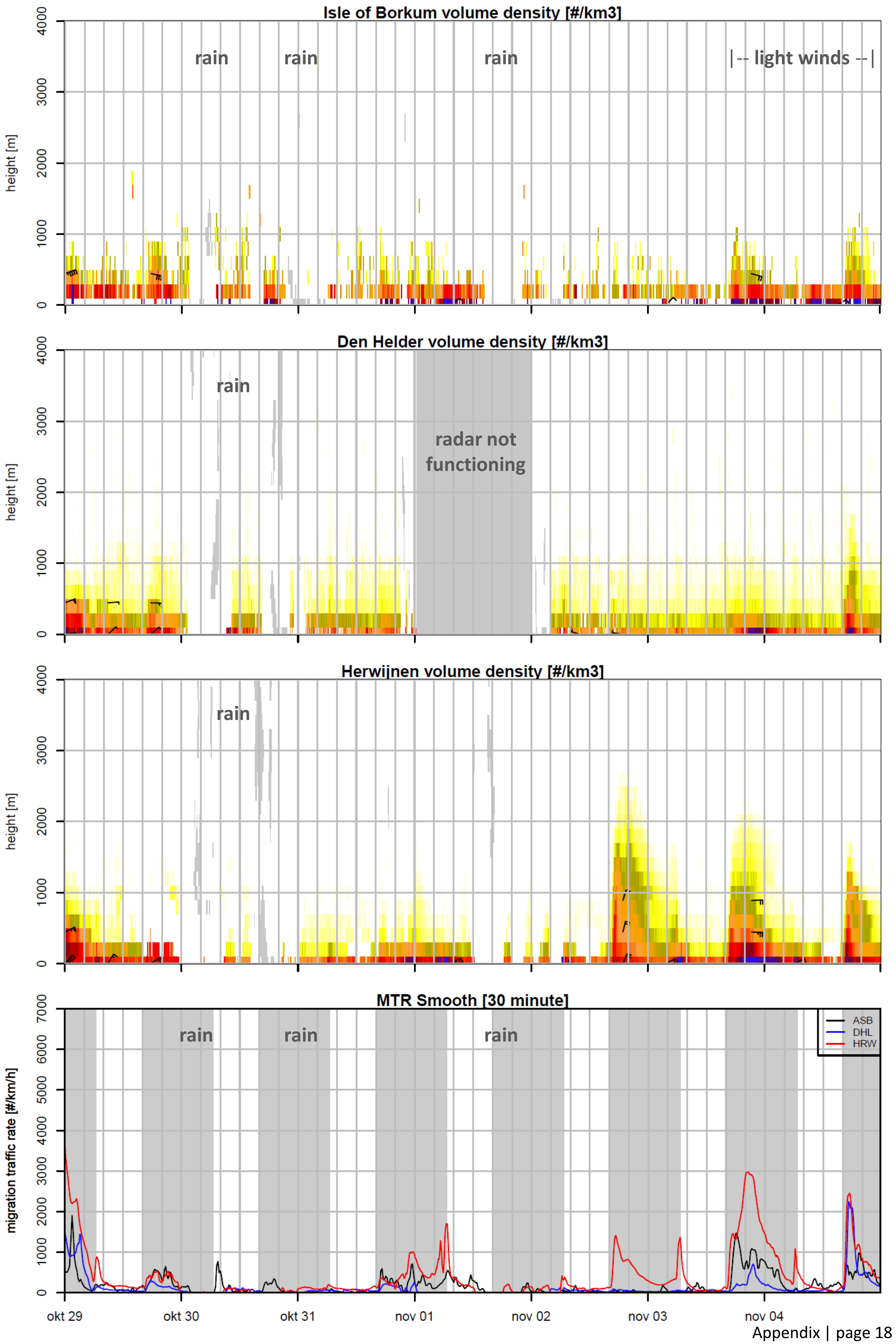



Isle of Borkum volume density [#/km3]
|---- rain ----|
|----------- light winds -----------|
rain
height [m]
0
1000
2000
3000
4000
Den Helder volume density [#/km3]
rain
Herwijnen volume density [#/km3]
MTR Smooth [30 minute]
ASB
DHL
HRW
peak
migration traffic rate [#/km/h]
0
1000
2000
3000
4000
5000
6000
7000
okt 01
okt 02
okt 03
okt 04
okt 05
okt 06
okt 07

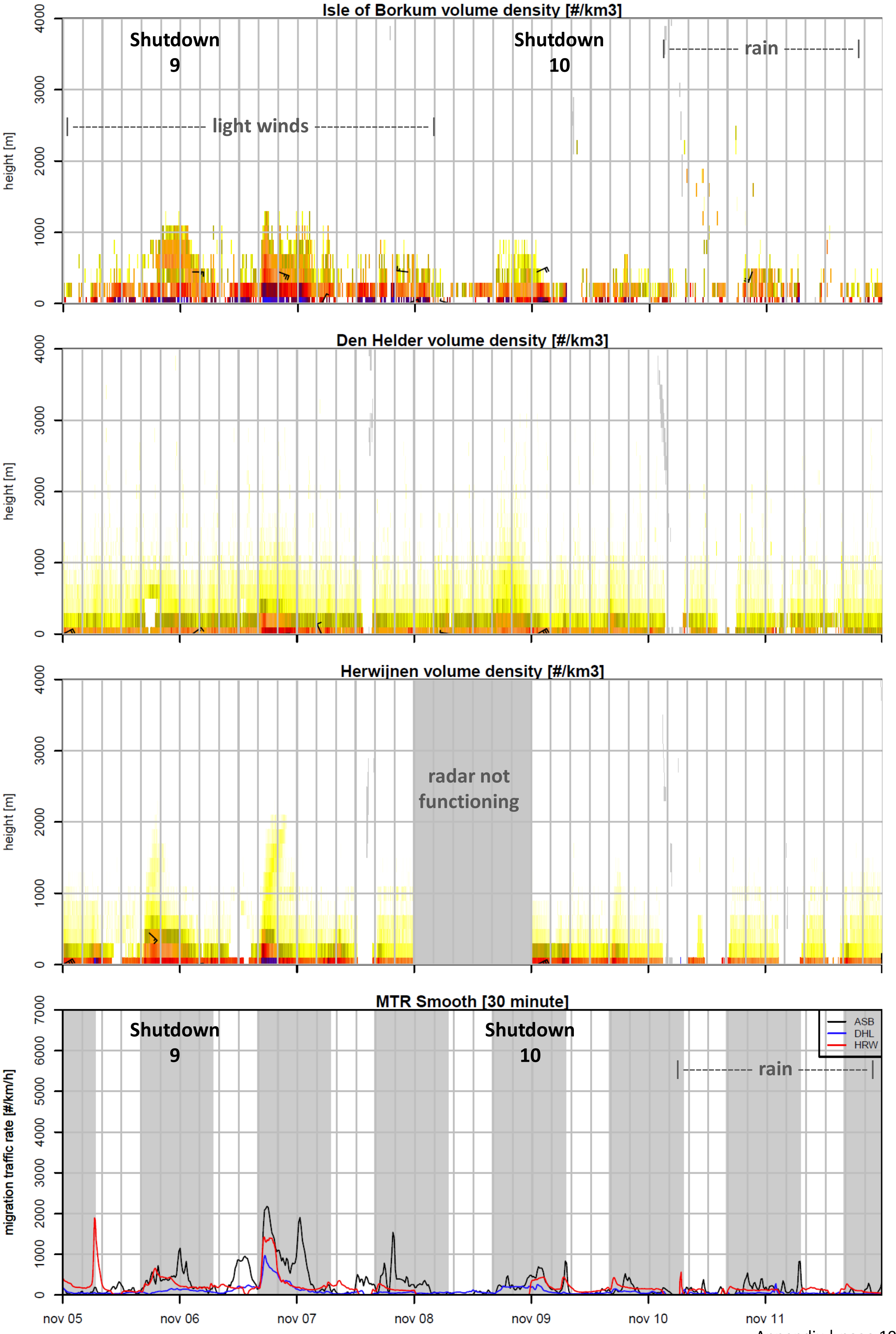

Isle of Borkum volume density [#/km3]
light winds
Shutdown 3
height [m]
Den Helder volume density [#/km3]
radar not functioning
height [m]
Herwijnen volume density [#/km3]
height [m]
MTR Smooth [30 minute]
Shutdown 3
peak
ASB
DHL
HRW
migration traffic rate [#/km/h]
okt 08
okt 09
okt 10
okt 11
okt 12
okt 13
okt 14


Isle of Borkum volume density [#/km3]
Shutdown 4
Shutdown 5
Shutdown 6
|-- strong winds --|
|------------------------ light winds --------------------|
rain
radar not functioning
height [m]
Den Helder volume density [#/km3]
height [m]
Herwijnen volume density [#/km3]
height [m]
MTR Smooth [30 minute]
Shutdown 4
Shutdown 5
Shutdown 6
Borkum radar not functioning
peak
rain
ASB
DHL
HRW
migration traffic rate [#/km/h]
okt 15
okt 16
okt 17
okt 18
okt 19
okt 20
okt 21


Isle of Borkum volume density [#/km3]
rain
Shutdown 7
Shutdown 8
moderate winds
height [m]
Den Helder volume density [#/km3]
Herwijnen volume density [#/km3]
MTR Smooth [30 minute]
rain
Shutdown 7
Shutdown 8
peak
ASB
DHL
HRW
migration traffic rate [#/km/h]
okt 22
okt 23
okt 24
okt 25
okt 26
okt 27
okt 28



Isle of Borkum volume density [#/km3]
rain
rain
rain
|-- light winds --|
height [m]
Den Helder volume density [#/km3]
rain
radar not functioning
height [m]
Herwijnen volume density [#/km3]
rain
height [m]
MTR Smooth [30 minute]
rain
rain
rain
ASB
DHL
HRW
migration traffic rate [#/km/h]
okt 29
okt 30
okt 31
nov 01
nov 02
nov 03
nov 04


Isle of Borkum volume density [#/km3]
Shutdown 9
Shutdown 10
rain
light winds
height [m]
Den Helder volume density [#/km3]
Herwijnen volume density [#/km3]
radar not functioning
MTR Smooth [30 minute]
ASB
DHL
HRW
migration traffic rate [#/km/h]
nov 05
nov 06
nov 07
nov 08
nov 09
nov 10
nov 11

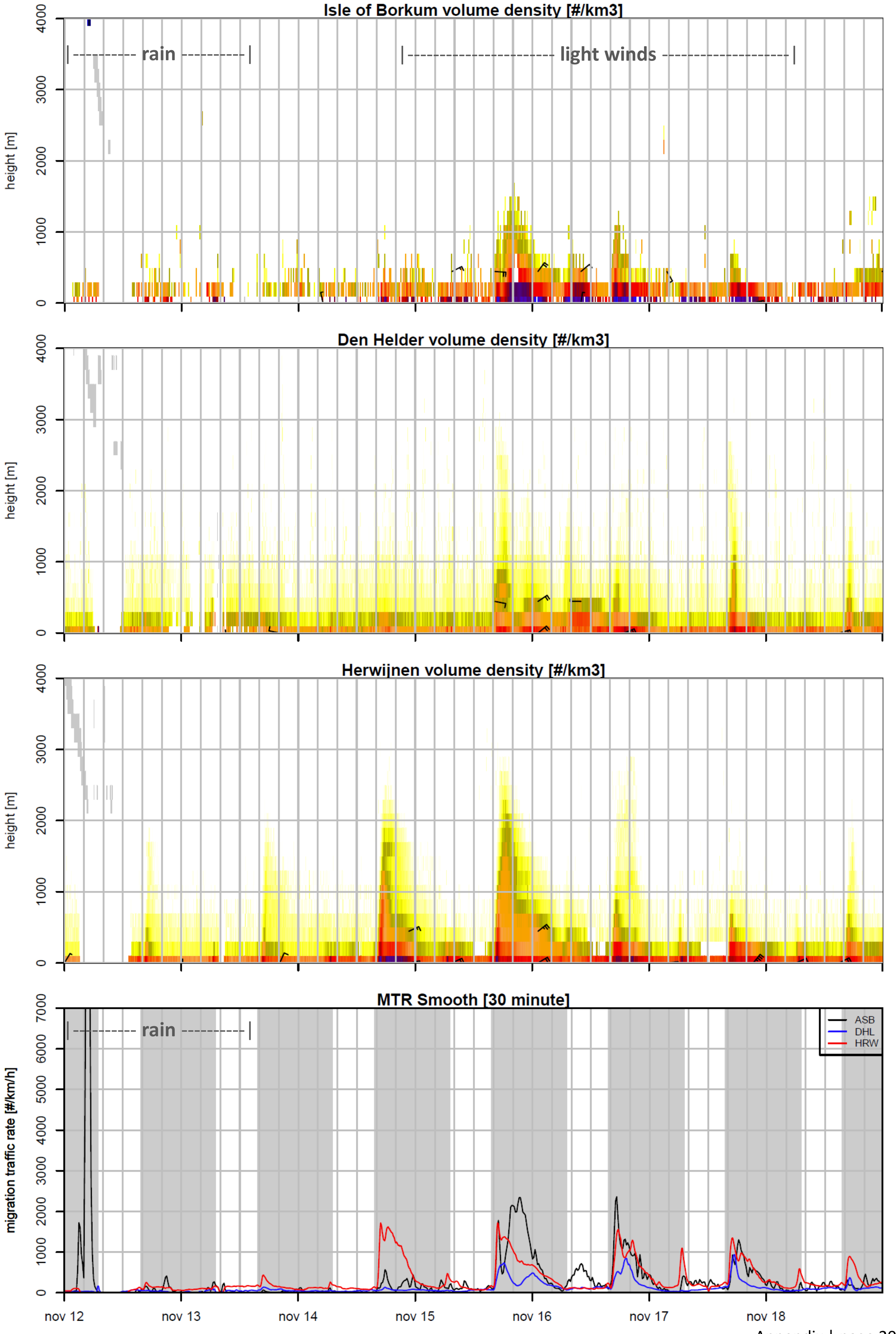
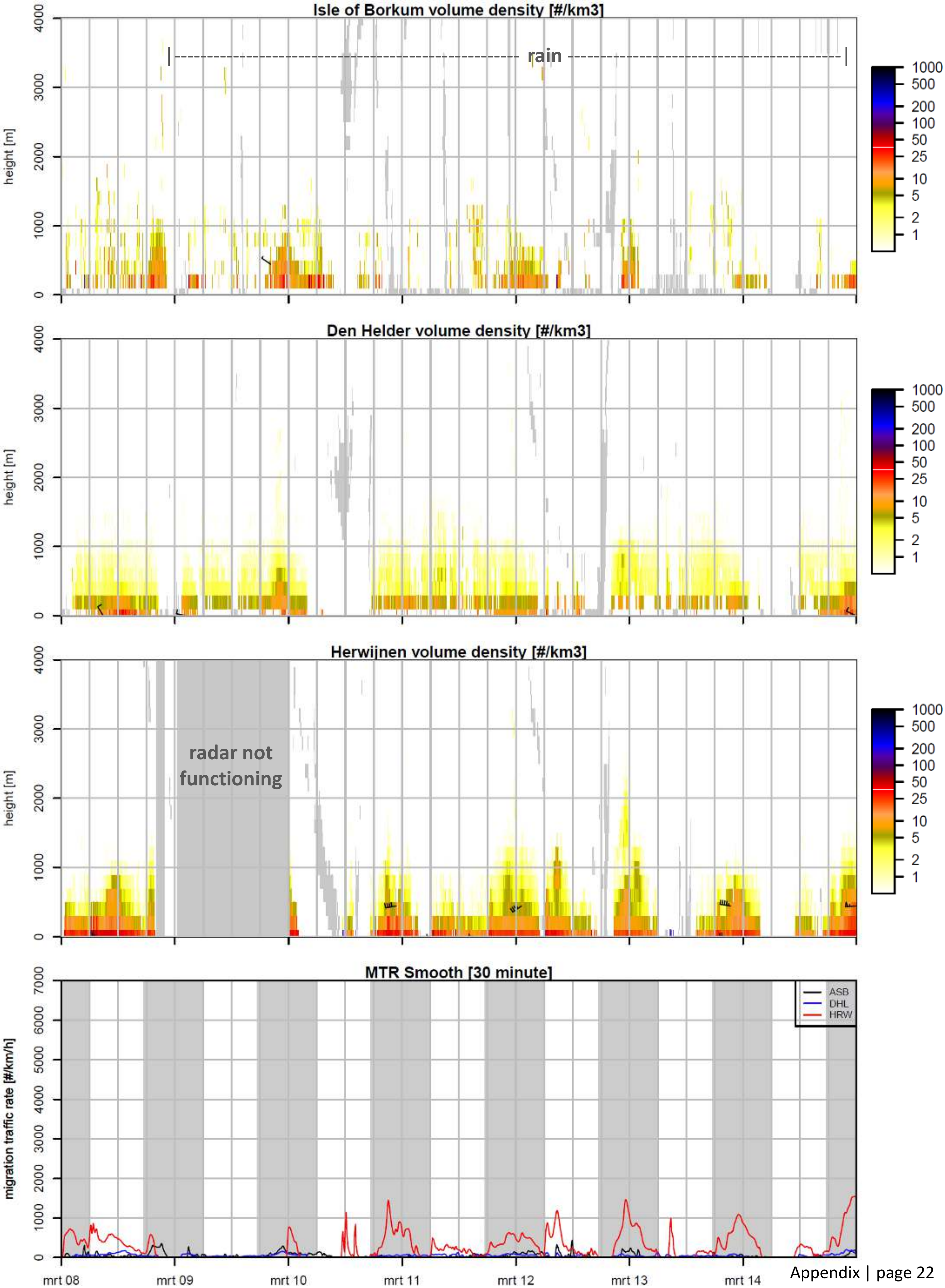
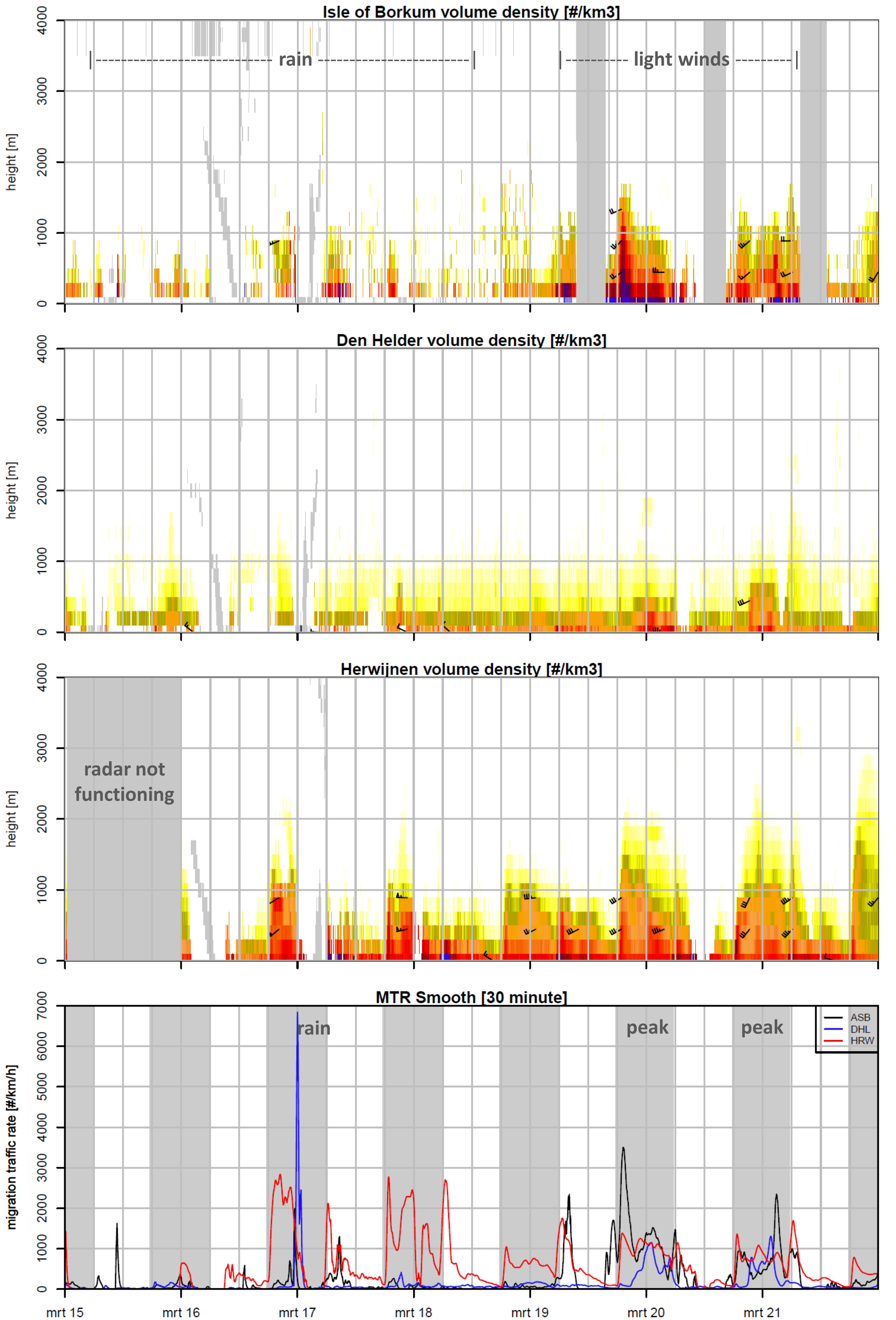
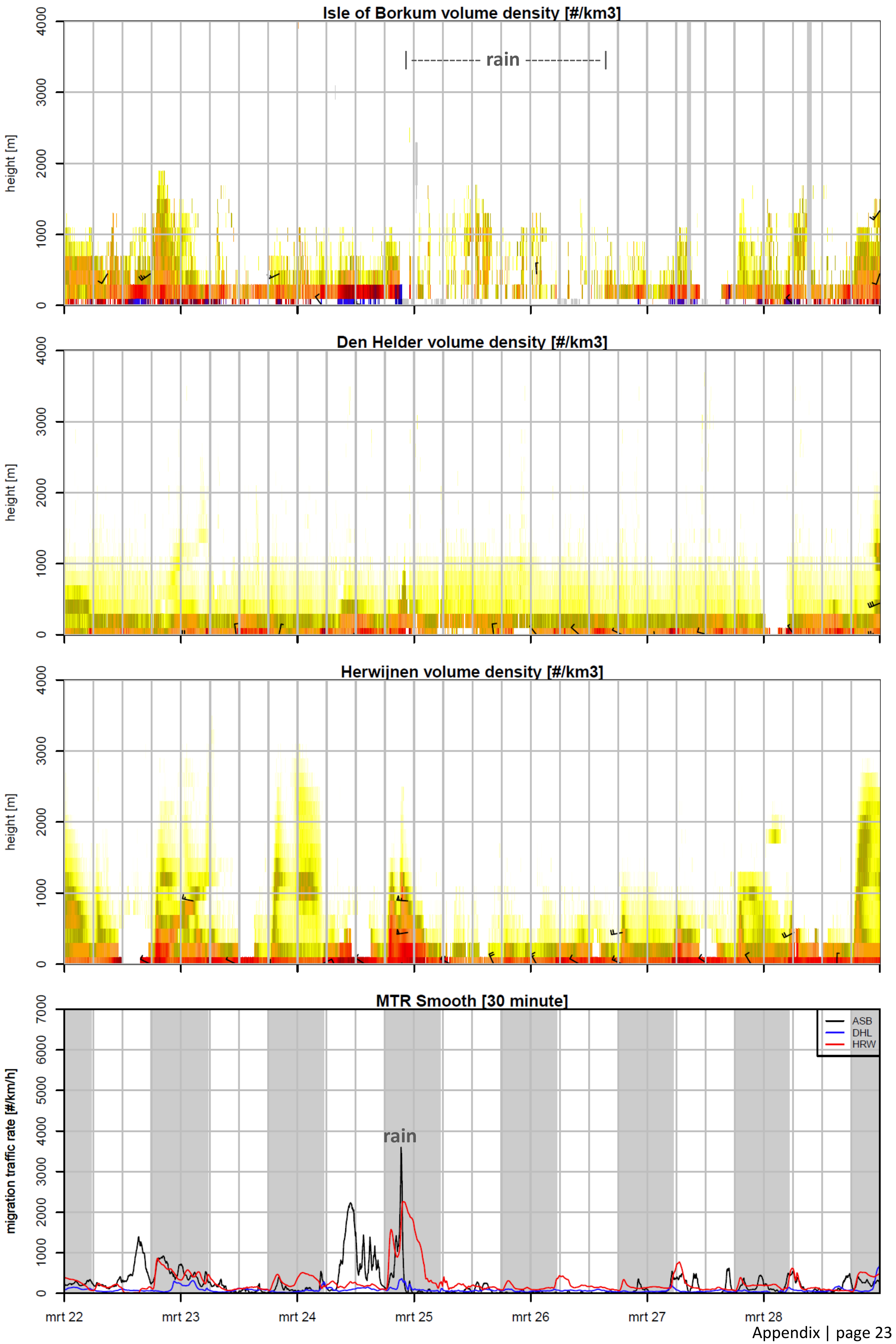
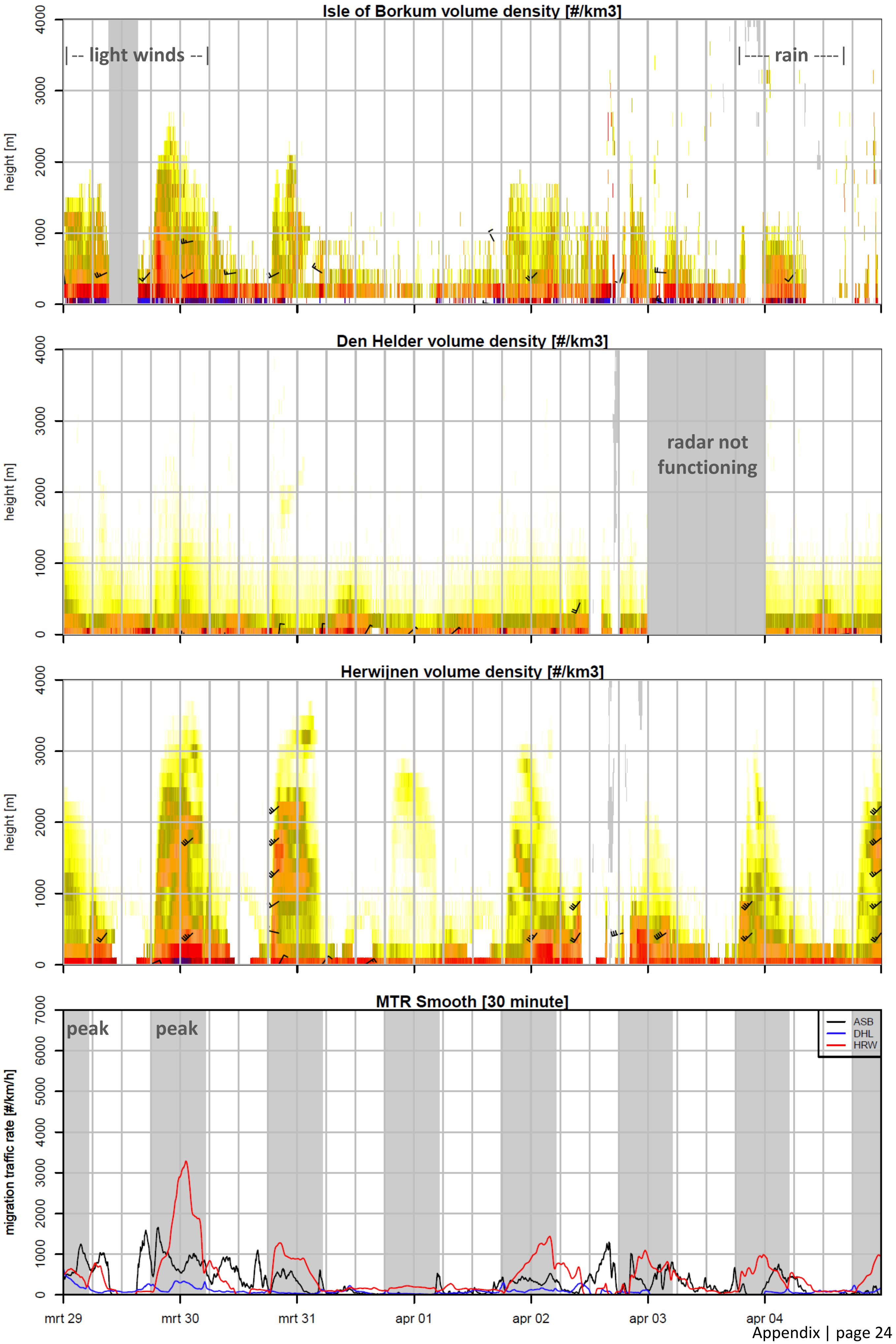

Isle of Borkum volume density [#/km3]
rain
light winds
height [m]
Den Helder volume density [#/km3]
height [m]
Herwijnen volume density [#/km3]
height [m]
MTR Smooth [30 minute]
rain
ASB
DHL
HRW
migration traffic rate [#/km/h]
nov 12
nov 13
nov 14
nov 15
nov 16
nov 17
nov 18

Figure A.6: Biological signals measured with Borkum (Germany), Den Helder and Herwijnen (Netherlands) radars for each week of the spring 2019 migration season. Top three graphs show vertical profiles of volume bird densities and flight directions are indicated using black barbs laid over high density areas. Bottom graph shows average migration traffic rate, which is a measure of total bird traffic per hour summed over the entire vertical profile.

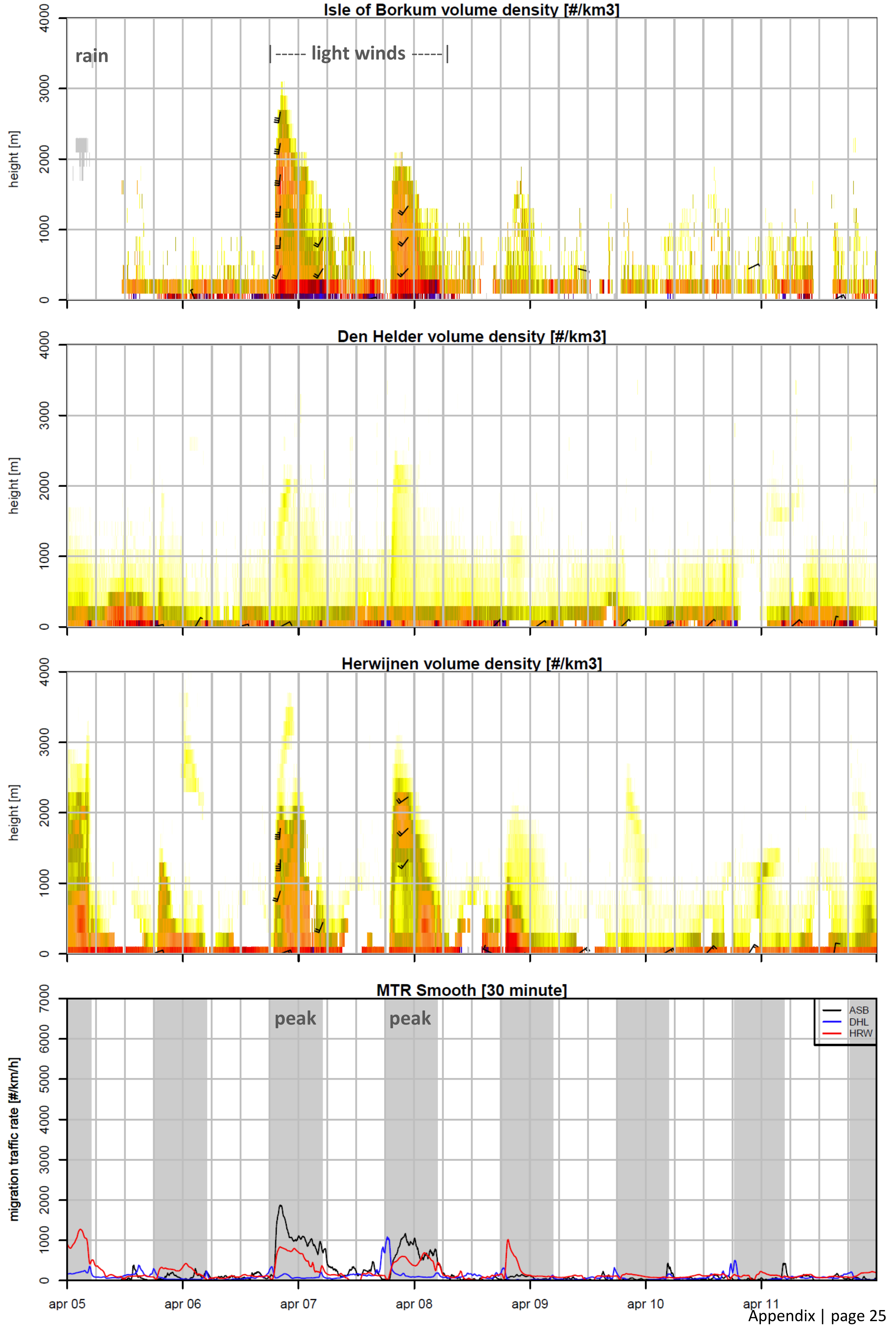


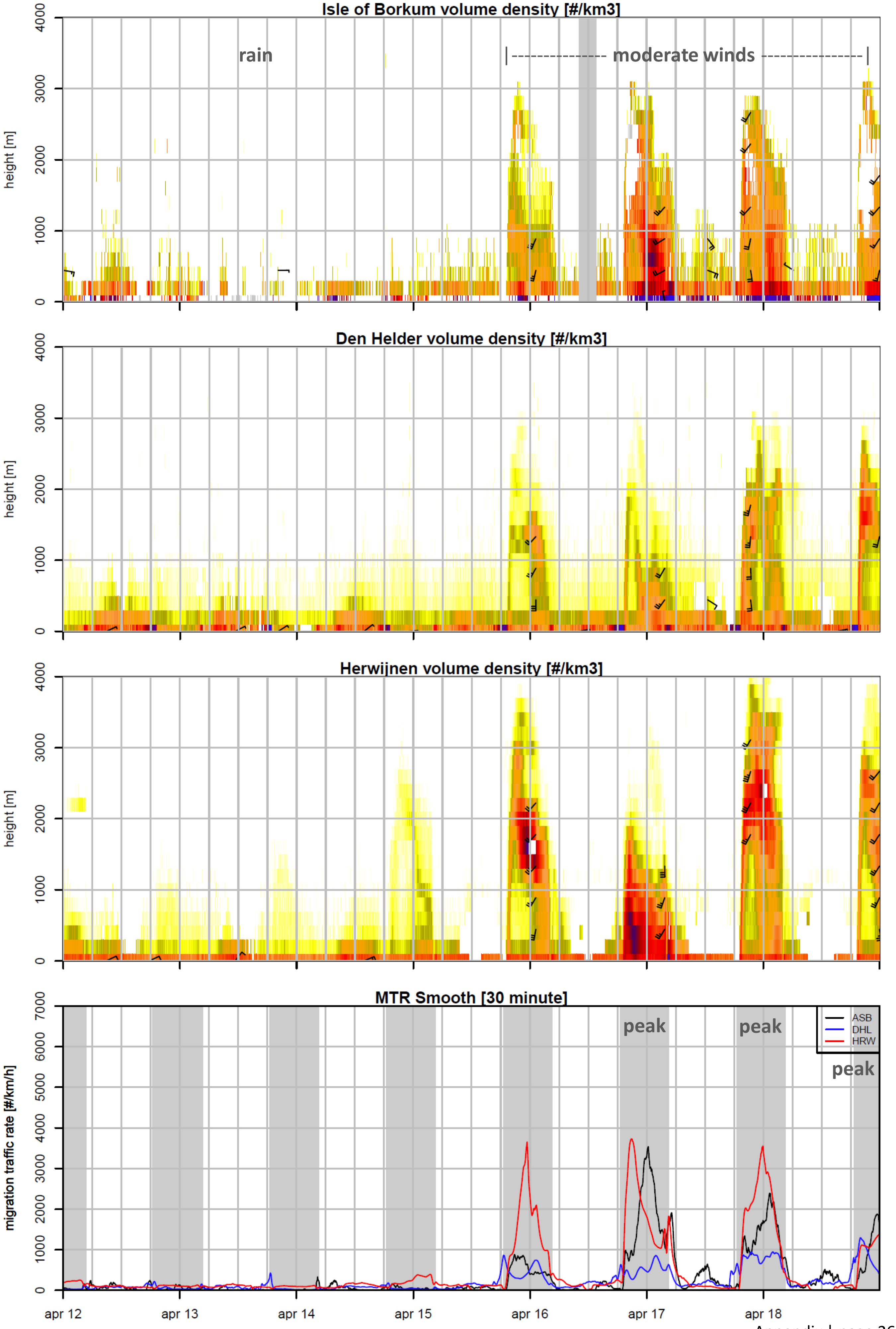

Isle of Borkum volume density [#/km3]
rain
light winds
height [m]
Den Helder volume density [#/km3]
Herwijnen volume density [#/km3]
radar not functioning
MTR Smooth [30 minute]
rain
peak
peak
ASB
DHL
HRW
migration traffic rate [#/km/h]
mrt 15
mrt 16
mrt 17
mrt 18
mrt 19
mrt 20
mrt 21

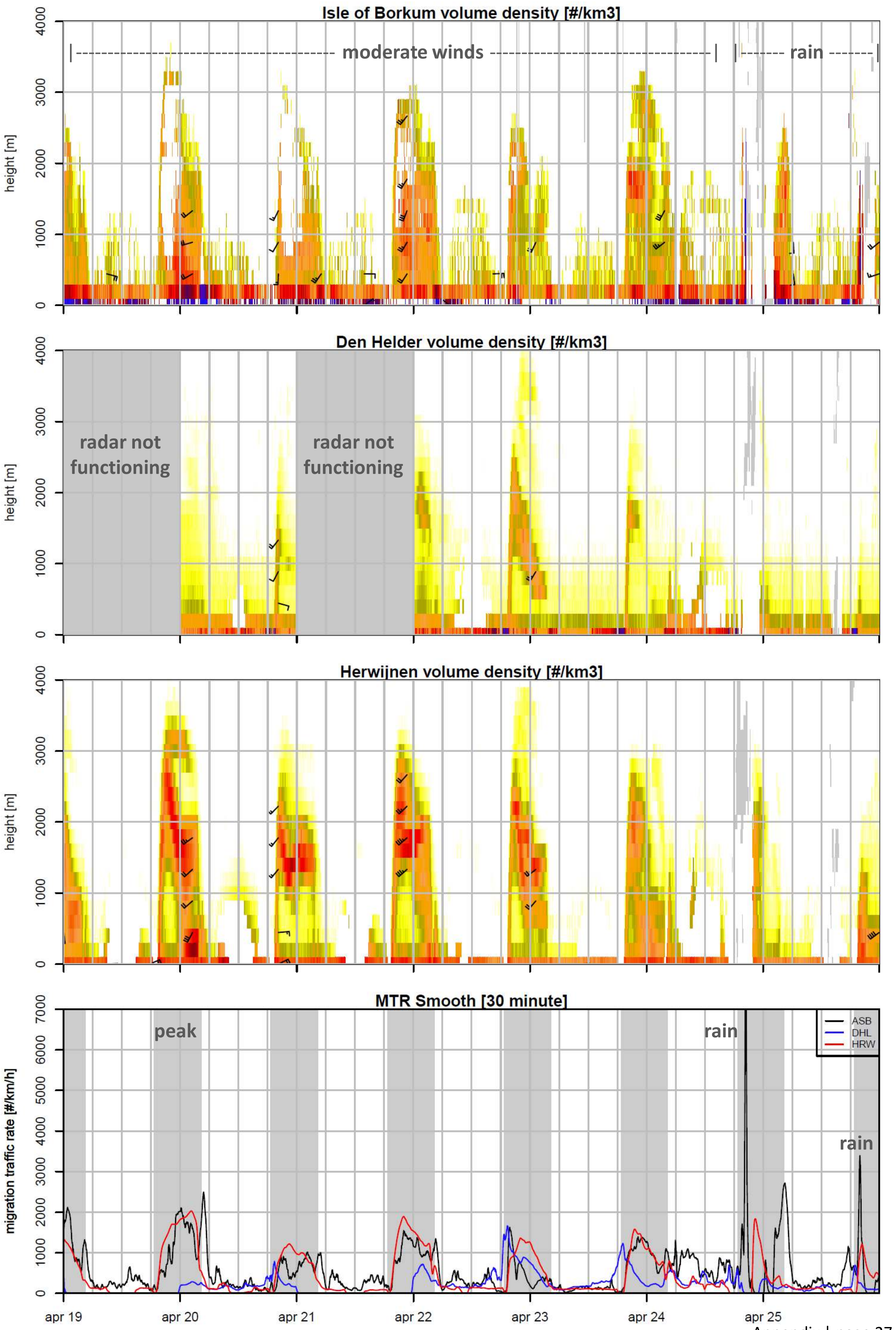

Isle of Borkum volume density [#/km3]
rain
height [m]
0
1000
2000
3000
4000
Den Helder volume density [#/km3]
Herwijnen volume density [#/km3]
MTR Smooth [30 minute]
ASB
DHL
HRW
migration traffic rate [#/km/h]
7000
6000
5000
4000
3000
2000
1000
0
mrt 22
mrt 23
mrt 24
mrt 25
mrt 26
mrt 27
mrt 28



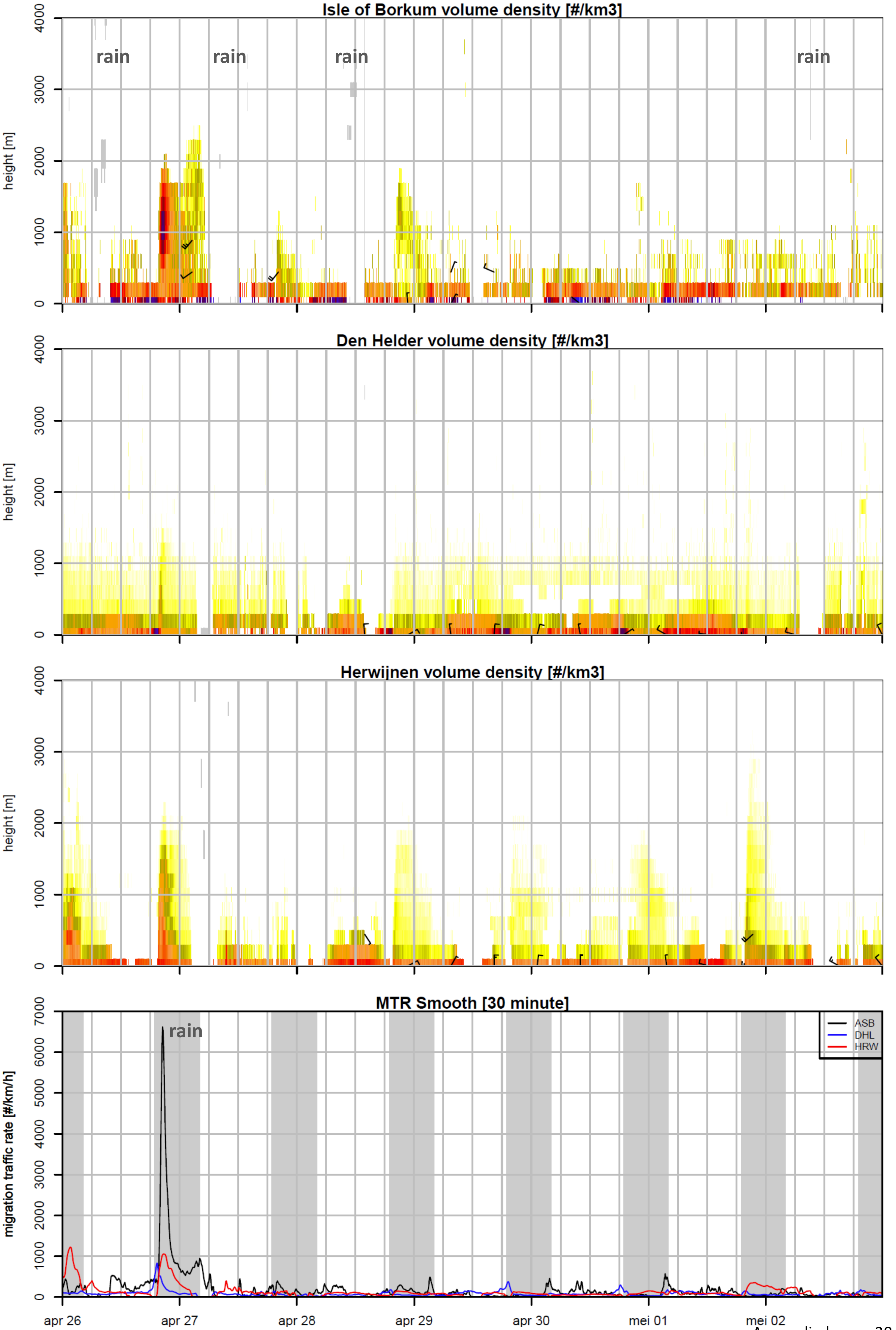
Isle of Borkum volume density [#/km3]
|-- light winds --|
|---- rain ----|
height [m]
Den Helder volume density [#/km3]
radar not functioning
height [m]
Herwijnen volume density [#/km3]
height [m]
MTR Smooth [30 minute]
peak
peak
ASB
DHL
HRW
migration traffic rate [#/km/h]
mrt 29
mrt 30
mrt 31
apr 01
apr 02
apr 03
apr 04

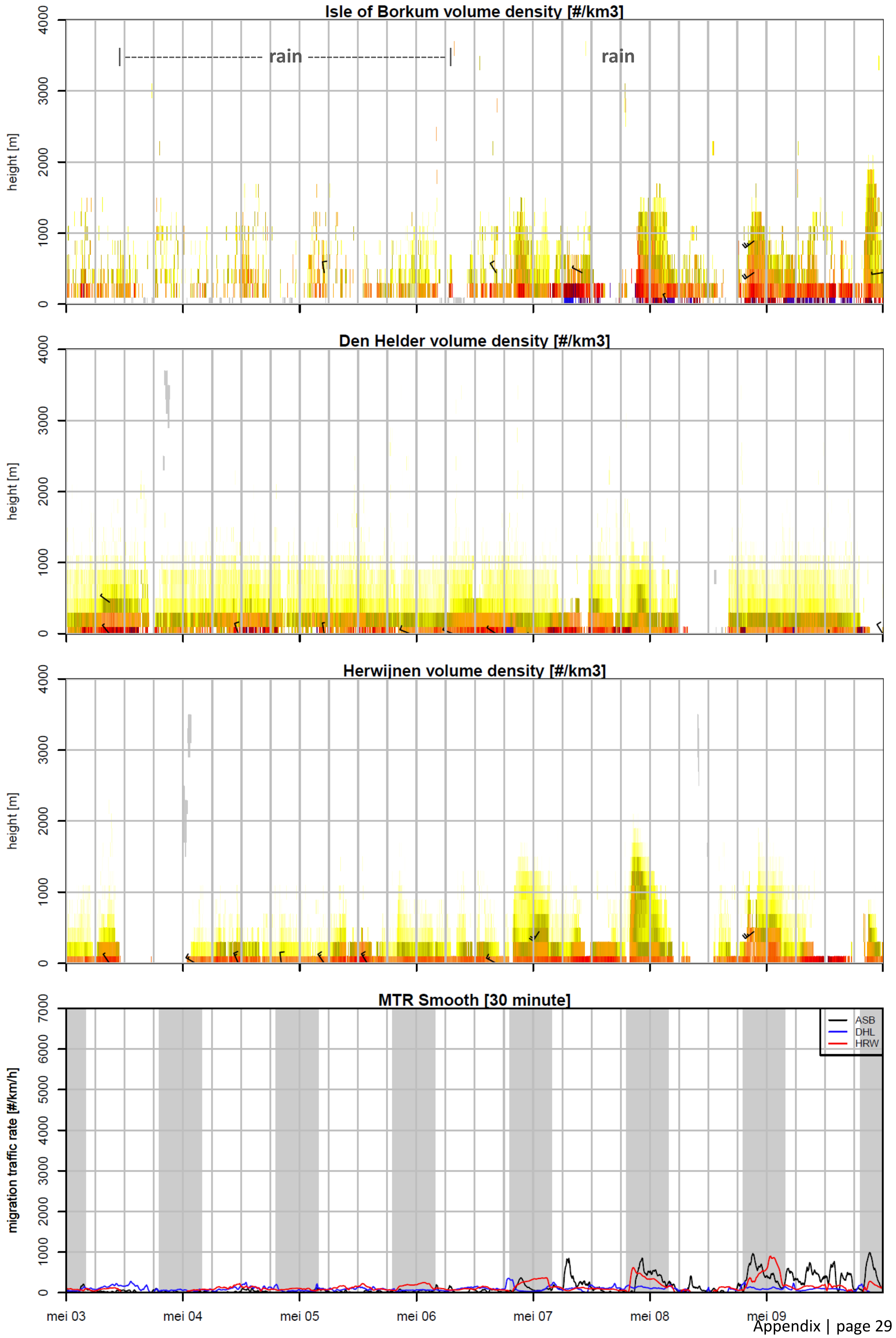

Isle of Borkum volume density [#/km3]
rain
|----- light winds -----|
Den Helder volume density [#/km3]
Herwijnen volume density [#/km3]
height [m]
MTR Smooth [30 minute]
peak
peak
ASB
DHL
HRW
migration traffic rate [#/km/h]
apr 05
apr 06
apr 07
apr 08
apr 09
apr 10
apr 11


Isle of Borkum volume density [#/km3]
rain
moderate winds
height [m]
Den Helder volume density [#/km3]
height [m]
Herwijnen volume density [#/km3]
height [m]
MTR Smooth [30 minute]
peak
peak
peak
ASB
DHL
HRW
migration traffic rate [#/km/h]
apr 12
apr 13
apr 14
apr 15
apr 16
apr 17
apr 18



Isle of Borkum volume density [#/km3]
moderate winds
rain
height [m]
Den Helder volume density [#/km3]
radar not functioning
radar not functioning
height [m]
Herwijnen volume density [#/km3]
height [m]
MTR Smooth [30 minute]
peak
rain
rain
ASB
DHL
HRW
migration traffic rate [#/km/h]
apr 19
apr 20
apr 21
apr 22
apr 23
apr 24
apr 25


Isle of Borkum volume density [#/km3]
rain
rain
rain
rain
height [m]
Den Helder volume density [#/km3]
height [m]
Herwijnen volume density [#/km3]
height [m]
MTR Smooth [30 minute]
rain
migration traffic rate [#/km/h]
ASB
DHL
HRW
apr 26
apr 27
apr 28
apr 29
apr 30
mei 01
mei 02


Isle of Borkum volume density [#/km3]
rain
rain
height [m]
Den Helder volume density [#/km3]
Herwijnen volume density [#/km3]
MTR Smooth [30 minute]
migration traffic rate [#/km/h]
ASB
DHL
HRW
mei 03
mei 04
mei 05
mei 06
mei 07
mei 08
mei 09