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Iodine-131 (I-131) in indoor air at the Breivika wastewater treatment plant in Tromsø, and subsequent possible sources of I-131 to the air over Tromsø

DSA
Direktoratet for strålevern og atomsikkerhet

Referanse
Gwynn JP, Møller B. Jod-131 (I-131) i inneluft ved Breivika renseanlegg i Tromsø, og påfølgende mulige kilder av I-131 til luften over Tromsø.
Teknisk dokument nr. 33. Østerås: Direktoratet for strålevern og atomsikkerhet, 2025.

Emneord
Jod-131. Medisinske radioisotoper. Renseanlegg. Atmosfæriske kilder. Nord-Norge.

Resymé
Bruk av Jod-131 (I-131) ved Universitetssykehuset for Nord-Norge til ablasjonsterapi fører til målbare nivåer av I-131 i inneluften ved Breivika renseanlegget i Tromsø. Dette fører imidlertid ikke til noen helserisiko for arbeidere ved renseanlegget. Denne studien diskuterer faktorene som påvirker nivåene av I-131 i inneluften ved renseanlegget og de påfølgende mulige kildene av I-131 til luften over Tromsø.

Reference
Gwynn JP, Møller B. F. Iodine-131 (I-131) in indoor air at the Breivika wastewater treatment plant in Tromsø, and subsequent possible sources of I-131 to the air over Tromsø.
Technical Document no. 33. Østerås: Norwegian Radiation and Nuclear Safety Authority, 2025.

Key words
Iodine-131. Medical radioisotopes. Wastewater treatment plant. Atmospheric sources. Northern Norway.

Abstract
The use of Iodine-131 (I-131) at the University Hospital for Northern Norway for ablation therapy leads to measurable levels of I-131 in indoor air at the Breivika wastewater treatment plant in Tromsø. However, this does not lead to any human health risk to workers at the water treatment plant. This study discusses the factors influencing the levels of I-131 in indoor air at the water treatment plant and the subsequent possible sources of I-131 to the air over Tromsø.

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fra Direktoratet for strålevern
og atomsikkerhet (DSA)

Østerås, 2025,
Norway

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1. Introduction

The use of radioisotopes in the field of medical diagnostic radiography and radiotherapy is a well-established and growing sector. Radioisotopes identified for medical procedures are mainly gamma and/or beta emitters, with typically short half-lives ranging between minutes and days. Two of the most commonly used medical radioisotopes are technetium-99m (Tc-99m; half-life 6 hours), used for diagnostic radiography, and iodine-131 (I-131; half-life 8 days), which is widely used for the radiotherapy of thyroid cancer. Medical facilities are normally authorised to discharge radioisotopes to sewage systems by national authorities. Discharges typically result from the excretion of radioisotopes in urine and faeces from patients undergoing diagnosis or treatment. When receiving high activity doses, it is often necessary for patients to remain at the medical facility until the activity of the radioisotope within the body has decayed or reduced below a certain threshold. Discharges from patients receiving medical radioisotopes may also occur to local sewage systems when patients are allowed to return home following their procedure. The activity of medical radioisotopes in use at an authorised medical facility typically increases with increasing population size. However, the activity discharged from a medical facility can be reduced though the use of delay tanks that capture waste from patients undergoing radiotherapy. This allows for the further physical decay of radioisotopes before the contents of the delay tanks are emptied into the local sewage system. However, the use of delay tanks by medical facilities varies between and within different countries. Medical radioisotopes discharged to the sewage system typically must pass through wastewater treatment plants (WTP) before being discharged to rivers or directly to the marine environment. The type of WTP (primary, secondary, or tertiary) and the time taken for any radioisotopes to pass through the WTP can impact the activity of the radioisotope that is finally discharged into the receiving water. Residence times for medical radioisotopes in wastewater processed by secondary and tertiary WTPs would be expected to be longer than for primary WTPs.

Norway (including Svalbard) currently has a network of 9 high-volume air sampling stations for monitoring levels of radioactivity in the air, with equivalent air monitoring stations in all neighbouring countries, across Europe and the rest of the world. The detection of radionuclides in the air above normal levels at just one sampling station may signal a minor local source, whereas the detection of the same radionuclide(s) across a national network or across more than one country can signify a larger release further field. In such circumstances, the timing and magnitude of the various observations can allow for the possible identification of the source when used in conjunction with wind patterns for the same time interval. It is not uncommon to detect relatively low levels of man-made radionuclides in the air over Norway that can result from the resuspension of previously deposited Cesium-137 (Cs-137; half-life 30 years) after the Chornobyl Accident in 1986, or as a result of authorised releases in Norway and further afield relating to the production, use and discharge of radiochemicals and medical radioisotopes. Other sources of radionuclides to the air over Norway in the past include other types of nuclear activities and following the Fukushima Accident in 2011. In the case of I-131, this radionuclide has been detected in the air over Norway on 56 occasions in total across the entire air sampling network between 2014 and 2023.

2. Background to study

The Norwegian Radiation and Nuclear Safety Authority (DSA) set up a high-volume air sampler at the Tromsø Fire and Rescue station (Figures 1 & 2) in October 2023 in order to add to the established network of air monitoring stations in Norway and as a response to the increased number of port visits by nuclear powered submarines to the Grøtsund port facility at Tønsvika. In March and April 2024, low levels of I-131 were detected on the filters from the high-volume air sampling station in Tromsø, that coincided with weekends when patients were undergoing I-131 thyroid ablation therapy at the University Hospital of North Norway (UNN). At these times, no I-131 was detected at the high-volume air sampling station at Skibotn (~60 km from Tromsø) or at any other air sampling station in Norway or in neighbouring countries. A previous study by the DSA (Gwynn & Kiel Jensen, 2019) had shown that I-131 and other medical radioisotopes could be detected in inflowing wastewater as well as filtered solid material and treated wastewater at the Breivika WTP, which receives all sewage from UNN. This study also showed uptake of I-131 in intertidal seaweed species close to and at distance from the discharge point of treated wastewater in Tromsøysundet. In order to investigate the possible sources of I-131 to air over Tromsø, and to further constrain exposures to workers at the Breivika WTP from I-131, the DSA carried out indoor air monitoring at the Breivika WTP as well as at a nearby related pump station.

Figure 1. The high-volume air sampler at the Tromsø Fire and Rescue station (Photo DSA).

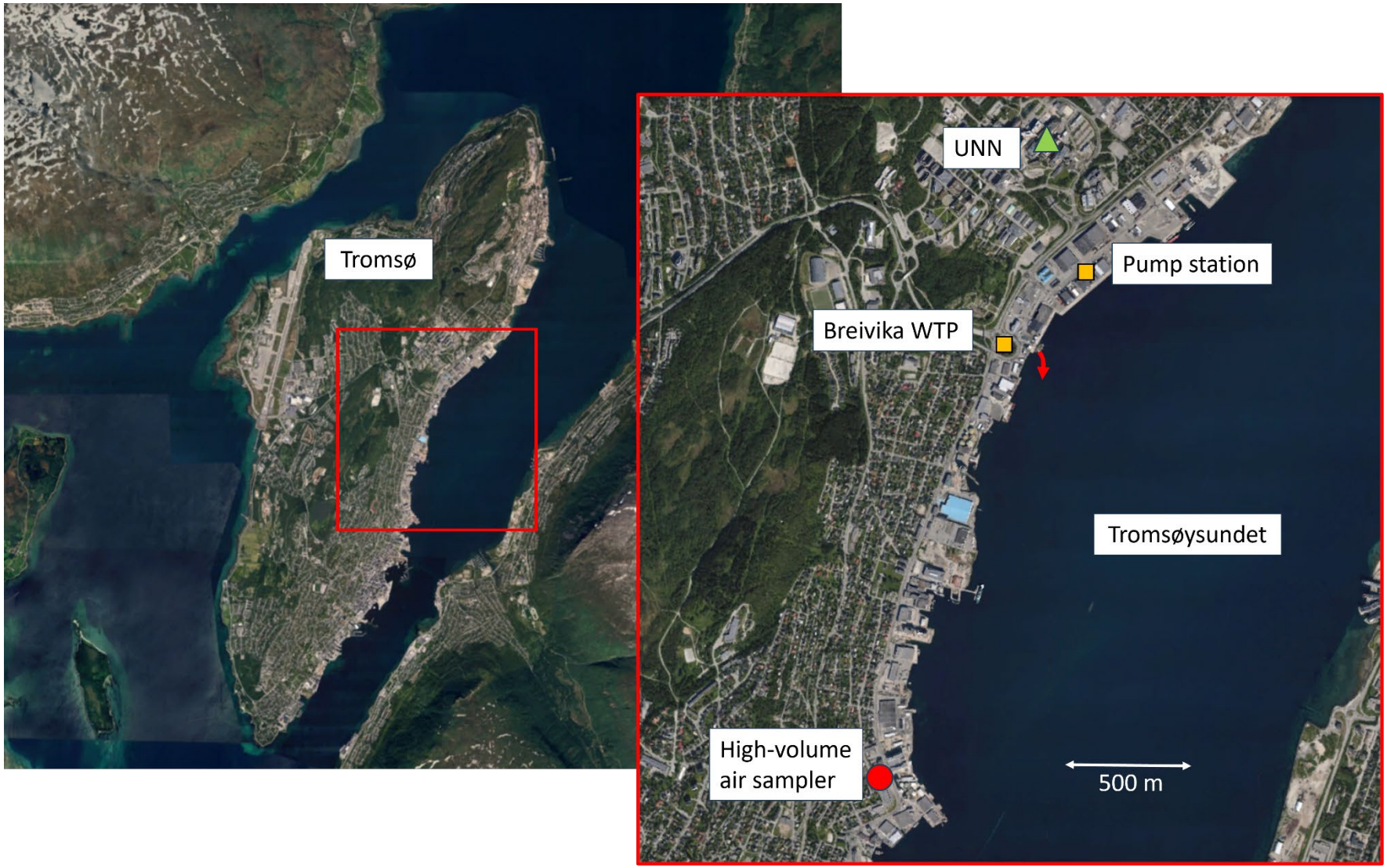


Figure 2. Location of high-volume air sampling station in Tromsø (red circle) in relation to the University Hospital of North Norway (UNN) (green triangle), the Breivika wastewater treatment plant (WTP), the pump station at Breivika (yellow squares) and the discharge point for treated effluent (indicated by red arrow). The Breivika WTP is ~1.8 km and at bearing of 194° SSW from the high-volume air sampling station in Tromsø.

2.1 Use and discharge of I-131 at the University Hospital of North Norway (UNN)

The University Hospital of North Norway (UNN) has permission from the Norwegian Radiation and Nuclear Safety Authority for the use and discharge of a range of different radioisotopes for the purposes of radiotherapy and diagnostic radiography. For regulatory purposes, the amount of each radioisotope discharged to the sewer for any given year through bodily wastes is calculated from the amount used in combination with recommended excretion factors for the chemical form of the radioisotope (IPEM, 2018). I-131 is given to patients as NaI in capsule form and patients undergoing thyroid ablation therapy are typically isolated for 3 days until their thyroid measurements give dose rates below 30 µSv/h. Urinary excretion is the predominant route for loss of iodine (35% to 75% in 24 hours), although there is some faecal excretion as well (Mettler and Guiberteau, 2012). From a regulatory perspective, it is assumed that 100% of the activity given to patients is excreted to the sewage system. However, according to the International Commission for Radiological Protection (ICRP) only 84% to 90% of I-131 activity given to patients for the treatment of thyroid carcinomas is discharged to sewage systems (ICRP, 2004). UNN does not currently have any decay tanks for initial handling of sewage from patients who are isolated when undergoing thyroid ablation therapy. From 2018 to 2024, between 13 and 30 patients have received GBq activities of I-131 for thyroid ablation therapy at UNN per year. The most common activity used for ablation therapy between 2018 and 2024 was around 3.7 GBq, but activities around 6 GBq or higher were also used during this period, with a total of 14 patients having received activities greater than 10 GBq (Figure 3). The maximum activity used between 2018 and 2024 was 13.2 GBq.

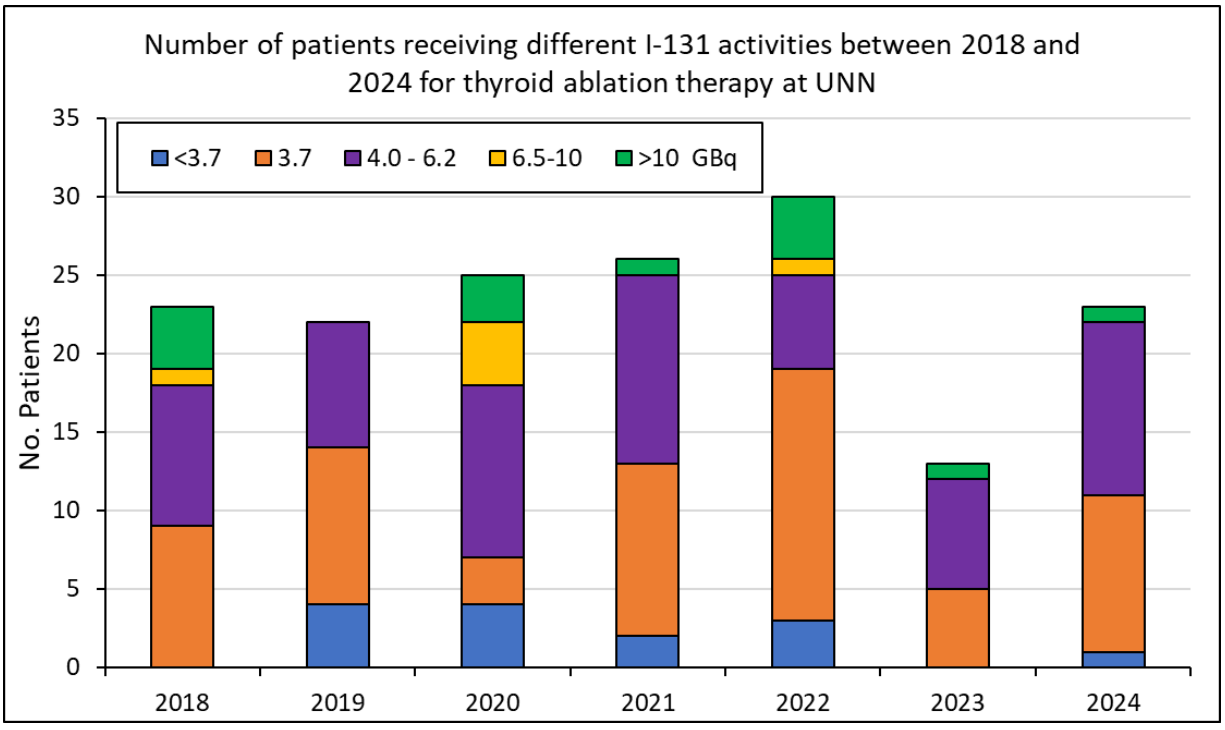


Figure 3. Number of patients receiving different activities of I-131 between 2018 and 2024 for thyroid ablation therapy at UNN. Data on use of I-131 provided by the Nuclear Medicine Section, University Hospital of North Norway.

Smaller activities of I-131 (typically 0.6 to 0.8 GBq) are also used at UNN for other treatments (e.g., hyperthyroidism), but in such cases the patient is not isolated at UNN and may, if not admitted for other

reasons, return home the same day. Patients receiving other radioisotopes for diagnostic radiography (e.g., Tc-99m) are also not required to be isolated at UNN.

2.2 The Breivika wastewater treatment plant (WTP) and pump station

The Breivika wastewater treatment plant (WTP) is a primary treatment facility (Figure 4) that filters solid material larger than 350 µm from incoming wastewater (mixture of sewage and surface run-off), before discharging treated wastewater directly to Tromsøysundet. The Breivika WTP is designed to handle waste from 18700 person equivalents at flow rates up to 230 l/s. In periods when flow rates exceed capacity or when the WTP is offline for routine cleaning or maintenance, unfiltered wastewater can be discharged. The Breivika WTP receives domestic sewage as well as sewage from the University of Tromsø (UiT) and UNN. Sewage from UNN flows first to a pump station at Breivika that is approximately 350 m from the WTP (Figure 2) and consists of a single room (circa 3 x 4 m) with an opening (14.5 cm in diameter) in the floor to a sump where wastewater collects. The wastewater is then pumped further to the Breivika WTP in a closed system of piping. The pipe from the pump station at Breivika merges with another wastewater pipe from the North of Tromsøya before arriving at the Breivika WTP where any sewage from UNN is further mixed with other wastewater before being filtered. Typically, the Breivika WTP processes around 3 million m^3 of wastewater per year and generates around 720 tonnes of solid waste per year. On a daily basis, the volume of wastewater passing through the Breivika WTP can vary (average around 8000 m^3), but typically only around 600 m^3 per day derives from the wastewater network that includes any sewage from UNN (Pers. Comm. Emil Brandstorp). Solid waste is collected in containers and then transported to a waste disposal site for open windrow composting at Skibotn, Storfjord.

Figure 4. The Breivika wastewater treatment plant (Photo DSA).

The Breivika WTP is fully automated, but workers are required to undertake routine cleaning and periodic maintenance, although normally not at weekends. Since October 2023, the WTP has only been offline for any unplanned reasons for 3 hours and this was not during a weekend (Pers. Comm. Emil Brandstorp). The room where filtration of wastewater occurs is installed with an air extraction system that vents air externally to the eastern side of the building. The extraction system is active continuously and there are no filters on any of the extraction vents. The pump station at Breivika typically requires less routine cleaning and maintenance than the WTP and there is no active ventilation system installed.

The discharge point for treated wastewater from the Breivika WTP is approximately 140 m from the shore at a depth of 17.4 m. Discharges of treated wastewater would be expected to be lower in salinity than the receiving sea water, so that any discharged I-131 or other radioisotopes are likely to be dispersed within surface layers of Tromsøysundet. The maximum tidal range in Tromsøysundet is around 3 m, with northward and southward water current flow rates in the area around the discharge point up to 0.5 m/s, although currents in other parts of Tromsøysundet can reach up to 1.5 m/s (Audunson & Næser, 1975; Statens Kartverk, 2008).

2.3 Previous exposure studies at the Breivika WTP

UNN has previous carried out assessments of doses to workers at the Breivika WTP and the ambient exposure at Breivika harbour. A worker at the Breivika WTP carried a dosimeter for 16 working days and recorded an average dose of 0.033 µSv/hr, equivalent to 67 µSv/a. The dosimeter placed in Breivika harbour for 44 days recorded an average dose of 0.085 µSv/hr, equivalent to 170 µSv/a.

The previous DSA investigation on I-131 (and other medical radioisotopes) in inflowing wastewater, filtered solid material and treated wastewater at the Breivika WTP calculated external effective doses based on proximity to filtered solid waste and detected activity concentrations of I-131, Tc-99m, I-123 and F-18 (Gwynn & Kiel Jensen, 2019). This study reported that annual occupational doses (where a working year is equivalent to 2000 hours) based on the summed dose rates from these four medical radioisotopes would be at least 2 orders of magnitude lower than the annual individual dose limit for public exposure of 1 mSv.

2.4 Sampling and analysis

Indoor air measurements were carried out at the Breivika WTP over 6 weekends when patients were admitted to UNN for I-131 thyroid ablation therapy. At the Breivika WTP, the air sampler was set up in the same room where incoming influent flows through four filtration units (Figures 5 & 6). On the fourth sampling weekend, indoor air measurements were also carried out inside the pump station at Breivika (Figure 7). All air sampling was carried out using Dwarf 100x9 portable air samplers (Senja Ltd) and Camfil A500GH filters, at flow rates around 135 m^3/h. These filters will capture aerosols and particulate forms of I-131, but not molecular I-131.

At the Breivika WTP, air sampling was carried out from Friday to Monday with filters changed on Saturdays and Sundays at approximately 24-hour intervals. For the first sampling weekend, air sampling began 1 hour and 46 minutes after the patient received their I-131 oral capsule. For the remaining five sampling weekends, air sampling was started before the patients were given I-131. When air sampling was carried out at the pump station at Breivika, the filter was not changed during the sampling period of Friday to Monday. See Table 1 for details of air monitoring and I-131 treatments.

In the laboratory, filters were compacted into defined geometry configurations using a hydraulic press, packed into plastic counting geometries and analysed for at least 24 hours on HPGe detectors. All results were decay corrected to the midpoint of the sampling interval and are stated with associated uncertainties to 1 sigma.

Figure 5. Upper photo shows the four filtration units in the filtration room at the Breivika WTP. The red arrow in the lower photo indicates the position of the Dwarf 100x9 portable air sampler for each of the five sampling weekends (Photo DSA).

Figure 6. Close up of the Dwarf 100x9 portable air sampler at the end of a sampling period in the filtration room at the Breivika WTP showing particulate material trapped on the filter (Photo DSA).

Figure 7. Dwarf 100x9 portable air sampler in the pump station at Breivika. The red arrow indicates the opening in the floor (14.5 cm in diameter) to the sump where wastewater collects before it is pumped further to the Breivika WTP through the pipework visible on the right-hand side (Photo DSA).

Table 1. Activities of I-131 given to patients for thyroid ablation therapy at UNN and air sampling information for the corresponding six sampling weekends at the Breivika WTP and pump station.

Sampling weekend	Date/time patient received I-131	Activity used (GBq)	Start day	Sampling start time	Sampling stop time	Hours sampled (hr)	Volume of air sampled (m^3)
1	12/04/2024 12:02	3.7	Friday	12/04/2024 13:48	13/04/2024 09:44	19.9	2628.4
			Saturday	13/04/2024 09:51	14/04/2024 10:02	24.2	3180.5
			Sunday	14/04/2024 10:07	15/04/2024 08:09	22.0	2930.3
2	19/04/2024 13:02	6.0	Friday	19/04/2024 11:13	20/04/2024 10:09	22.9	3032.1
			Saturday	20/04/2024 10:13	21/04/2024 09:58	23.8	3165.5
			Sunday	21/04/2024 10:04	22/04/2024 07:48	21.7	2908.6
3	26/04/2024 11:50	3.7	Friday	26/04/2024 11:04	27/04/2024 11:56	24.9	3304.7
			Saturday	27/04/2024 12:00	28/04/2024 11:02	23.0	3070.7
			Sunday	28/04/2024 11:07	29/04/2024 08:22	21.3	2831.1
4[1]	24/05/2024 11:51	11.2	Friday	24/05/2024 10:51	25/05/2024 08:21	21.5	2892.9
			Saturday	25/05/2024 08:26	26/05/2024 09:11	24.8	3300.2
			Sunday	26/05/2024 09:16	27/05/2024 08:09	22.9	3026.3
			Friday[2]	24/05/2024 11:04	27/05/2024 10:53	71.8	9592.5
5	28/06/2024 11:30	3.7	Friday	28/06/2024 10:51	29/06/2024 10:18	23.5	3010.4
			Saturday	29/06/2024 10:23	30/06/2024 10:06	23.7	2893.2
			Sunday	30/06/2024 10:09	01/07/2024 08:15	22.1	3068.6
6	08/11/2024 11:45	4.6	Friday	08/11/2024 09:45	09/11/2024 10:15	24.5	3264.4
			Saturday	09/11/2024 10:19	10/11/2024 08:54	22.6	3039.0
			Sunday	10/11/2024 08:56	11/11/2024 07:50	22.9	3068.6

1 - Air sampling at Breivika WTP and pump station on the 4th sampling weekend.
2 - Air sampling at the pump station where the filter was not changed during the sampling period of Friday to Monday.

Note, no patients received I-131 for any other radiotherapy purposes during the weeks before these sampling periods, with the exception of the 4th sampling weekend when two patients received 0.6 and 0.8 GBq on the 23rd of May.

3. Results of air monitoring at the Breivika WTP and pump station

Activity concentrations of I-131 in indoor air in the filtration room at the Breivika WTP were detected for all sampling intervals over the six sampling weekends when patients were in isolation at UNN for thyroid ablation therapy (Table 2 and Figure 8). For each sampling weekend, activity concentrations of I-131 in indoor air showed highest values for the sampling interval 'Friday to Saturday' with a decreasing trend for the sampling intervals 'Saturday to Sunday' and 'Sunday to Monday'. These trends likely reflect the biokinetics of I-131 excretion from the human body. According to Mettler and Guiberteau (2012), 35% to 75% of iodine is excreted from the body in the first 24 hours, predominately in urine. In addition, Demir et al. (2013) reported that on average 66% of I-131 given to patients is excreted in urine after 24 hours, with 87% excreted after 48 hours. However, it can be expected that amount of I-131 excreted within 24 or 48 hours will vary between patients. Indeed, it has been previously reported that the excretion of I-131 after 48 hours for 8 patients at UNN varied between 62% and 92% (Gwynn & Kiel Jensen, 2019).

Although activity concentrations of I-131 in indoor air in the filtration room at Breivika WTP over the first four sampling weekends showed a clear link to the activities received by patients, this was not the case for the fifth sampling weekend. The indoor air values of I-131 that were detected for the fifth sampling weekend, when the activity of I-131 that was given to the patient was only 3.7 GBq, were higher than for sampling weekends when patients received 6 and 11.2 GBq and an order of magnitude higher than the other two sampling weekends when patients also received 3.7 GBq. This is likely due to the degree of dilution that the sewage from UNN undergoes before filtration. The flow rate of wastewater through the Breivika WTP can vary throughout a 24-hour period and from day to day. Daily trends result from changes in the production of domestic sewage (greater during the day than at night), which can then be overprinted by increased contributions from surface run-off as a result of rainfall and from seasonal snow melting. Looking at the comparison for average flow rates of wastewater (m^3/hr) for the different sampling intervals for each of the six weekends when indoor air monitoring was carried out at the Breivika WTP (Figure 9), it is clear that the flow rates of wastewater on the fifth sampling weekend were far lower than for any other weekend. The lowest activity concentrations of I-131 in indoor air at the Breivika WTP were detected on the sixth sampling weekend when a patient received 4.6 GBq. The average flow rates of wastewater (m^3/hr) for the different sampling intervals over the sixth sampling weekend were elevated and only somewhat lower than the average flow rates for the first sampling weekend (Figure 9) when a patient received 3.7 GBq. Taking the analytical uncertainties into consideration, the indoor air values for I-131 for the first and sixth sampling weekend are directly comparable (Table 2). In this case, variations in the biokinetics of excretion of I-131 between the patients that received 3.7 GBq and 4.6 GBq on the first and sixth sampling weekend probably account for the similarities in detected activity concentrations of I-131 in indoor air at the Breivika WTP.

At the pump station at Breivika, the indoor air I-131 activity concentration when a patient received 11.2 GBq on the fourth sampling weekend was 5.9 ±0.8 μBq/m^3. Although this value represents the average activity concentration from Friday to Monday, it is still two orders of magnitude lower than the values detected for each of the three sampling intervals over the same weekend at the Breivika WTP (Table 2). As any I-131 that passes through the pump station will be more concentrated than compared with I-131 in any wastewater that is then filtered at the Breivika WTP (due to the subsequent dilution of sewage from UNN with other wastewater), this would suggest that the degree of transfer of I-131 to indoor air at the pump station is low. However, when interpreting the detected levels at the Breivika WTP and pump station it should be remembered that the filters used in this study only capture aerosols and particulate forms of I-131, and so further work should be carried out to determine the presence and relative contributions of the different chemical forms of I-131 that are produced at both locations.

In the filtration room at the Breivika WTP, I-131 is likely to be transferred to the air through the formation of aerosols as the wastewater flows through the filter screens of the four filtration units, in addition to evaporation and volatilization processes particularly when excess water is removed from filtered solid material. Any I-131 present in indoor air in the filtration room at the Breivika WTP would be expected to be removed over time by the air extraction system. At the pump station in Breivika, the transfer of I-131 to indoor air likely occurs via evaporation and volatilization processes from wastewater when present in the sump, with subsequent airborne exchange through the opening to the sump that is set in the floor of the pump station.

With one exception, no other medical radioisotopes in use at UNN were detected above the detection limit for any sampling interval at either the Breivika WTP or pump station. For the sampling period 'Friday to Saturday' of the fifth sampling weekend, an indoor air activity concentration of 23 ±3 μBq/m^3 for Tc-99m (half-life 6 hours) was detected. This was the same sampling interval and sampling weekend where the highest value of I-131 in indoor air was detected at Breivika WTP. Tc-99m is used at UNN for diagnostic radiography on a daily basis from Monday to Fridays but only between 07:30 am and 15:00 pm, with the total amount used on any day dependent on the number of patients and the activities of Tc-99m given to each patient. Gwynn & Kiel Jensen (2019) reported activity concentrations of Tc-99m in inflowing wastewater, filtered solid material and treated wastewater that reflected the daily use of Tc-99m at UNN. The total activity of Tc-99m used on the Friday of the fifth sampling weekend was higher than four sampling weekend Fridays, but lower than that used on the Friday of the second sampling weekend (Figure 10), although it is not possible to control for where any patients urinate after receiving Tc-99m (e.g. at UNN or at home). However, we might speculate that the detection of Tc-99m in indoor air for the sampling interval 'Friday to Saturday' of the fifth sampling weekend was also due to the lower degree of dilution of sewage from UNN by additional wastewater.

Table 2. Activity concentrations of I-131 (μBq/m3) in indoor air in the filtration room at the Breivika WTP over each of the six sampling weekends.

Sampling	Fri-Sat		Sat-Sun		Sun-Mon	
weekend	μBq/m^3	±	μBq/m^3	±	μBq/m^3	±
1	25	5	17	3	11	3
2	199	16	109	9	71	6
3	44	4	17	3	9	2
4	657	39	368	6	148	7
5	911	46	379	23	109	9
6	21	3	12	2	10	2

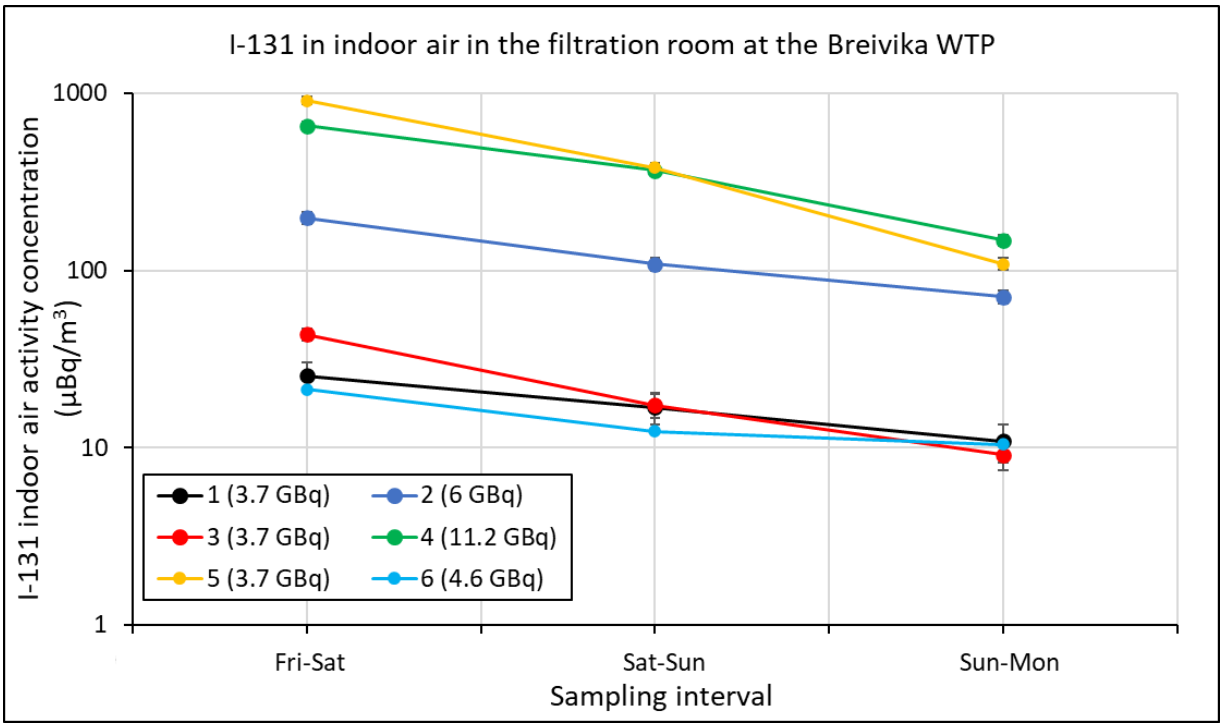


Figure 8. Activity concentrations of I-131 (µBq/m³) in indoor air in the filtration room at Breivika WTP over each of the six sampling weekends when patients received different activities of I-131 for thyroid ablation therapy. Note, vertical axis shows a logarithmic scale.

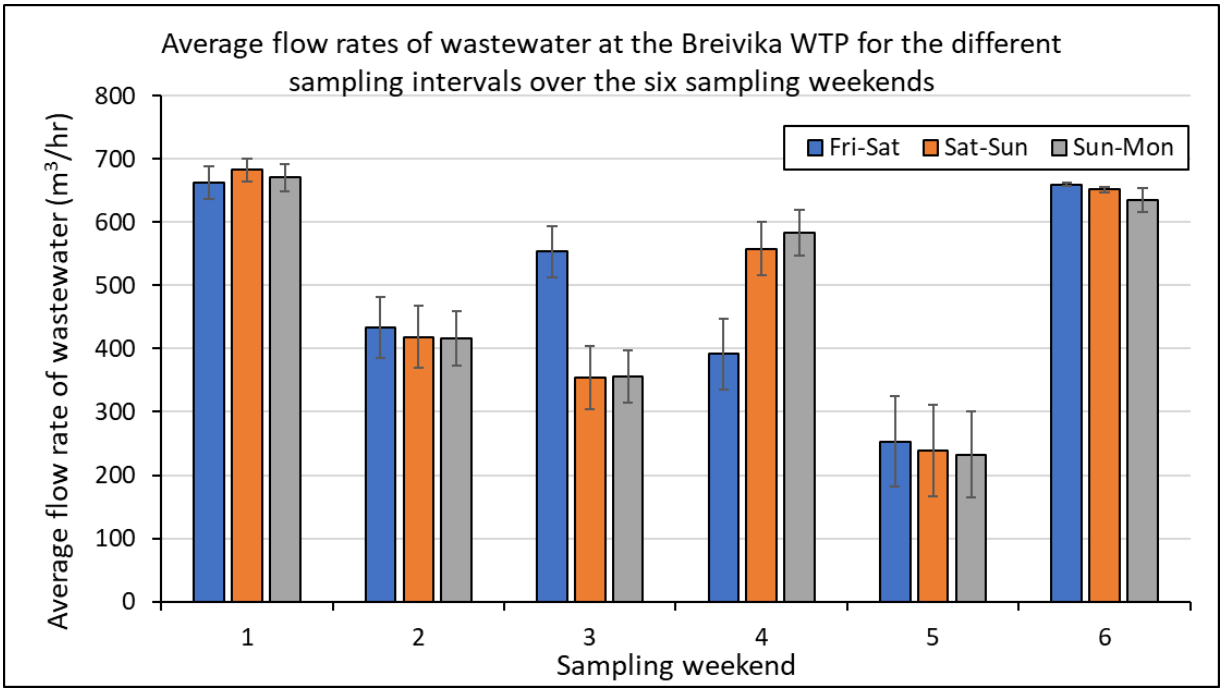


Figure 9. Average flow rates (± SD) of wastewater (m³/hr) at the Breivika WTP for the sampling intervals over the six sampling weekends when indoor air monitoring was carried out in the filtration room at Breivika WTP. Average values are based on reported hourly volumes for the actual time period of each individual sampling interval. Wastewater volume data provided by the Tromsø Municipal Water & Sewage Department.

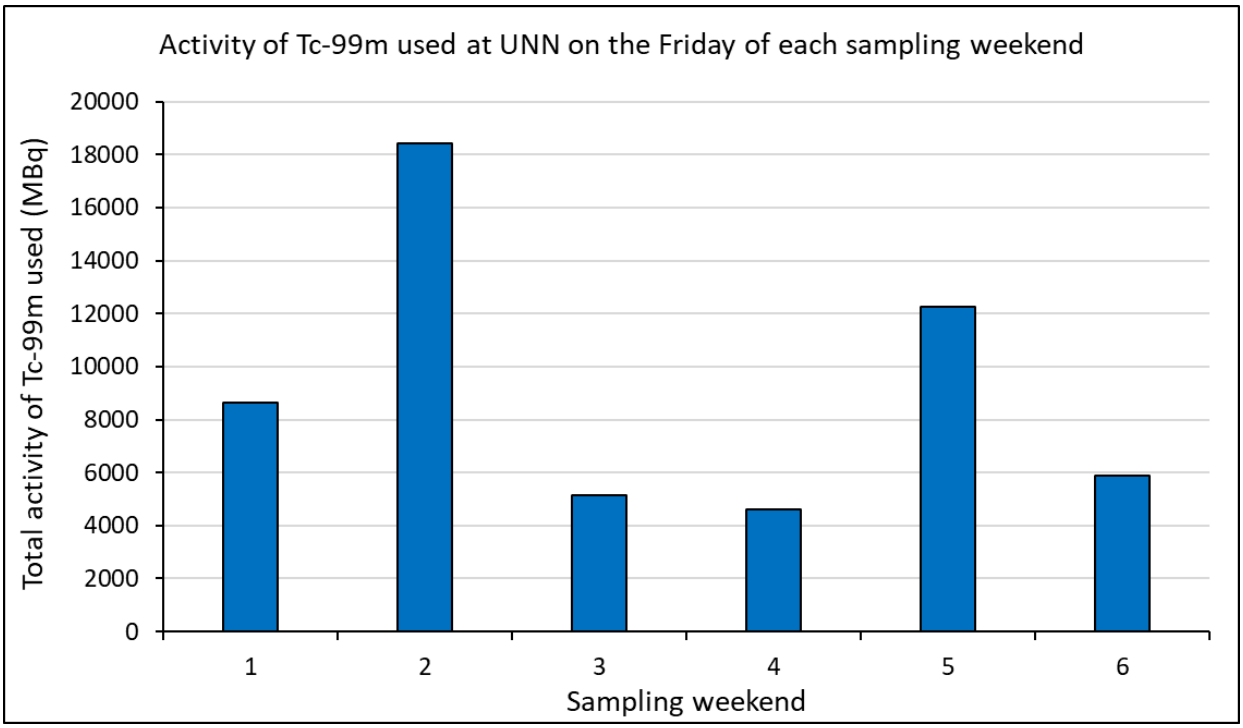


Figure 10. Activity of Tc-99m (MBq) used at UNN on the Friday of each sampling weekend. Activities stated for each Friday are the sum of all activities of Tc-99m from the range of medical applications used on these days. Data on use of Tc-99m provided by the Nuclear Medicine Section, University Hospital of North Norway.

From the results of the six sampling weekends, it is clear that the level of I-131 generated in indoor air at the Breivika WTP is determined partly by the activity of I-131 given to a patient but with the controlling factor of the degree of dilution that any I-131 in sewage from UNN undergoes when mixing with other wastewater streams prior to filtration. The impact of dilution can be investigated by normalising the data for indoor air activity concentrations with the corresponding activities given to patients on respective sampling weekends and comparing these with average flow rates (m^3/hr) for each respective sampling interval (Figure 11). In this approach, all indoor air activity concentrations were first normalised to a standard 24-hour sampling interval to reduce the impact of any variations in the duration of the actual sampling intervals (see Table 1). When fitted with a power trend line, the sampling interval 'Friday to Saturday' showed an R^2 value of 0.99, with progressively lower R^2 values for power trend lines for the sampling intervals 'Saturday to Sunday' (R^2 = 0.80) and 'Sunday to Monday' (R^2 = 0.68). In the period when patients have received thyroid ablation therapy since the establishment of the high-volume air sampler in Tromsø and up to the last sampling weekend (i.e. 27th of October 2023 to the 11th of November 2024), the daily volume of wastewater treated at the Breivika WTP varied from 4100 to 17000 m^3 (Figure 12) with an average of 8600 m^3. Using the model for the sampling interval 'Friday to Saturday', we might predict that if the hourly flow rate was 172 m^3/hr (the mean hourly flow rate based on lowest daily volume of 4100 m^3) when a patient underwent thyroid ablation therapy, then the indoor air activity concentration of I-131 in the filtration room at the Breivika WTP would be 1300 µBq/m^3 per GBq of I-131 received by a patient. Caution should be used at present when interpreting such an estimate as the model is only based on six sampling weekends. Further indoor air monitoring at the Breivika WTP at different times of year may help further understand the impacts of different flow rates of wastewater on the dilution of I-131 and any other medical radioisotopes in sewage from UNN.

To put the detected and modelled values of indoor air I-131 activity concentrations at Breivika WTP into context, the levels of I-131 detected in air over Norway after the Fukushima Accident in 2011 and the Chornobyl Accident in 1983 were ~1000 µBq/m^3 and ~1000000 µBq/m^3, respectively. For further context,

the Norwegian action level for I-131 in air (measured for 2 consecutive days) when it would be recommended to take oral iodine prophylaxis tablets (e.g. following a nuclear accident) is 1000000000 µBq/m^3 (https://dsa.no/atomberedskap/overvaking-av-radioaktivitet-i-luft).

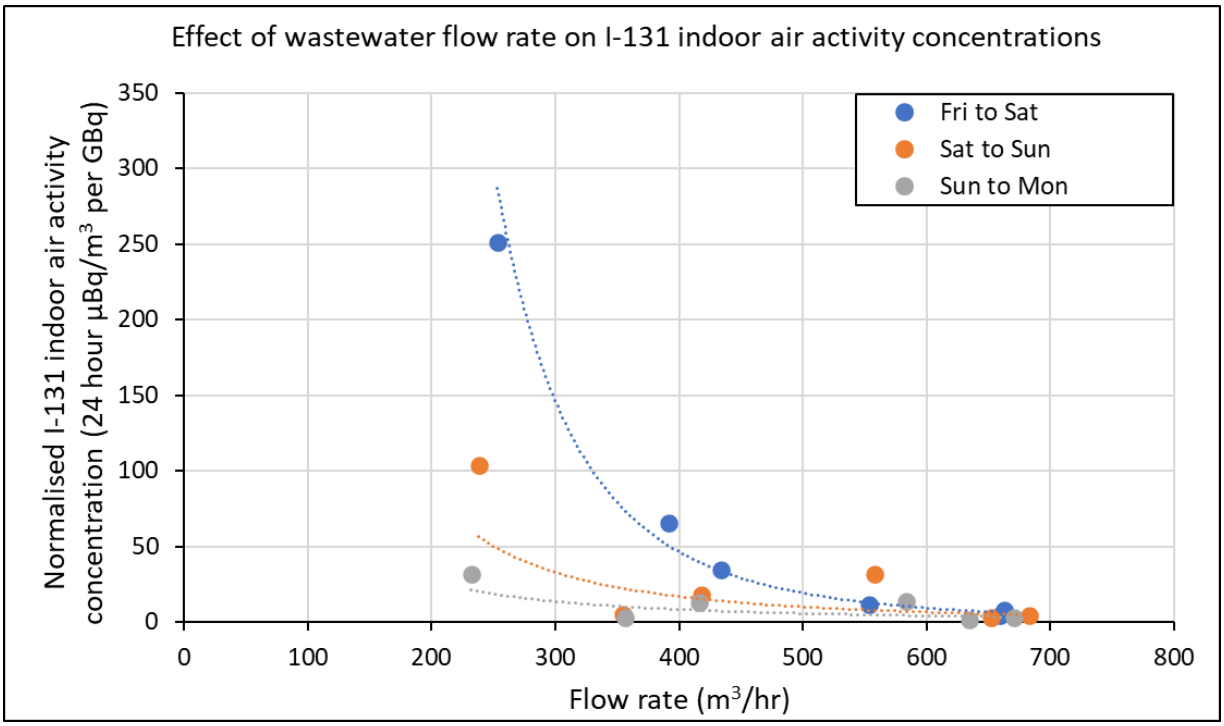


Figure 11. Effect of wastewater flow rates on normalised I-131 indoor air activity concentrations (µBq/m^3 per GBq) in the filtration room at the Breivika WTP for sampling intervals 'Friday to Saturday', 'Saturday to Sunday' and 'Sunday to Monday'. In this approach, the indoor air activity concentrations from the different sampling intervals over all six sampling weekends were first inormalised to a standard 24-hour sampling interval and then normalised against the respective activity that was given to each patient. R^2 values for power trend lines are 0.99 for 'Friday to Saturday', 0.80 for 'Saturday to Sunday' and 0.68 for 'Sunday to Monday'. Wastewater volume data provided by the Tromsø Municipal Water & Sewage Department.

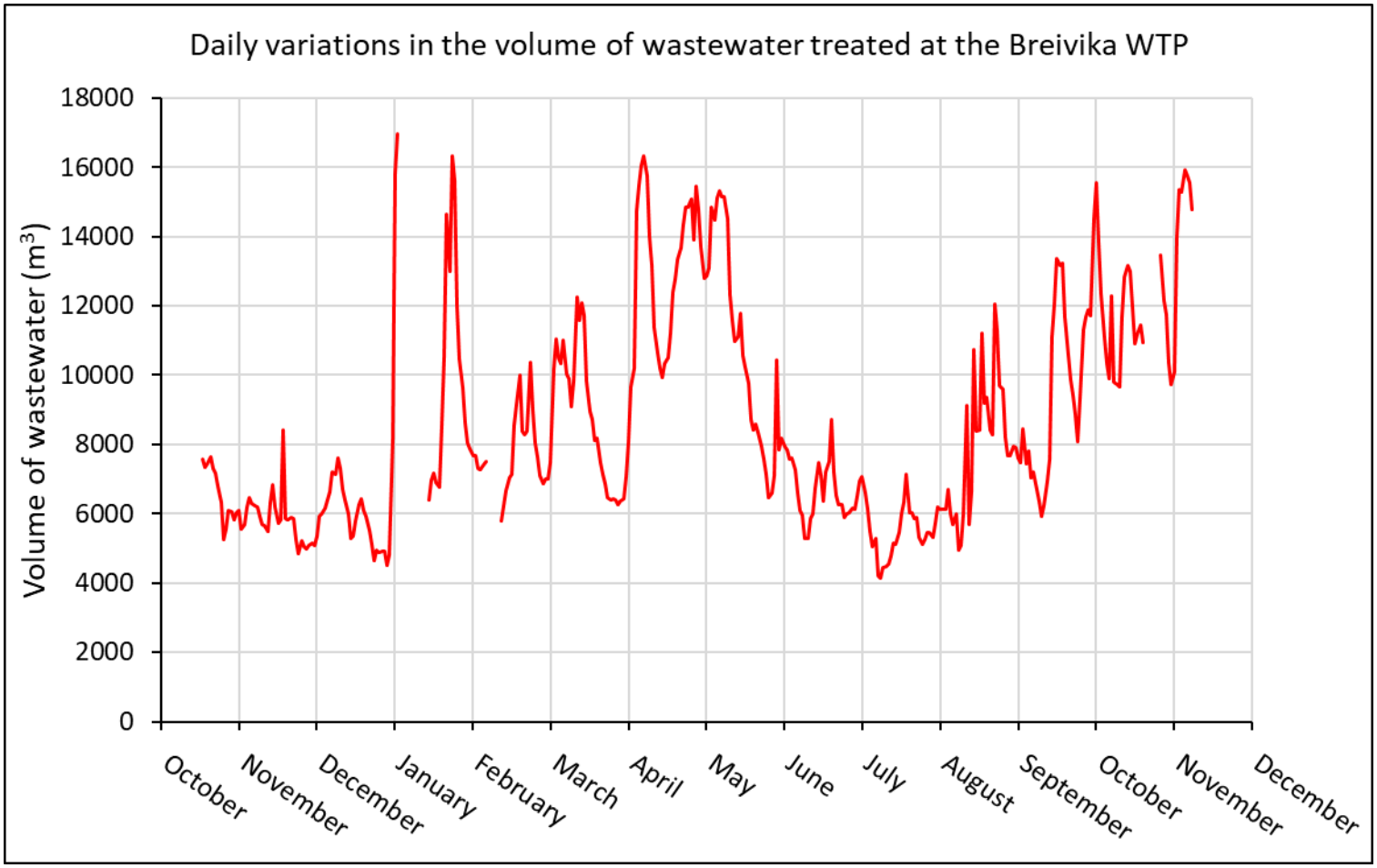


Figure 12. Daily variations in the volume (m^3) of wastewater treated at the Breivika WTP over the period from the 27th of October 2023 to the 11th of November 2024. Data gaps daily wastewater volumes represent days when no volume data was recorded. Wastewater volume data provided by the Tromsø Municipal Water & Sewage Department.

4. Consideration of possible exposures and doses to workers at the Breivika WTP and pump station

The ICRP (ICRP, 2012) recommends different inhalation dose coefficients depending on the chemical form of iodine that is present (gaseous, organic or particulate). As it is not possible to be certain which form of I-131 is present in indoor air in the filtration room at the Breivika WTP, we calculate hourly inhalation doses for all possible forms of I-131 for workers/adults, using an inhalation rate (1.2 m^3/h) recommended by the ICRP for workers (ICRP, 2015). This includes a consideration that the levels of I-131 detected were present as molecular I-131 as the inhalation dose coefficient for molecular iodine is higher than for all other forms. Inhalation doses are calculated based on the maximum detected activity concentration as well as the theoretical total air activity concentration which represents the actual total activity detected on the filter in 1 m^3. The analytical result for each filter is the average I-131 activity concentration for each respective sampling interval and as it is likely that the transfer of I-131 to the air in the filtration room occurs in pulses (when patients urinate), deriving an inhalation dose for the total activity detected on a filter allows for a more conservative approach.

In the filtration room at the Breivika WTP, hourly worker inhalation doses based on the maximum detected activity concentration and the corresponding theoretical total air activity concentration were of the order of 1 x 10^{-7} to 1 x 10^{-5} µSv and 1 x 10^{-4} to 1 x 10^{-2} µSv, respectively, for the different possible forms of iodine (Table 4). For the modelled estimates of indoor air activity concentrations in the filtration room at the Breivika WTP when flow rates of wastewater were lowest over the period from the 27th of October 2023 to the 11th of November 2024, hourly worker inhalation doses and corresponding estimated theoretical total air activity concentrations doses (derived from a hypothetical air sampling volume of 3000 m^3) per GBq of I-131 received by a patient were of the order of 1 x 10^{-5} µSv and 1 x 10^{-2} µSv to 10^{-1} µSv, respectively, for the different possible forms of iodine. Again, care should be used when interpreting any inhalation doses based on modelled estimates of I-131 in indoor air at Breivika WTP at present.

Considering that patients undergoing thyroid ablation therapy are isolated at UNN over the weekend, and that such therapy does not occur every weekend, and that under normal operating conditions there are no workers present at the Breivika WTP at weekends, it would be highly unlikely for any worker to be exposed to the hourly inhalation doses in Table 4 on an annual basis (i.e. for 2000 hours per year). However, even if this was possible, these hourly dose rates translate to annual worker inhalation doses that are at least five orders of magnitude lower for the maximum detected indoor air activity concentrations and one order of magnitude lower for the corresponding theoretical total indoor air activity concentrations when comparing against the annual individual dose limit for public exposure of 1 mSv.

For the one sampling interval when Tc-99m was detected in indoor air in the filtration room at the Breivika WTP, hourly worker inhalation and corresponding theoretical total air activity concentration doses were of the order of 1 x 10^{-10} µSv and 1 x 10^{-7} to 1 x 10^{-6} µSv, respectively (Table 5).

In the pump station, hourly worker inhalation doses based on the detected activity concentration and the corresponding theoretical total air activity concentration were of the order of 1 x 10^{-8} to 1 x 10^{-7} µSv and 1 x 10^{-4} to 1 x 10^{-3} µSv, respectively, for the different possible forms of iodine (Table 6). Again, although highly unlikely to occur for the same reasons as discussed above, these hourly dose rates translate to annual worker inhalation doses that are at least 7 orders of magnitude lower for the detected indoor air activity concentration and 3 orders of magnitude lower for the corresponding theoretical total indoor air activity concentration when comparing against the annual individual dose limit for public exposure of 1 mSv.

In summary, based on the inhalation doses derived in this study as well as the external exposure doses derived in previous studies, it can be concluded that use of GBq activities of I-131 at UNN for thyroid ablation therapy does not lead to any human health risk to workers at the Breivika WTP and pump station.

Table 4. Hourly I-131 inhalation doses (µSv) to workers based on the maximum detected indoor air activity concentration and the corresponding theoretical total indoor air activity concentration for each of the six sampling weekends in the filtration room at the Breivika WTP.

	Sampling weekend	Form of I-131			
		I_2	CH_3I	Particulate 1 µm	Particulate 5 µm
Hourly inhalation dose (µSv)	1				
	For maximum detected indoor air activity concentration of 25 µBq/m³				
		6.10E-07	4.57E-07	2.32E-07	3.35E-07
	For corresponding theoretical total indoor air activity concentration of 0.067 Bq/m³				
		1.60E-03	1.20E-03	6.09E-04	8.81E-04
	2				
	For maximum detected indoor air activity concentration of 199 µBq/m³				
		4.77E-06	3.58E-06	1.81E-06	2.62E-06
	For corresponding theoretical total indoor air activity concentration of 0.60 Bq/m³				
		1.45E-02	1.08E-02	5.49E-03	7.95E-03
	3				
	For maximum detected indoor air activity concentration of 44 µBq/m³				
		1.05E-06	7.87E-07	3.99E-07	5.77E-07
	For corresponding theoretical total indoor air activity concentration of 0.14 Bq/m³				
		3.47E-03	2.60E-03	1.32E-03	1.91E-03
	4				
	For maximum detected indoor air activity concentration of 657 µBq/m³				
		1.58E-05	1.18E-05	5.99E-06	8.67E-06
	For corresponding theoretical total indoor air activity concentration of 1.90 Bq/m³				
		4.56E-02	3.42E-02	1.73E-02	2.51E-02
	5				
	For maximum detected indoor air activity concentration of 911 µBq/m³				
		2.19E-05	1.64E-05	8.31E-06	1.20E-05
	For corresponding theoretical total indoor air activity concentration of 2.74 Bq/m3				
		6.58E-02	4.94E-02	2.50E-02	3.62E-02
	6				
	For maximum detected indoor air activity concentration of 21 µBq/m³				
		5.11E-07	3.83E-07	1.94E-07	2.81E-07
	For corresponding theoretical total indoor air activity concentration of 0.070 Bq/m³				
		1.67E-03	1.25E-03	6.34E-04	9.18E-04

I-131 inhalation dose coefficient used for workers (µSv/Bq) were 2.0E-02 for I_2, 1.5E-02 for CH_3I, 7.6E-03 for 1 µm particulates and 1.1E-02 for 5 µm particulates (ICRP, 2012). Theoretical total air activity concentrations represent the actual total activity detected on each filter in 1 m³.

Table 5. Hourly Tc-99m inhalation doses (µSv) to workers based on the detected indoor air activity concentration for the 'Friday to Saturday' sampling interval of the fifth sampling weekend and the corresponding theoretical total indoor air activity concentration in the filtration room at the Breivika WTP.

	Form of Tc-99m			
	Particulate 1 µm		Particulate 5 µm	
	Type F	Type M	Type F	Type M
Hourly inhalation dose (µSv)				
For detected indoor air activity concentration of 23 µBq/m^3				
	3.3E-10	5.22E-10	5.5E-10	7.97E-10
For corresponding theoretical total indoor air activity concentration of 0.07 Bq/m^3				
	9.93E-07	1.57E-06	1.65E-06	2.4E-06

Tc-99m inhalation dose coefficient used for workers (µSv/Bq) were 1.2E-05 for Type F and 1.9E-05 for Type M 1 µm particulates and 2.0E-05 for Type F and 2.9E-05 for Type M 5 µm particulates (ICRP, 2012). ICRP (2012) defines Type F materials as those that have a fast rate of absorption into the blood from the respiratory tract, and Type M materials as those that have a moderate rate of absorption into blood from the respiratory tract. Theoretical total air activity concentrations represent the actual total activity detected on each filter in 1 m^3.

Table 6. Hourly I-131 inhalation doses (µSv) to workers based on the detected indoor air activity concentration and the corresponding theoretical total indoor air activity concentration in the pump station at Breivika.

	Form of I-131			
	I_2	CH_3I	Particulate 1 µm	Particulate 5 µm
Hourly inhalation dose (µSv)				
For detected indoor air activity concentration of 5.9 µBq/m^3				
	1.42E-07	1.07E-07	5.4E-08	7.81E-08
For corresponding theoretical total indoor air activity concentration of 0.06 Bq/m^3				
	1.36E-03	1.02E-03	5.18E-04	7.50E-04

I-131 inhalation dose coefficient used for workers (µSv/Bq) were 2.0E-02 for I_2, 1.5E-02 for CH_3I, 7.6E-03 for 1 µm particulates and 1.1E-02 for 5 µm particulates (ICRP, 2012). Theoretical total air activity concentrations represent the actual total activity detected on each filter in 1 m^3.

5. Consideration of subsequent possible sources of I-131 to the air over Tromsø

A high-volume air sampling station was established at the Tromsø Fire and Rescue station in October 2023 and since then and up to week 45 of 2024, there have been 26 occasions when patients have received I-131 for thyroid ablation therapy at UNN. However, I-131 has only been detected (above the detection limit) at this air sampling station on nine of these occasions (Table 7) and on five of the six sampling weekends (Figure 13). No I-131 was detected at the high-volume air sampler in Tromsø for any other week during the study period (i.e. for weeks where no patient underwent thyroid ablation therapy at the weekend). The I-131 activity concentrations detected at the high-volume air sampling station were lower than the levels detected in indoor air in the filtration room at the Breivika WTP and do not pose any risk to human health.

Table 7. Weekly measurements of I-131 (μBq/m^3) at the high-volume air sampling station in Tromsø for the corresponding weekends when patients underwent thyroid ablation therapy at UNN since the high-volume air sampling station was established in October 2023 and up to week 45 of 2004.

Date	Patient I-131 activity (GBq)	Week	Activity concentration of I-131 at Tromsø air sampling station (μBq/m^3)
27.10.2023	3.7	43	<0.38
03.11.2023	6.0	44	<0.33
10.11.2023	4.6	45	<0.32
08.12.2023	3.7	49	<0.40
19.01.2024	3.7	3	<0.28
26.01.2024	6.1	4	<0.25
02.02.2024	6.1	5	<0.31
16.02.2024	4.6	7	<0.28
23.02.2024	6.1	8	<0.51
08.03.2024	3.7	10	<0.31
15.03.2024	6.1	11	<0.35
22.03.2024	1.1	12	0.30 ±0.07
05.04.2024	3.7	14	0.36 ±0.08
12.04.2024	3.7	15	0.60 ±0.11
19.04.2024	6.0	16	1.48 ±0.22
26.04.2024	3.7	17	1.66 ±0.15
10.05.2024	3.7	19	<0.33
24.05.2024	11.2	21	1.91 ±0.17
07.06.2024	3.7	23	1.35 ±0.15
14.06.2024	3.7	24	1.18 ±0.26
28.06.2024	3.7	26	0.38 ±0.08
16.08.2024	6.1	33	<0.41
27.09.2024	4.5	39	<0.30
25.10.2024	6.1	43	<0.31
01.11.2024	6.1	44	<0.32
08.11.2024	4.6	45	<0.32

Analytical uncertainties are given to 1 sigma.

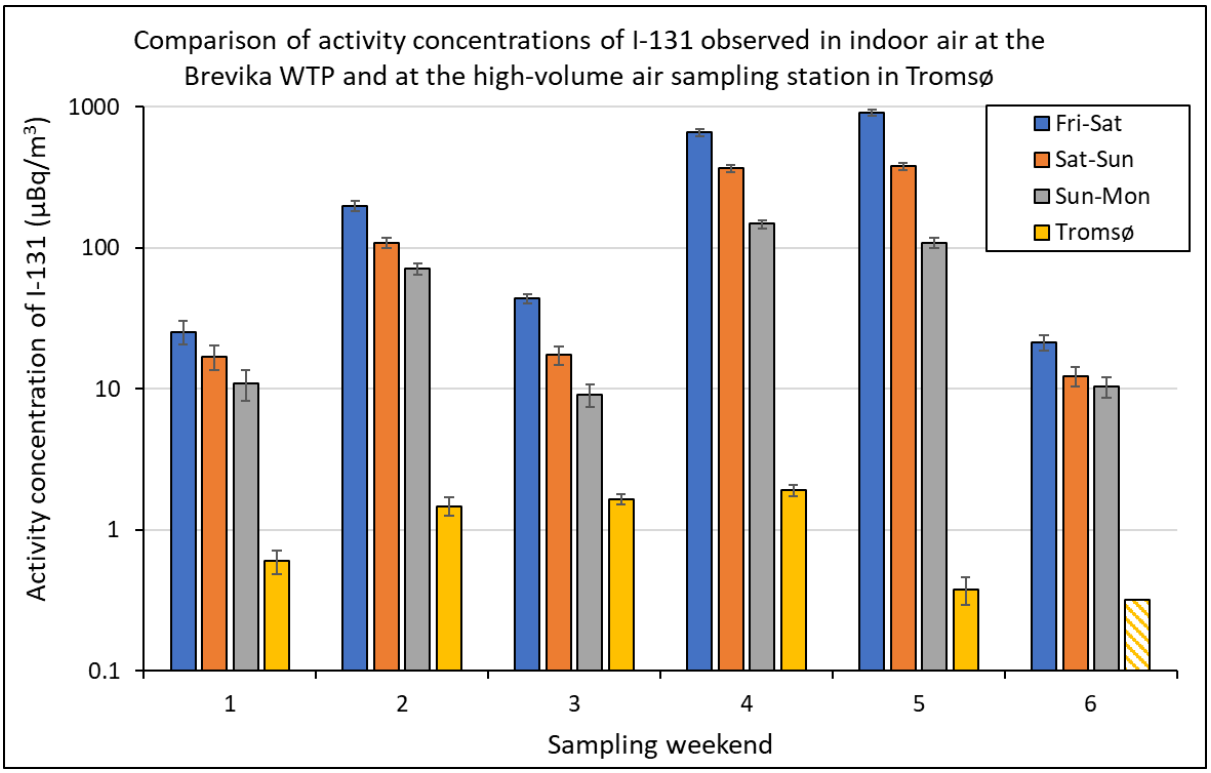


Figure 13. Comparison of I-131 activity concentrations (µBq/m³) in indoor air in the filtration room at Breivika WTP over each of the six sampling weekends and the corresponding I-131 activity concentrations at the high-volume air sampling station in Tromsø. Solid bars represent values for I-131 above detection limits, where error bars show analytical uncertainties (1 sigma). Striped bars represent values for I-131 below detection limits. Note, vertical axis shows a logarithmic scale.

The primary filters at the high-volume air sampling station in Tromsø are changed each week (typically on a Thursday) so that any detected activity concentrations represent an average for the volume (~100000 m³) of air sampled for any given week. The type of primary filter used is similar to those used in this study for indoor air sampling at the Breivika WTP, i.e. they will trap aerosols and particulate forms of iodine, but not molecular iodine. Each high-volume air sampler is equipped with a secondary activated carbon filter that will trap molecular iodine, but only 1/50th of the air volume that flows through the primary filter then passes through the secondary activated carbon filter. These activated carbon filters are changed each month, and no I-131 has been detected on these to date.

When simply comparing the activities of I-131 that each patient received with the measurements of I-131 in air at the high-volume air sampling station in Tromsø, there appears to be no obvious overall correlation (Figure 14). For example, the one occasion when a patient received only 1.1 GBq of I-131 (22.03.2024) corresponded to a measurement above the detection limit (week 12), whereas for all weeks where the measured activity concentration of I-131 in air were below the detection limit, patients received between 3.7 and 6.1 GBq.

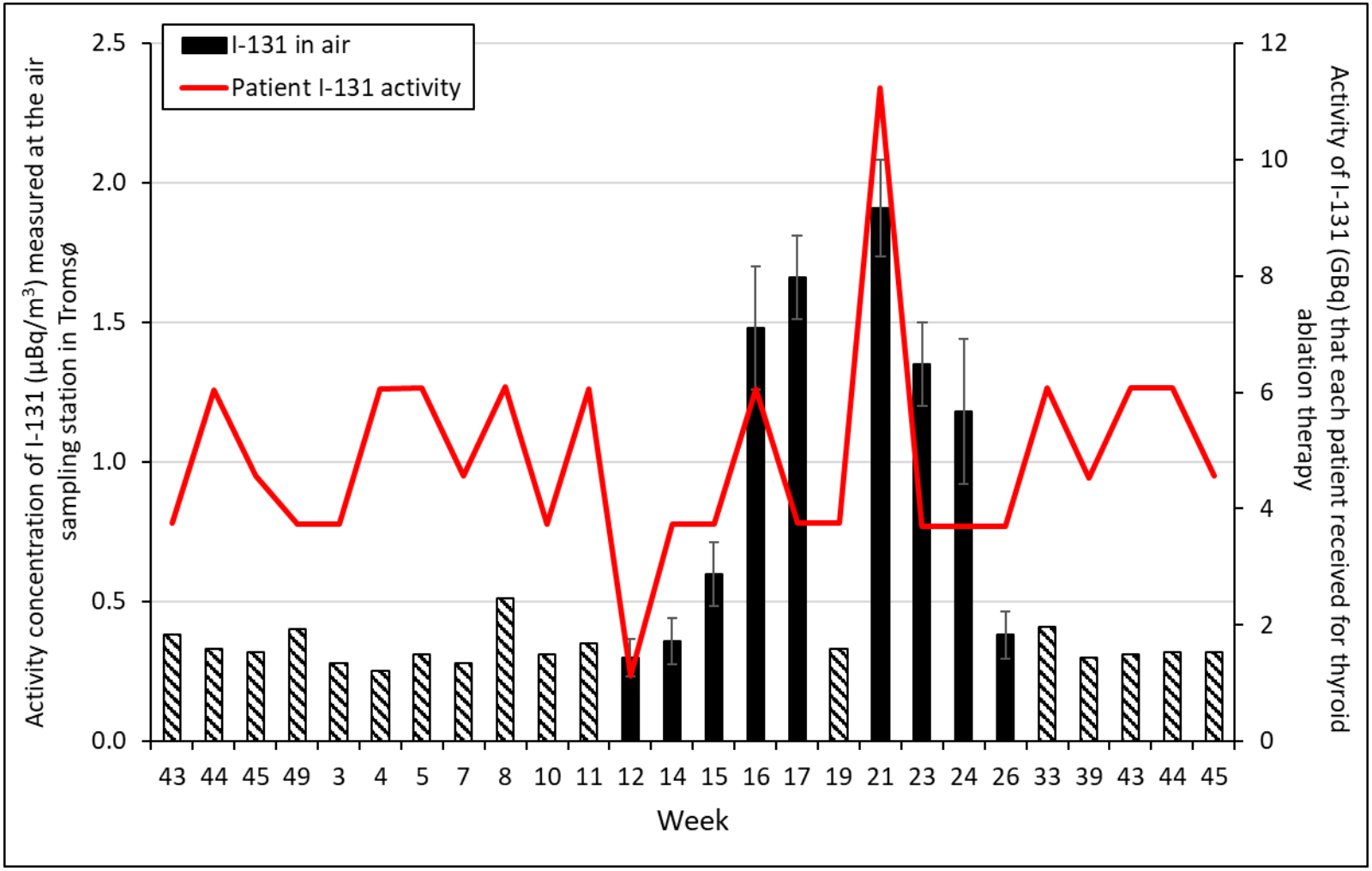


Figure 14. Comparison of I-131 activity concentrations (µBq/m³) at the high-volume air sampling station in Tromsø for the weeks that included weekends when patients underwent thyroid ablation therapy at UNN between week 43 in 2023 and week 45 in 2024 (bars) and the corresponding I-131 activity that patients received for thyroid ablation therapy at UNN (line). Striped bars represent values for I-131 below detection limits. Solid bars represent values for I-131 above detection limits, where error bars show analytical uncertainties (1 sigma). Data on use of I-131 provided by the Nuclear Medicine Section, University Hospital of North Norway.

In terms of the possible sources of the I-131 that have been detected at the high-volume air sampling station in Tromsø, it is conceivable that this is simply due to the subsequent venting of I-131 from the filtration room at the Breivika WTP (and possibly smaller contributions from the pump station). However, I-131 in the air over Tromsø may potentially also derive from the production of sea-salt aerosols and/or volatilisation of I-131 after treated wastewater has been discharged to Tromsøysundet, as well as the from the release of bioaccumulated I-131 from intertidal seaweed species when they exposed to the air during tidal cycles.

A comparison of the I-131 activity concentrations detected in indoor air in this study compared to the I-131 activity concentrations reported previously in influent and effluent at Breivika WTP (Gwynn & Kiel-Jensen, 2019), would suggest that the vast majority of the I-131 that is excreted from patients is discharged directly to Tromsøysundet. Globally, the oceans provide the main source of iodine to the atmosphere through the complex release of molecular iodine and the volatilisation of various chemical forms of iodine that can then undergo rapid photolysis and reaction with ozone to form particulate forms of iodine (e.g. Saiz-Lopez et al., 2012; Prados-Roman et al., 2015). Although the discharge point for effluent from the Breivika WTP is at a depth of 17.4 m, the discharged effluent would be expected to have a lower salinity than the receiving sea water, so that any discharged I-131 is likely to be dispersed within the surface layers of Tromsøysundet. This is supported by the observations of I-131 in intertidal seaweed species at locations up to 5 km south and up to 10 km north of the discharge point in Tromsøysundet as well as on the western side of Tromsøya (Gwynn & Kiel-Jensen, 2019). Therefore, in theory it would be possible for the recipient seawater in Tromsøysundet to act as source of I-131 to the air over Tromsø. However, the fate of any I-131 discharged into seawater will be dependent on the initial chemical form and subsequent in situ controls on any changes in chemical speciation.

Seaweed species show a high affinity for the bioaccumulation of iodine (e.g. Leblanc et al., 2006), with an International Atomic Energy Agency (IAEA) recommended biological concentration factor of 10000 for iodine (IAEA 2004). Activity concentrations of I-131 in samples of the brown seaweed *Fucus vesiculosus* from the shore at Breivika showed a relatively rapid increase after patients had received I-131 for thyroid ablation therapy at UNN, with estimated effective (includes physical decay) and biological half-lives of 3.2 and 5.3 days (Gwynn & Kiel-Jensen, 2019). Activity concentrations of I-131 in *F. vesiculosus* of up to 400 Bq/kg (fresh weight (fw)) were detected in samples collected from the shore at Breivika after a patient received 6 GBq, with lower activity concentrations (<10 Bq/kg fw) in *F. vesiculosus* at sites further North and South within Tromsøysundet (Gwynn & Kiel-Jensen, 2019). Higher activity concentrations of up to 700 Bq/kg (fw) in *F. vesiculosus* from the shore at Breivika were detected when two patients both received 6 GBq within four days of each other (Gwynn & Kiel-Jensen, 2019). When exposed to the air during tidal cycles, intertidal seaweeds such as *F. vesiculosus* can release molecular iodine and organic iodine species as a stress response that are then converted through photolysis and reaction with ozone to form particulate forms of iodine (e.g., Huang et al., 2013) as is the case for sources of iodine released directly from the sea surface. In coastal areas the main source of iodine to the atmosphere is from the release of molecular iodine from marine algae (e.g. Saiz-Lopez & Plane, 2004). As the further conversion of molecular iodine and other released chemical forms of iodine are dependent on ambient light levels, the production of particulate forms of iodine in coastal areas shows a clear diurnal signal at temperate latitudes (Saiz-Lopez & Plane, 2004). Thus, it might be expected that intertidal seaweed species and in particular those along the shore at Breivika could be an additional source of I-131 to the air over Tromsø. In the case of any I-131 released either from intertidal seaweed species or directly from the sea surface, further conversion to particulate forms would be expected to be influenced by the latitudinal seasonal changes in ambient light levels in Tromsø, where the sun remains below the horizon between November and January and does not set between May and July.

5.1. Breivika WTP as a subsequent possible source of I-131 to the air over Tromsø

Although sampling of indoor air in the filtration room at the Breivika WTP have only been carried out over six weekends, it is likely that measurable activity concentrations of I-131 in indoor air at the Breivika WTP are produced every time a patient undergoes thyroid ablation therapy at UNN. From this we could infer that any I-131 in indoor air at the Breivika WTP will then be vented externally leading to local activity concentrations of I-131 in the air in the area around the Breivika WTP. When considering the further airborne transport of any I-131 vented from the Breivika WTP, or indeed I-131 released from intertidal seaweeds at Breivika, it should be noted that the high-volume air sampling station in Tromsø is located 1.8 km South-Southwest from the Breivika WTP. The average predominant wind direction for all weekends when patients underwent thyroid ablation therapy at UNN during the study period was from the South-Southwest, whether I-131 was (Figure 15a) or was not (Figure 15b) detected at the high-volume air sampling station in Tromsø. However, on average there was a greater proportion of winds with a Northerly component when I-131 was detected (Figure 15c) than when I-131 was not detected (Figure 15d) at the high-volume air sampling station.

Therefore, it is possible that it is simply the degree of direct windblown transport of I-131 from the Breivika area that accounts for the occasions when I-131 has been detected at the high-volume air sampler in Tromsø. We might assume that winds from the North, North-Northeast and Northeast are most relevant for the direct transport of I-131 from the Breivika area to the high-volume air sampler in Tromsø due to their respective locations. However, the further transport of any I-131 from the Breivika area is likely to be complex when considering the urban setting and possible recirculation of I-131 due to the topography of the area around Tromsøya and shifting wind directions and speeds over time. The individual wind roses for each weekend when I-131 was detected at the high-volume air sampling station in Tromsø (Figure 16) show considerable variation in terms of the proportion of winds with a Northerly component.

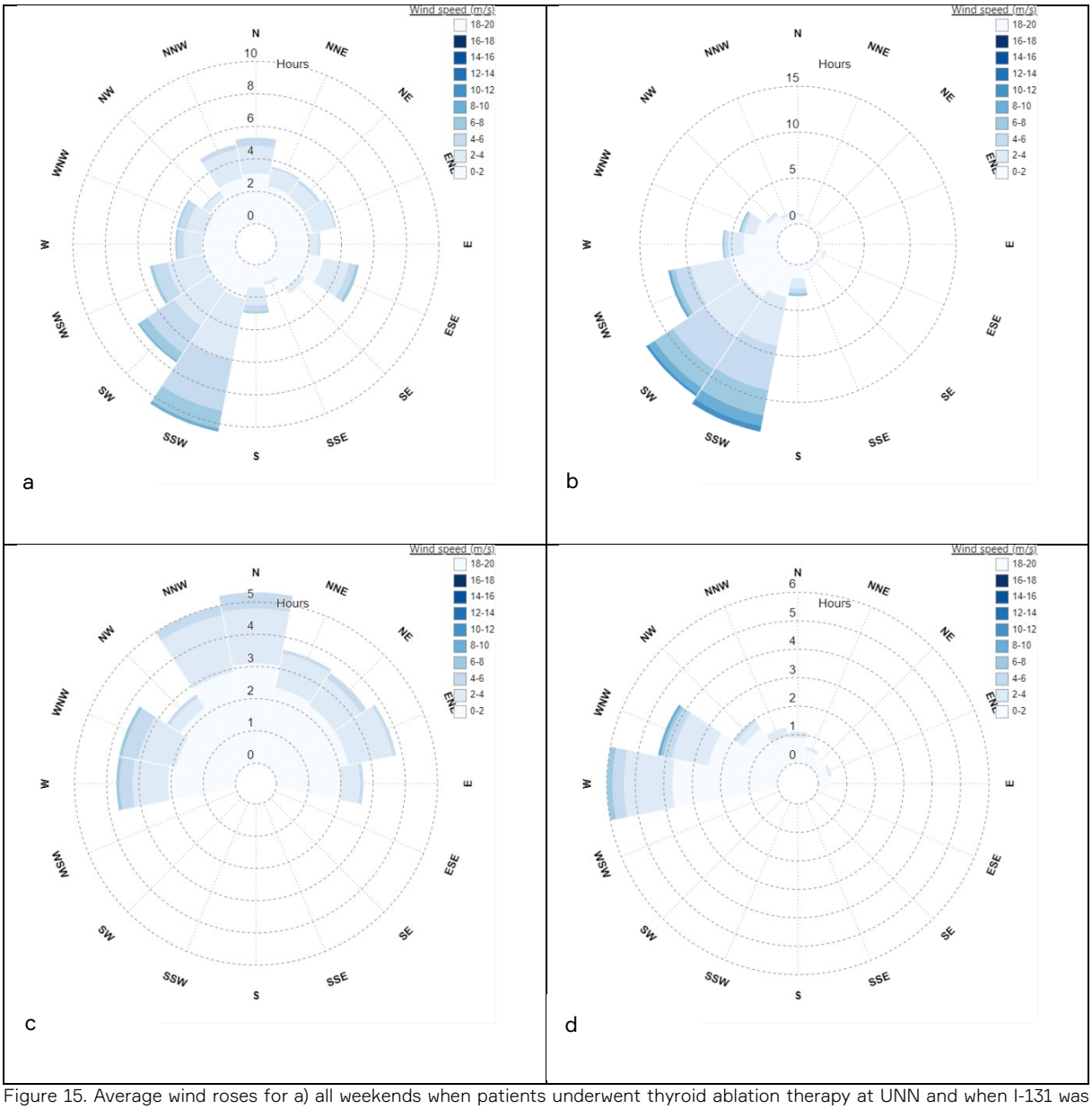
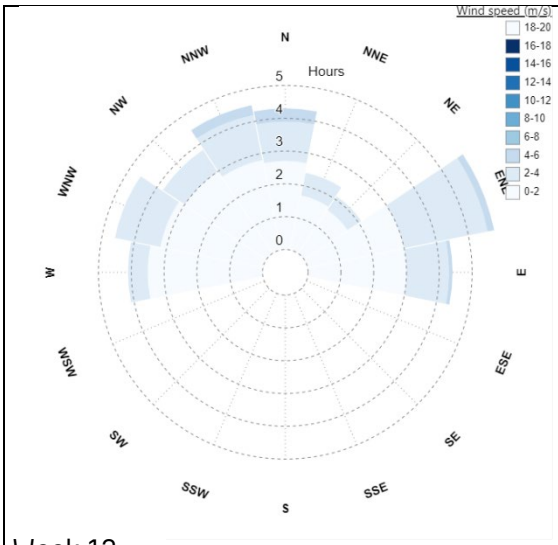
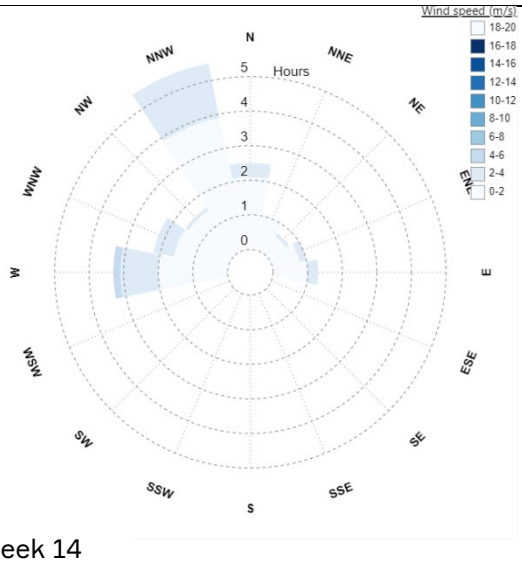


Figure 15. Average wind roses for a) all weekends when patients underwent thyroid ablation therapy at UNN and when I-131 was detected at the high-volume air sampling station in Tromsø for the corresponding weeks between week 43 in 2023 and week 45 in 2024; b) all weekends when patients underwent thyroid ablation therapy and when I-131 was not detected at the high-volume air sampling station in Tromsø for the corresponding weeks between week 43 in 2023 and week 45 in 2024; c) same as figure a, but only showing data for all directions between W-N-E; and d) same as figure b, but only showing data for all directions between W-N-E. Average wind roses are based on total wind rose data for all relevant weekends where observations for wind direction and speed were taken every minute from Friday 12:00 pm to Monday 12:00 pm at the University of Tromsø weather station (https://weather.cs.uit.no/).



Week 12



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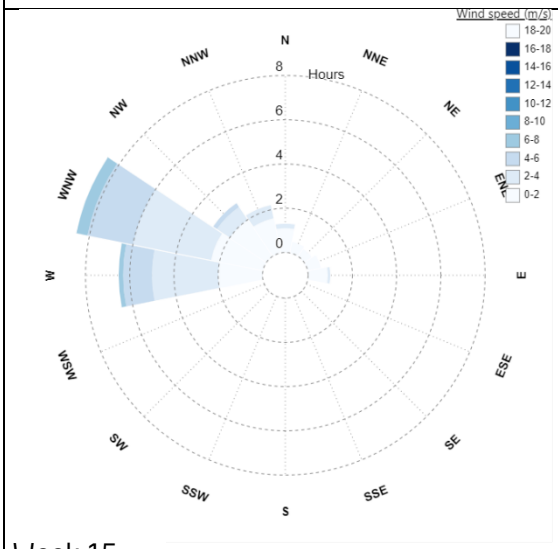
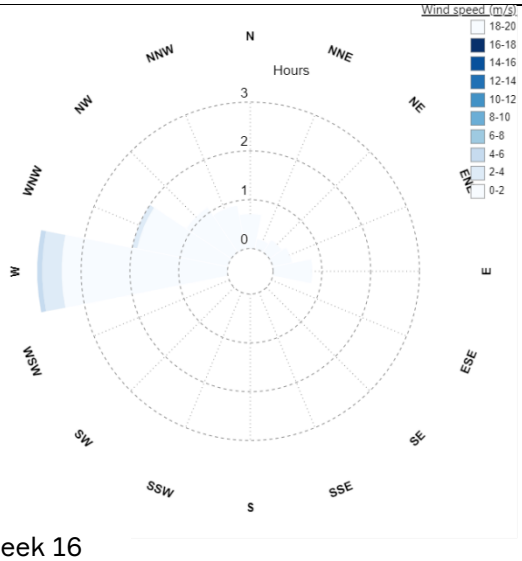
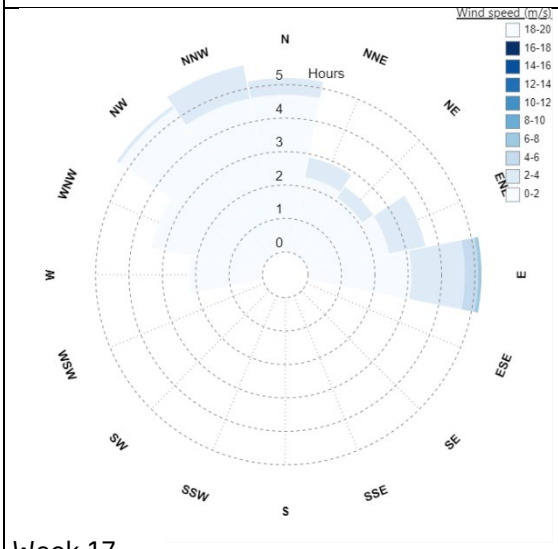


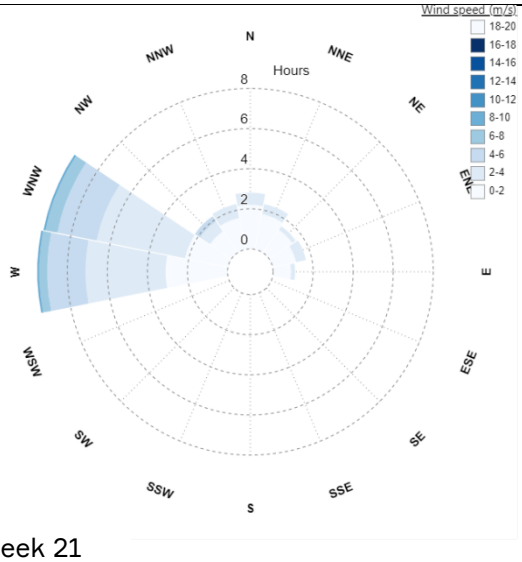
Week 15



Week 16



Week 17



Week 21

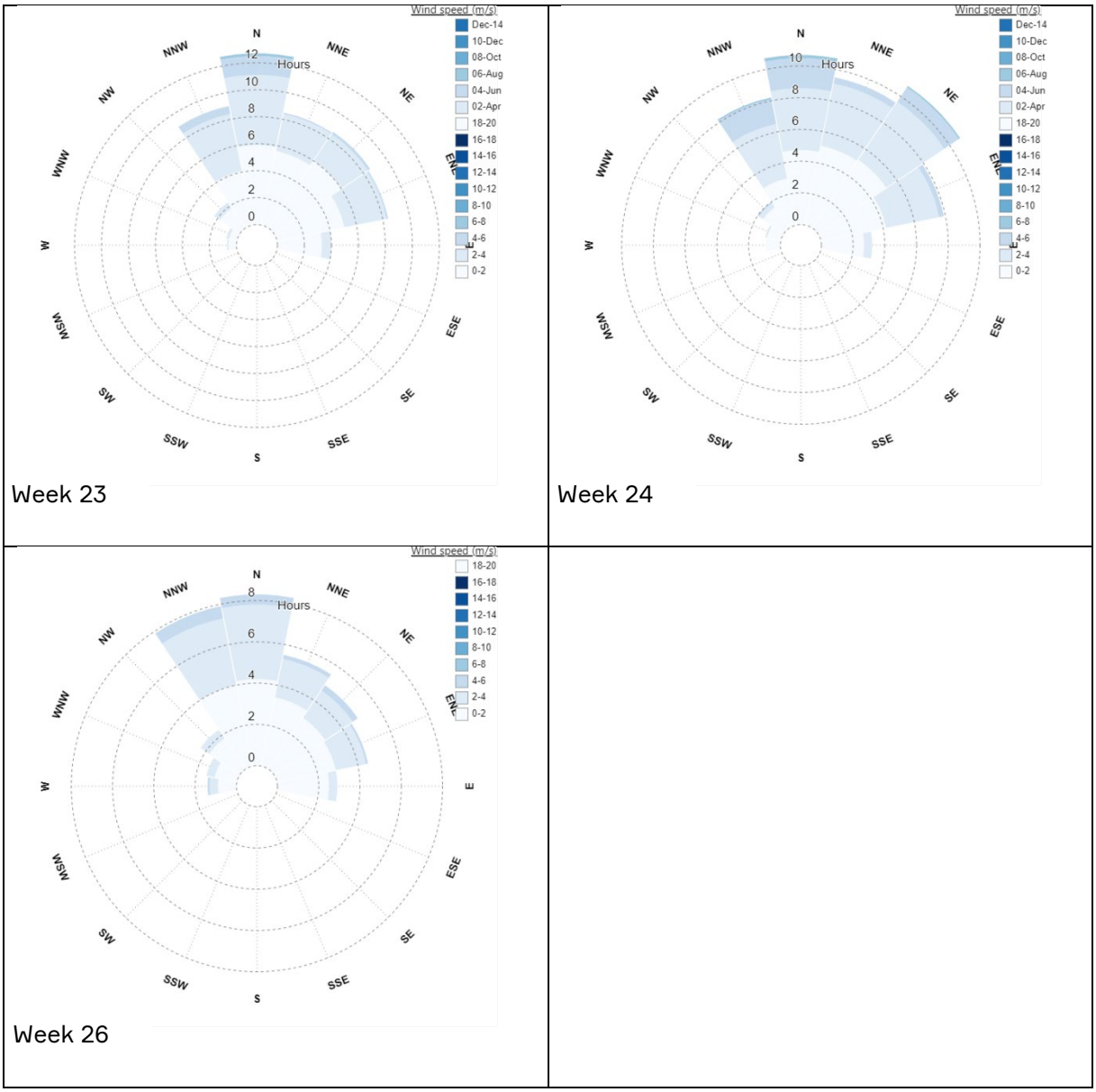


Figure 16. Total wind roses for all directions between W-N-E only and from Friday 12:00 pm to Monday 12:00 pm for the weekends when patients underwent thyroid ablation therapy at UNN and when I-131 was detected at the high-volume air sampling station in Tromsø for the corresponding weeks during the study period (above weeks were all in 2024). Total wind roses are based on observations of wind direction and speed taken every minute at the University of Tromsø weather station (https://weather.cs.uit.no/).

Notably in week 16, the proportion of winds with a Northerly component was far lower than for any other weekend when I-131 was detected at the high-volume air sampling station in Tromsø. Indeed, the total wind duration of winds from the North, North-Northeast and Northeast in week 16 was similar to week 19 and lower than a number of other weeks when I-131 was not detected at the high-volume air sampling station in Tromsø (Figure 17). The degree of spread of any airborne transport of radionuclides will be influenced by the wind speed, with slower wind speeds enabling greater spread with distance than higher wind speeds. Although there was some clear variation in mean wind speeds from the North, North-Northeast and Northeast for weekends when patients underwent thyroid ablation therapy, there was no obvious relationship to whether I-131 was (or was not) detected at the high-volume air sampler in Tromsø (Figure 18). The overall mean wind speed from the North, North-Northeast and Northeast for all weekends in the study period when patients underwent thyroid ablation therapy was 1.2 ±0.5 m/s with a range of 0.4 ±0.3 to 2.3 ±0.9m/s for individual weekend means.

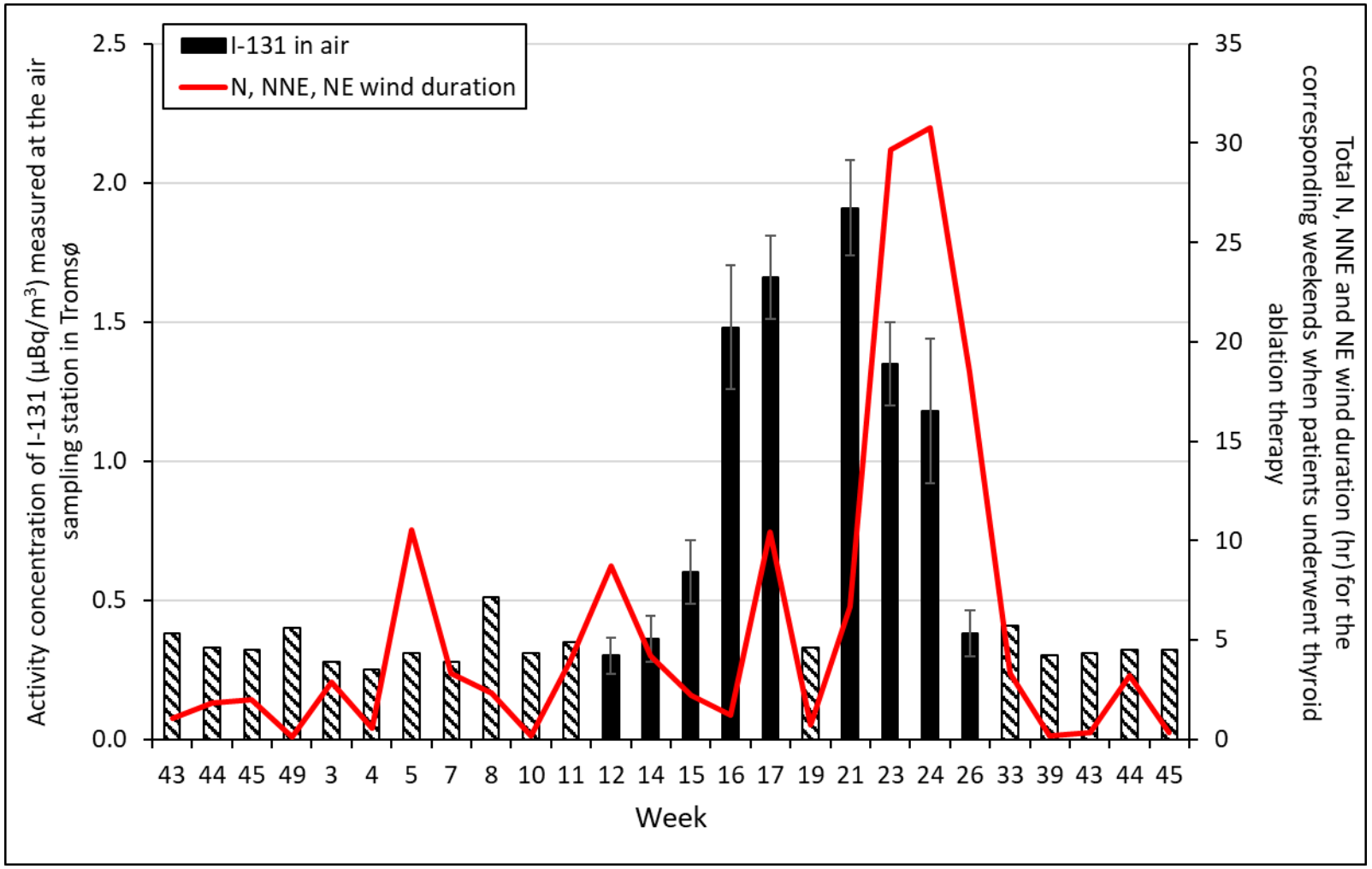


Figure 17. Comparison of I-131 activity concentrations (µBq/m³) at the high-volume air sampling station in Tromsø for the weeks that included weekends when patients underwent thyroid ablation therapy at UNN between week 43 in 2023 and week 45 in 2024 (bars) and total wind duration (hr) of winds from the North, North-Northeast and Northeast for each corresponding Friday 12:00 pm to Monday 12:00 pm (line). Striped bars represent values for I-131 below detection limits. Solid bars represent values for I-131 above detection limits, where error bars show analytical uncertainties (1 sigma). Total wind duration values are based on observations taken every minute at the University of Tromsø weather station (https://weather.cs.uit.no/).

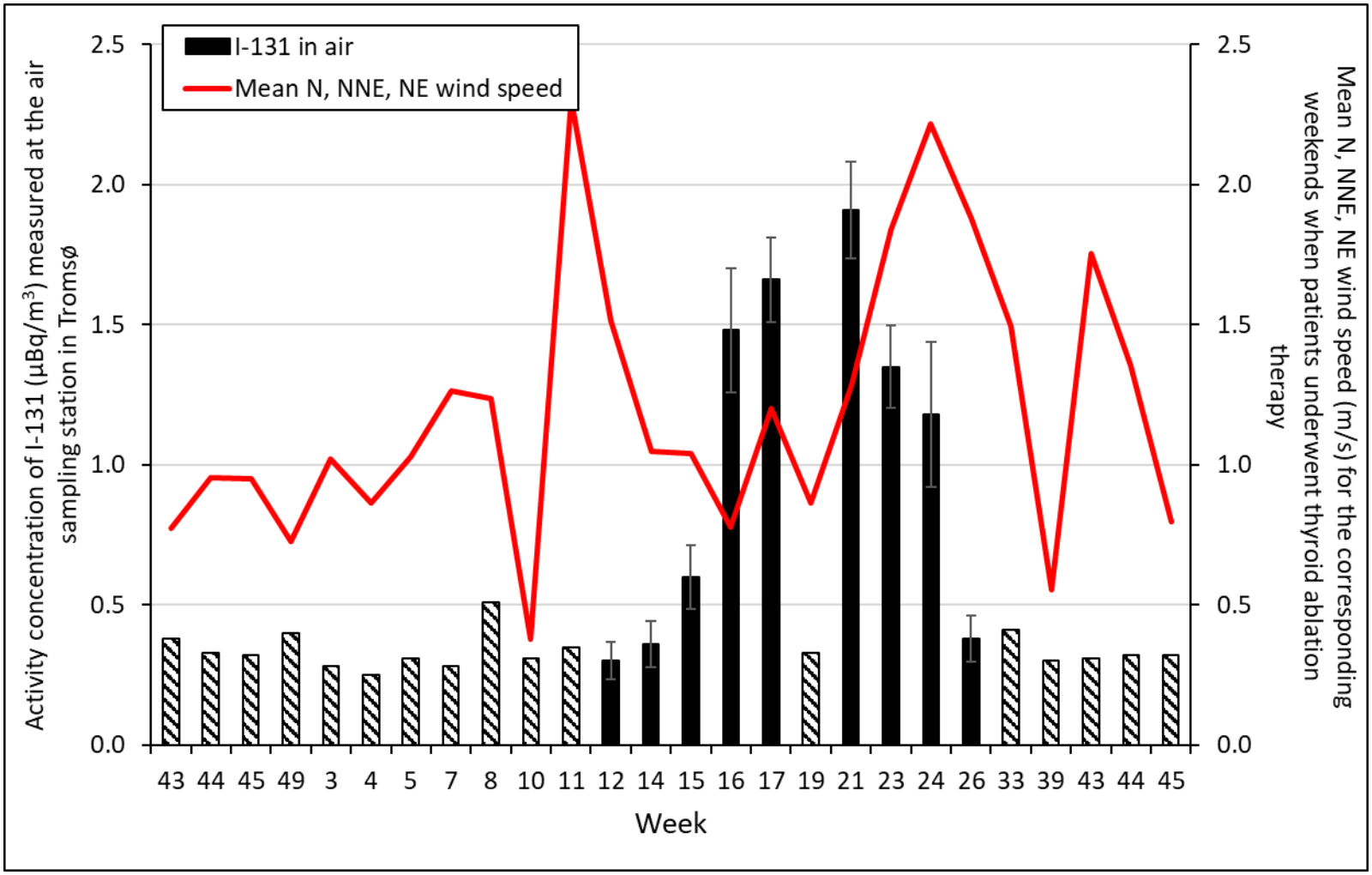


Figure 18. Comparison of I-131 activity concentrations (µBq/m³) at the high-volume air sampling station in Tromsø for the weeks that included weekends when patients underwent thyroid ablation therapy at UNN between week 43 in 2023 and week 45 in 2024 (bars) and mean wind speed (m/s) of winds from the North, North-Northeast and Northeast for each corresponding Friday 12:00 pm to Monday 12:00 pm (line). Striped bars represent values for I-131 below detection limits. Solid bars represent values for I-131 above detection limits, where error bars show analytical uncertainties (1 sigma). Mean wind speed values are based on observations taken every minute at the University of Tromsø weather station (https://weather.cs.uit.no/).

In terms of timing, it is not possible at present to know when pulses of I-131 arrive at the Breivika WTP, nor how much or for what duration I-131 is then vented externally or whether these events then coincide with any winds from the North, North-Northeast or Northeast. It can be expected that the largest amount of activity discharged will occur the first time the patient urinates after taking their I-131 oral capsule and in total over the first 24 hours (Pers. Comm. Ola Engelsen), and this is supported by the indoor air measurements in this study where the highest I-131 activity concentrations were detected during the sampling interval 'Friday to Saturday'. However, the I-131 activity concentrations in indoor air at the Breivika WTP that were detected in the subsequent sampling intervals in this study (i.e. 'Saturday to Sunday' and 'Sunday to Monday') may also give rise or contribute to the I-131 activity concentrations that have been detected at the high-volume air sampling station in Tromsø. When patients leave the isolation unit, no information is available as to whether they remain at UNN or if allowed home, whether they live locally or not.

A comparison of the timing of winds from the North, North-Northeast or Northeast for selected weekends when patients underwent thyroid ablation therapy (Figure 18), may explain the similarity in the activity concentrations of I-131 detected at the high-volume air sampling station in Tromsø for weeks 12 (0.30 ±0.07 μBq/m^3) and 14 (0.36 ±0.08 μBq/m^3), despite that the difference in activities (1.1 and 3.7 GBq, respectively) given to the patients on these occasions. For the first 48 hours of the weekend in week 12, there were consistently winds that could transport I-131 in the Breivika area directly towards the high-volume air sampling station in Tromsø. Whereas for week 14, such winds did not occur until Sunday morning, when the activity concentration of I-131 vented from the Breivika WTP would be expected to be lower. However, in the case of week 21 and 26, when indoor air measurements at the Breivika WTP were lower for the corresponding weekend in week 21 than for week 26, the activity concentration of I-131 detected at the high-volume air sampler in Tromsø was higher for week 21 (1.91 ±0.17 μBq/m^3) than for week 26 (0.38 ±0.08 μBq/m^3), despite greater wind durations, mean wind speeds and more frequent winds on Friday and Saturday from the North, North-Northeast or Northeast in week 26 (Figures 17, 18 & 19). In the case of week 19, when no I-131 was detected at the high-volume air sampling station in Tromsø, there were hardly any winds from the North, North-Northeast or Northeast over the course of the corresponding weekend (Figure 19). Yet, given the wind speeds and temporal trends for weeks 5 and 11 (Figures 18 & 19), it is curious that no I-131 was detected at the high-volume air sampling station in Tromsø for these weeks. Although wind direction and wind speed will be important factors in the further transport of any I-131 in air from Breivika, these observations would suggest that other factors may have a role in determining whether I-131 is detected at the high-volume air sampling station in Tromsø.

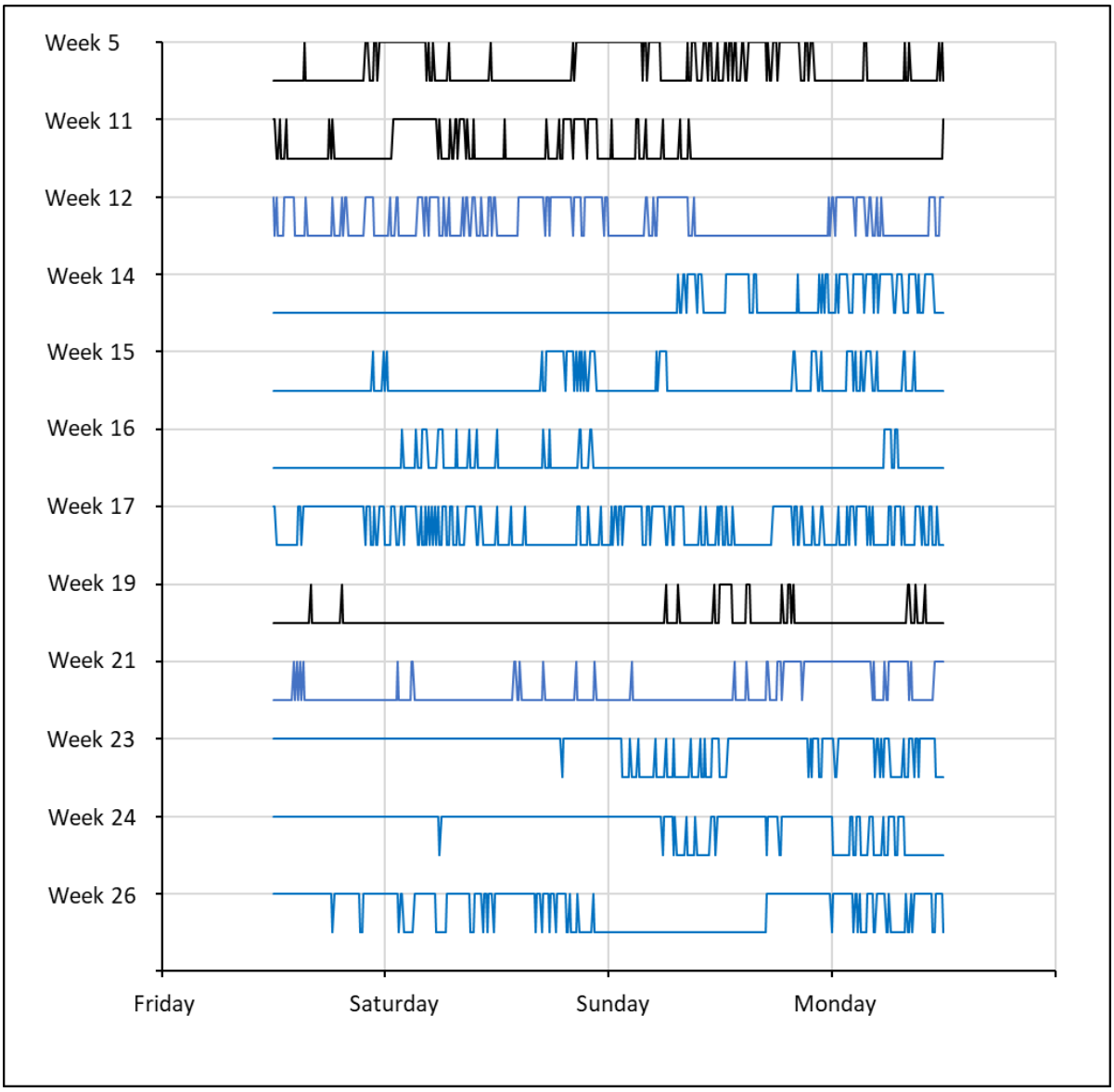


Figure 19. Comparison of temporal trends for any winds from the North, North-Northeast or Northeast (Up) for 1 minute or more in any consecutive 10-minute period or when the wind was from any other direction in any consecutive 10-minute period (Down) from Friday 12:00 pm to Monday 12:00 pm for selected weekends (all in 2024) when patients underwent thyroid ablation therapy at UNN. I-131 was not detected at the high-volume air sampling station in Tromsø for Weeks 5, 11 and 19 (Black trend lines). I-131 was detected at the high-volume air sampling station in Tromsø for all other weeks (Blue trend lines). Wind direction observations taken at the University of Tromsø weather station (https://weather.cs.uit.no/).

When considering other meteorological parameters, there appears to be no obvious relationship between mean air temperature and air humidity and whether I-131 was (or was not) detected at the high-volume air sampling station (Figure 20 & 21). As mentioned previously the conversion of molecular and other forms of iodine to particulate forms is mediated via photolysis. The observed trend in mean solar radiation (Figure 22) reflects the latitudinal seasonality in ambient light levels in Tromsø, with mean values not exceeding 50 W/m^2 per weekend until week 12, which was the first week when I-131 was detected at the high-volume air sampling station in Tromsø. It should be remembered that the primary filter type in use at the high-volume air sampling station does not trap molecular iodine and although no I-131 has been detected on any secondary activated carbon filter, these filters only sample 1/50th of the air volume that passes through the primary filter. These observations may indicate a necessity for the photolytic conversion to particulate forms of iodine for the detection of I-131 at the high-volume air sampler in Tromsø. This further reinforces the need to understand the chemical forms produced in indoor air at the Breivika WTP, as I-131 was

detected on the filters from the sixth sampling weekend. No I-131 was detected at the high-volume air sampler for the corresponding week (45), when the mean solar irradiance value for the sampling weekend was only 2.3 W/m^2. So, it is possible that I-131 is mainly produced in aerosol form in indoor air at the Breivika WTP and that any detection of I-131 at the high-volume air sampling station is dependent on photolytic conversion of any vented I-131 from the Breivika WTP.

The weekend in week 19 showed a mean solar radiation value of less than 100 W/m^2, and although this was also the case for weeks 12 and 15, it is possible that a lower conversion rate to particulate forms of I-131 in addition to a lower degree of direct transport may provide the reason why I-131 was not detected during this week at the high-volume air sampling station in Tromsø. Furthermore, the weekend in week 19 also had a relatively high total precipitation (17 mm), as was the case for the weekends in weeks 4, 5, 7, 11, 33, 39, 43, 44 and 45 in 2024 and unlike the weekends in weeks when I-131 was detected at the high-volume air sampling station in Tromsø (Figure 23). Increased precipitation will result in larger volumes of wastewater (from run-off), leading to greater dilution of any I-131 in sewage from UNN and lower levels of I-131 in indoor air at the Breivika WTP as discussed previously. Therefore, we can expect that the overall source term of I-131 from the Breivika WTP over weekends when precipitation occurs to be lower. However, there is no clear relationship between mean daily volumes of wastewater processed at the Breivika WTP and whether I-131 was (or was not) detected at the high-volume air sampling station (Figure 24). In addition, the various chemical forms of iodine that exist in the atmosphere can be removed by dry deposition as well as wet deposition (e.g. Baker et al., 2001), so we might expect increased washout of any I-131 in the air when a certain degree of precipitation occurs. However, this does not then directly explain the lack of detection of I-131 on the weekends of 43, 44, 45 and 49 in 2023 and the weekends of 3, 8 and 10 in 2024 (Figure 23)

The results of this study highlight the complex nature of the airborne dispersion of I-131 and particularly for an urban setting. Further investigation of the climatic controls on the transport and fate of different chemical forms of I-131 in the air should be investigated.

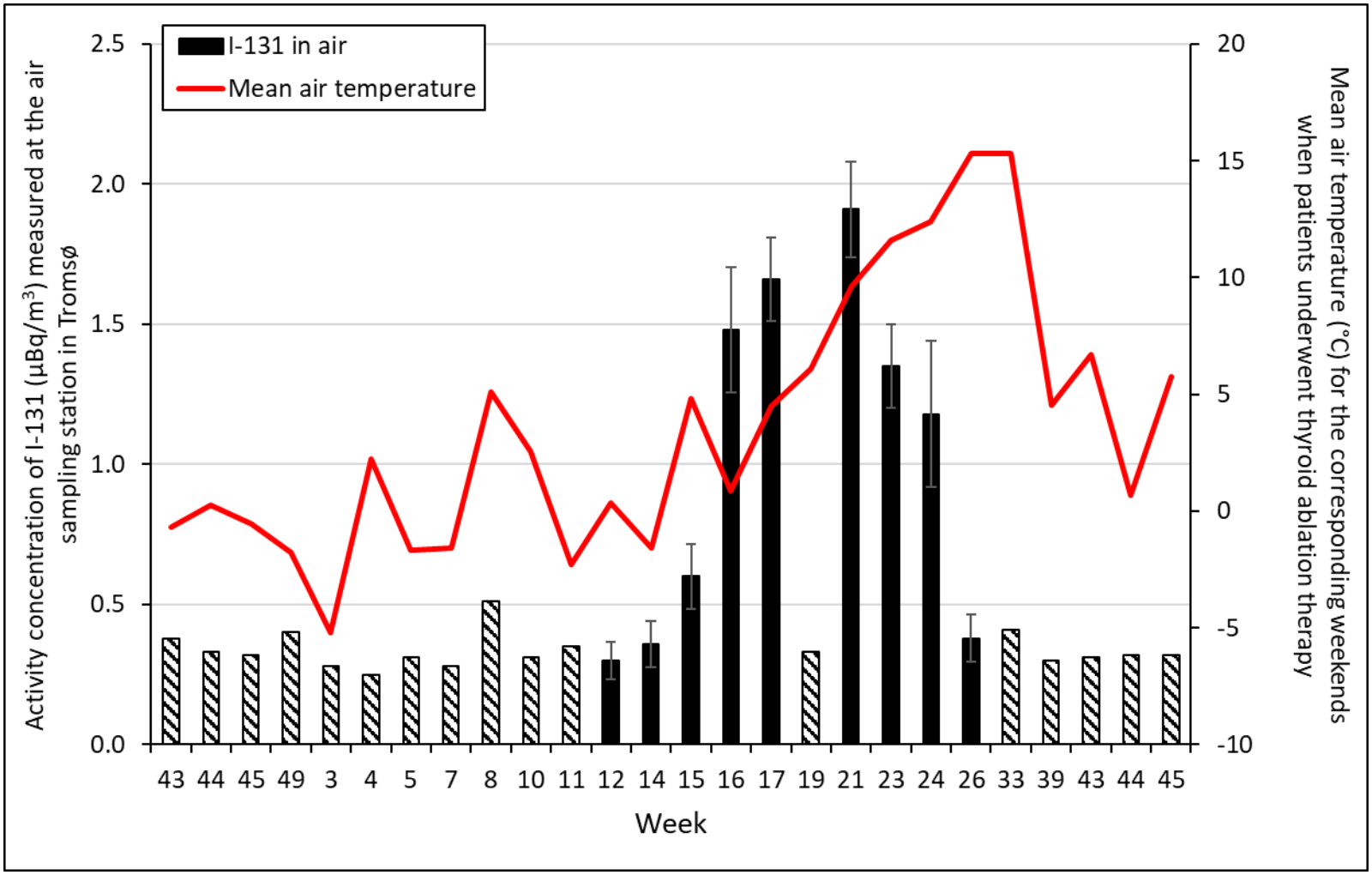


Figure 20. Comparison of I-131 activity concentrations (µBq/m³) at the high-volume air sampling station in Tromsø for the weeks that included weekends when patients underwent thyroid ablation therapy at UNN between week 43 in 2023 and week 45 in 2024 (bars) and mean air temperature (ºC) for each corresponding Friday 12:00 pm to Monday 12:00 pm (line). Striped bars represent values for I-131 below detection limits. Solid bars represent values for I-131 above detection limits, where error bars show analytical uncertainties (1 sigma). Mean air temperature values are based on observations taken every minute at the University of Tromsø weather station (https://weather.cs.uit.no/).

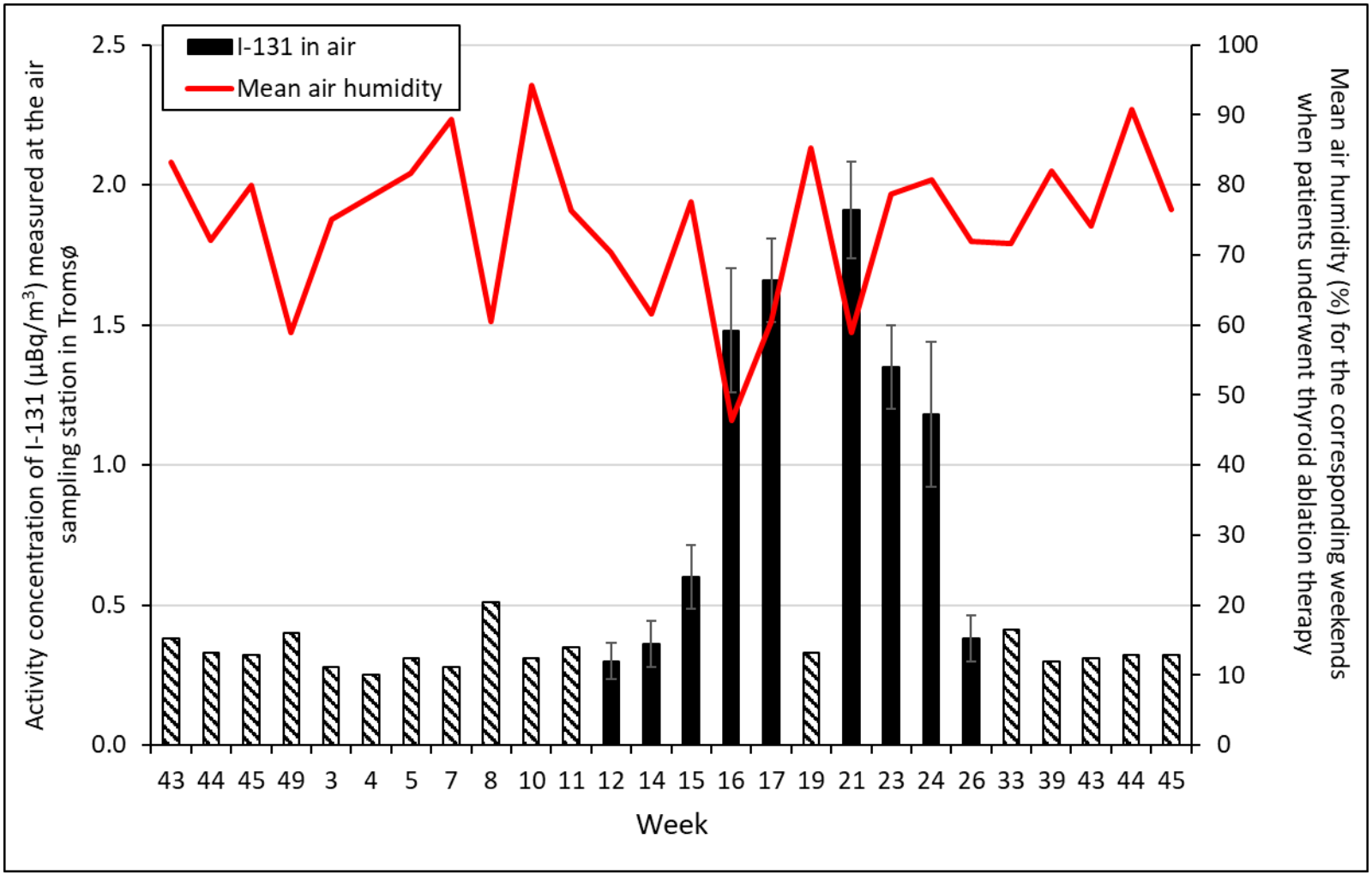


Figure 21. Comparison of I-131 activity concentrations (µBq/m³) at the high-volume air sampling station in Tromsø for the weeks that included weekends when patients underwent thyroid ablation therapy at UNN between week 43 in 2023 and week 45 in 2024 (bars) and mean air humidity (%) for each corresponding Friday 12:00 pm to Monday 12:00 pm (line). Striped bars represent values for I-131 below detection limits. Solid bars represent values for I-131 above detection limits, where error bars show analytical uncertainties (1 sigma). Mean air humidity values are based on observations taken every minute at the University of Tromsø weather station (https://weather.cs.uit.no/).

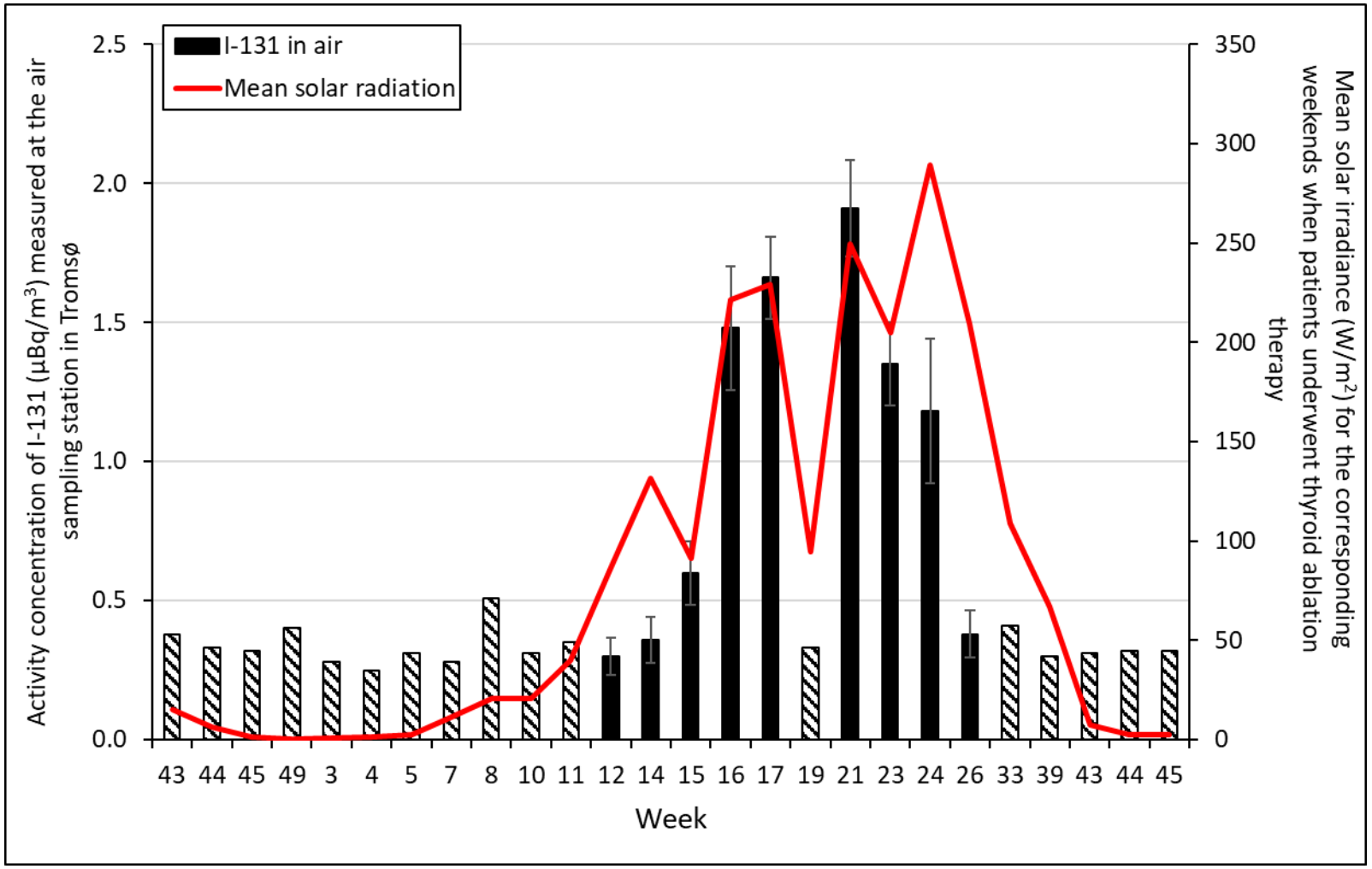


Figure 22. Comparison of I-131 activity concentrations (µBq/m³) at the high-volume air sampling station in Tromsø for the weeks that included weekends when patients underwent thyroid ablation therapy at UNN between week 43 in 2023 and week 45 in 2024 (bars) and mean solar irradiance (W/m²) for each corresponding Friday 12:00 pm to Monday 12:00 pm (lines). Striped bars represent values for I-131 below detection limits. Solid bars represent values for I-131 above detection limits, where error bars show analytical uncertainties (1 sigma). Mean solar irradiance values are based on observations taken every minute at the University of Tromsø weather station (https://weather.cs.uit.no/).

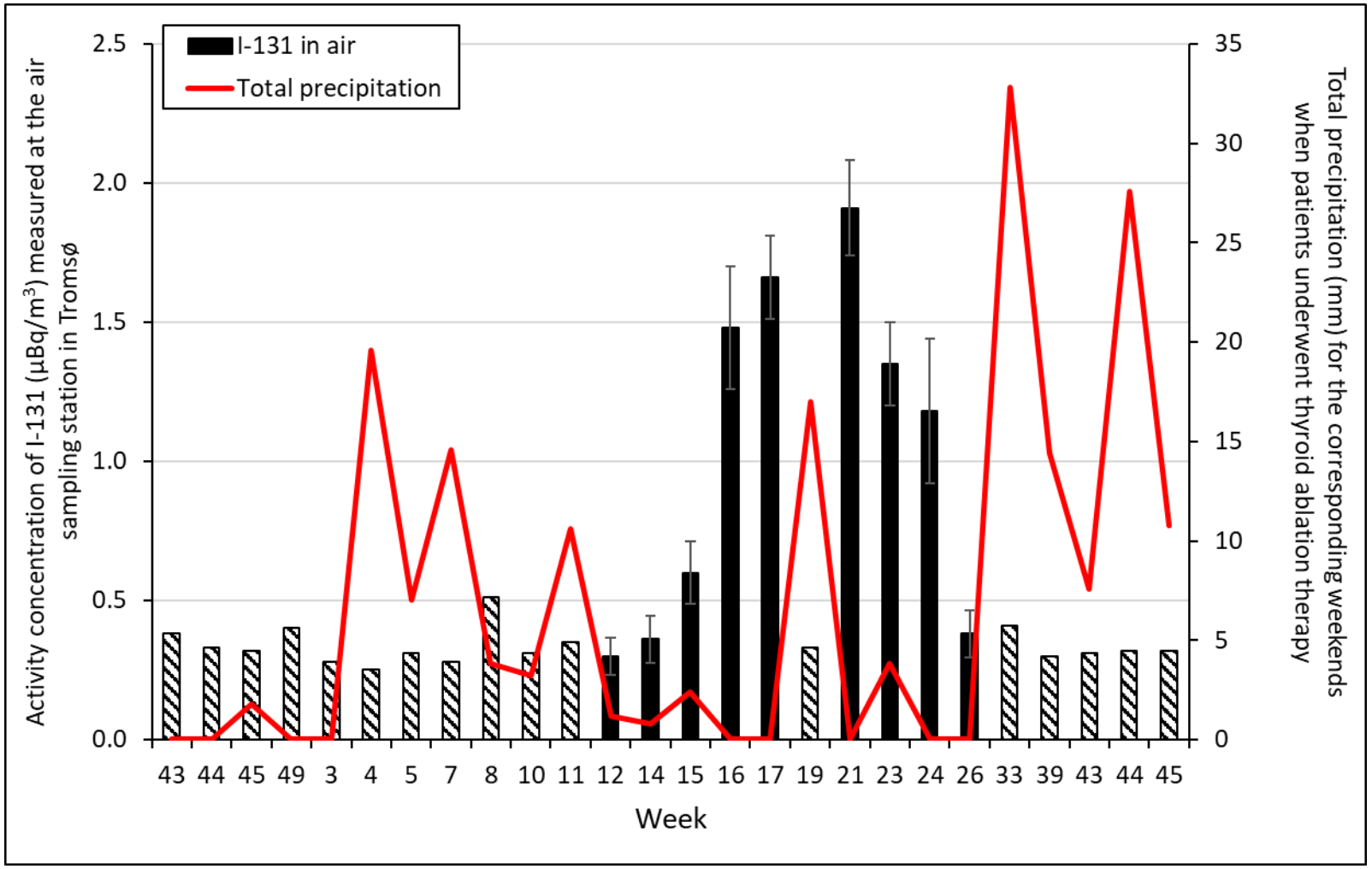


Figure 23. Comparison of I-131 activity concentrations (µBq/m³) at the high-volume air sampling station in Tromsø for the weeks that included weekends when patients underwent thyroid ablation therapy at UNN between week 43 in 2023 and week 45 in 2024 (bars) and total precipitation (mm) for each corresponding Friday 12:00 pm to Monday 12:00 pm (line). Striped bars represent values for I-131 below detection limits. Solid bars represent values for I-131 above detection limits, where error bars show analytical uncertainties (1 sigma). Total precipitation values for meteorological data are based on observations taken every minute at the University of Tromsø weather station (https://weather.cs.uit.no/).

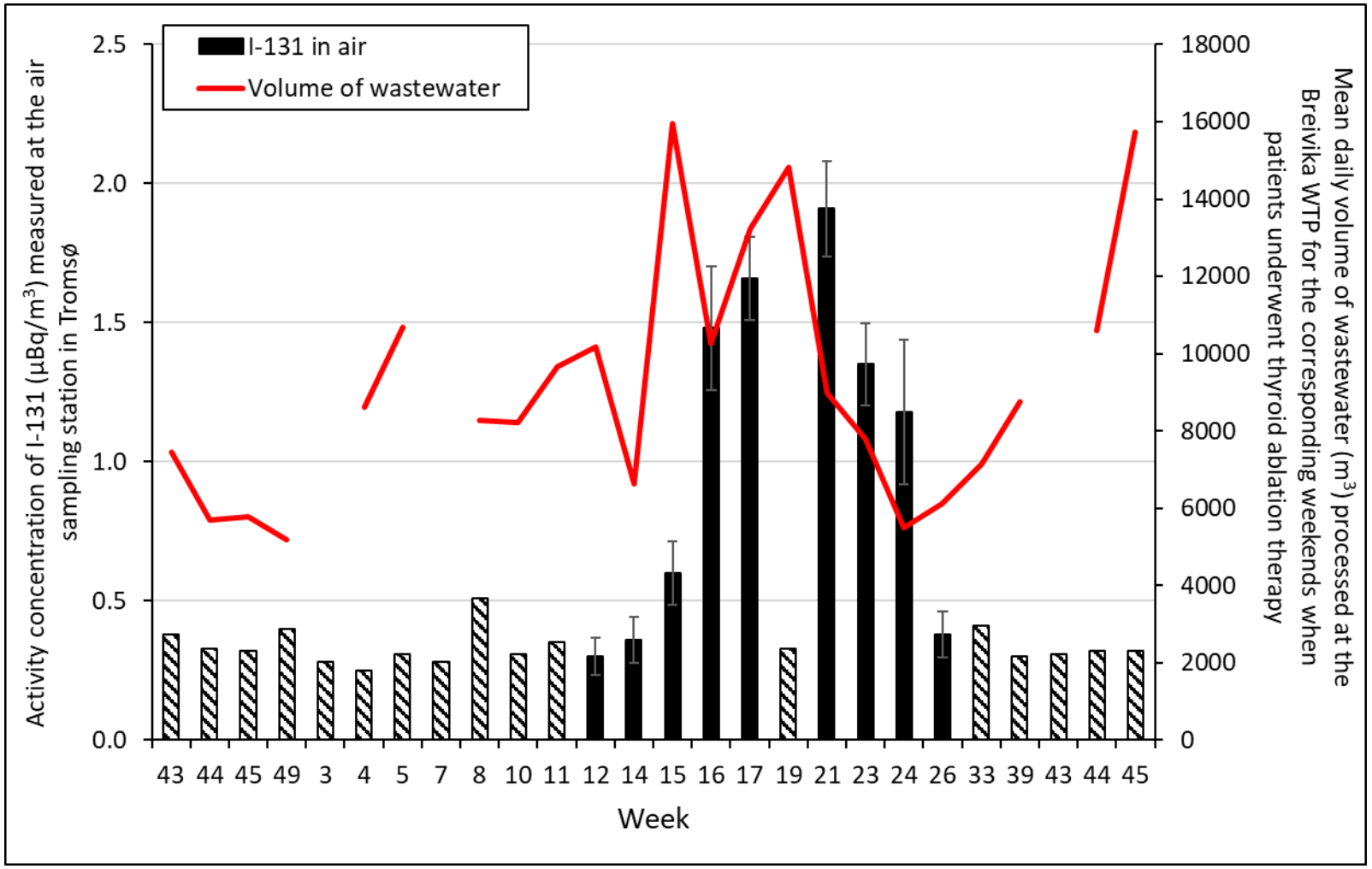


Figure 24. Comparison of I-131 activity concentrations (µBq/m³) at the high-volume air sampling station in Tromsø for the weeks that included weekends when patients underwent thyroid ablation therapy at UNN between week 43 in 2023 and week 45 in 2024 (bars) and daily mean volumes of wastewater processed at the Breivika WTP (m3) for each corresponding Friday, Saturday and Sunday. Striped bars represent values for I-131 below detection limits. Solid bars represent values for I-131 above detection limits, where error bars show analytical uncertainties (1 sigma). Data gaps for mean daily wastewater volumes represent times when no volume data was recorded. Wastewater volume data provided by the Tromsø Municipal Water & Sewage Department.

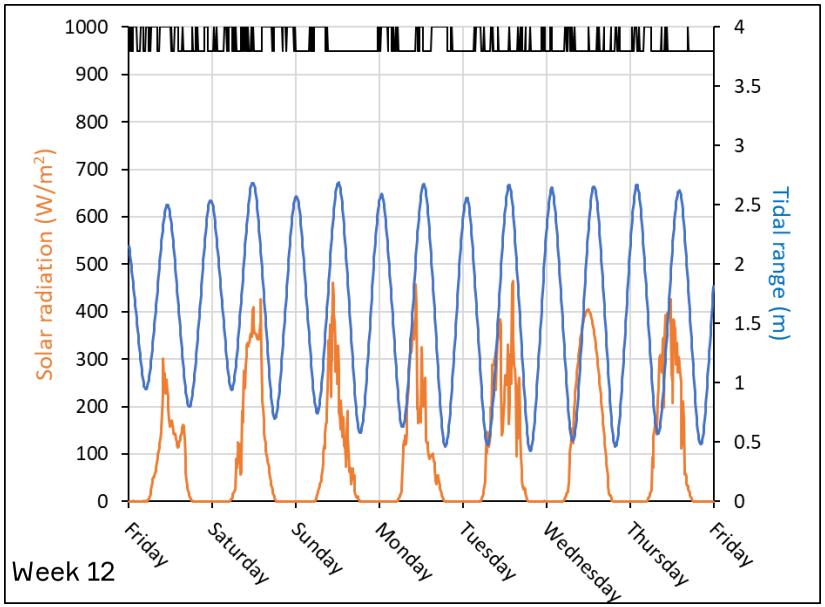
5.2 Tromsøysundet and intertidal seaweed as subsequent possible sources of I-131 to the air over Tromsø

Once discharged to Tromsøysundet, any release of I-131 directly to the air via the production of sea-salt aerosols and/or volatilisation of I-131 (and the further conversion to particulate forms of I-131) would be subject to the same climatic controls as I-131 vented from the Breivika WTP. Activity concentrations in seawater would be expected to be highest in the immediate area around the discharge point, with decreasing levels further afield as any discharged I-131 is diluted in the surrounding seawater. Thus, the potential for discharged I-131 to act as a source of I-131 to the air over Tromsø would be expected to be greatest in the offshore area around Breivika where the discharges occur.

As mentioned previously, intertidal seaweeds can release molecular iodine and organic iodine species as a stress response when exposed to the air during tidal cycles, and such seaweed species along the shore at Breivika show a relatively rapid uptake of I-131 following any discharge to Tromsøysundet (Gwynn & Kiel-Jensen, 2019). The degree of aerial exposure of seaweed species within the intertidal zone will be dependent on the amplitude of the tidal range, while further conversion of any released molecular iodine and organic iodine species to particulate forms will be dependent on the ambient light levels (Saiz-Lopez & Plane, 2004). Therefore, if intertidal seaweeds can act as a source of I-131 to the air, we might expect the highest release and local conversion to particulate forms of I-131 during spring low tides at times in the day and year with a given level of solar irradiance. However, there is no detailed information available on the exact light threshold required to initiate the conversion of molecular iodine and organic iodine species to particulate forms, so this reaction maybe possible even when solar radiation levels are relatively low. It should also be noted that any initial uptake of I-131 by intertidal seaweed species would require that the seaweed was immersed in seawater when any discharges of I-131 to Tromsøysundet occurred. It follows then that any I-131 discharged to Tromsøysundet during a low tide, may be transported further afield and diluted without any uptake by exposed intertidal seaweeds in the immediate Breivika area.

However, to illustrate the potential for intertidal seaweeds to act as a source of I-131 to the air over Tromsø. Figure 25 shows the tidal range and solar radiation data for the weeks (Friday to Thursday) which include the weekends when patients underwent thyroid ablation therapy from week 12 (when I-131 was first detected at the high-volume air sampler in Tromsø) to week 26 (when I-131 was last detected at the high-volume air sampler in Tromsø). Figure 21 also includes the temporal trends for any winds from the North, North-Northeast or Northeast which might then transport any released I-131 from intertidal seaweed species in the Breivika area in the direction of the high-volume air sampler in Tromsø. Tidal and solar radiation data for week 19 (when no I-131 was detected at the high-volume air sampler in Tromsø) are also included in Figure 25. Interestingly, the tidal range during week 19 was relatively low which would have led to a lower aerial exposure of the intertidal zone and there were relatively lower levels of solar radiation during week 19 as has been discussed previously. In addition, the temporal trends for winds during week 19 show that there were hardly any winds from the North, North-Northeast or Northeast that week. For all weeks when I-131 was detected at the high-volume air sampler, there were typically varying degrees of asynchrony between tidal cycles and solar radiation (i.e. occasions when low tides overlapped with periods of maximal solar radiation), when conditions would be expected to be most favourable for the release of molecular iodine and organic iodine species and their conversion to particulate forms in the local area.

The potential for I-131 to be released to the air from seawater and intertidal seaweed species has obvious implications to understanding the fate of any large-scale release of I-131 to seawater from a nuclear-powered vessel reactor accident. Further work and dedicated sampling methodologies would be required to assess these potential pathways.


Solar radiation (W/m²)
Tidal range (m)
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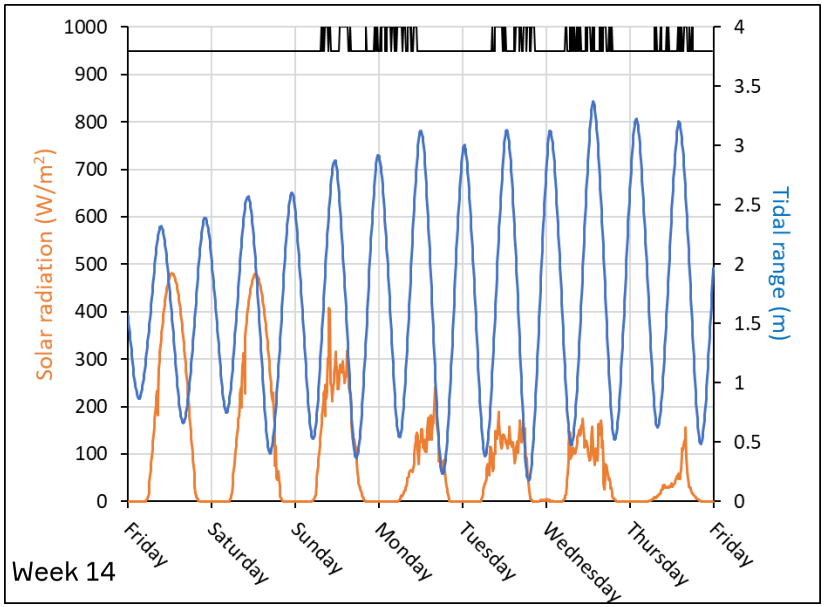
Week 12


Solar radiation (W/m²)
Tidal range (m)
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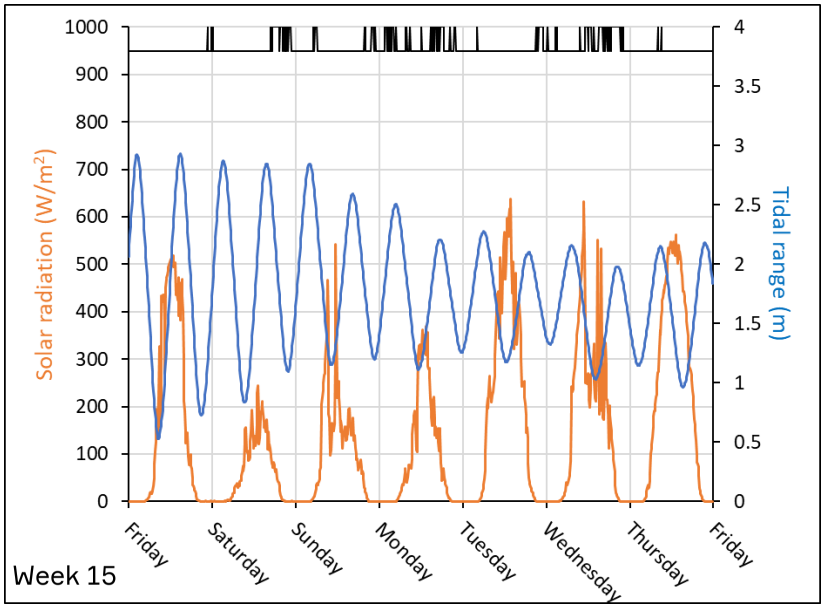
Solar radiation (W/m²)
Tidal range (m)
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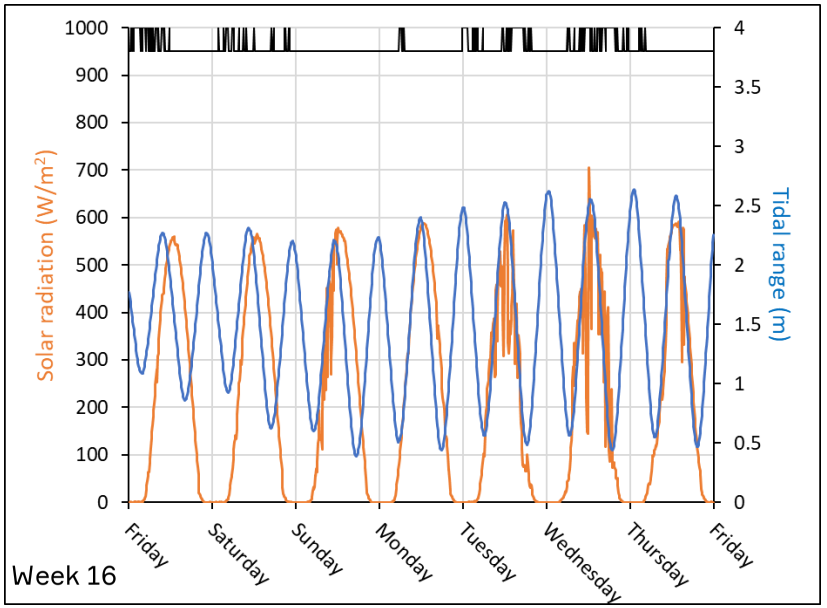
Solar radiation (W/m²)
Tidal range (m)
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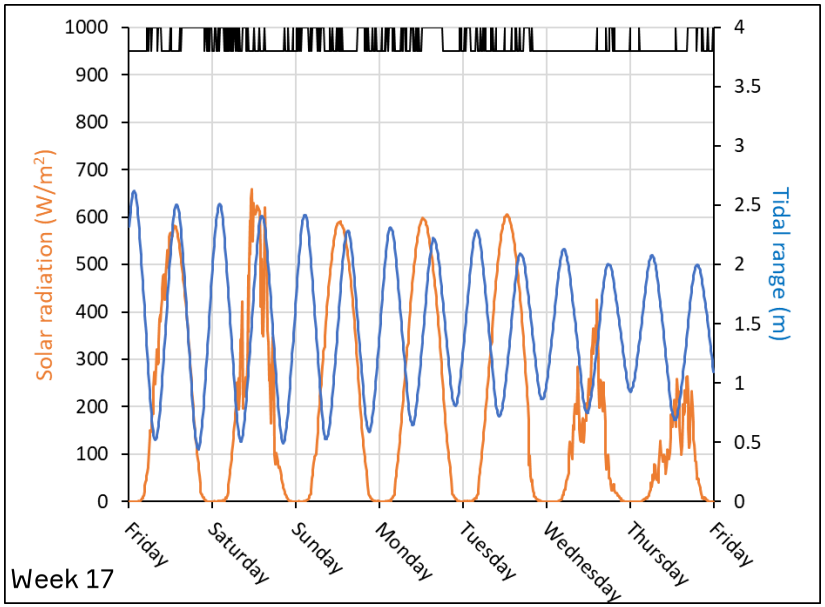
Solar radiation (W/m²)
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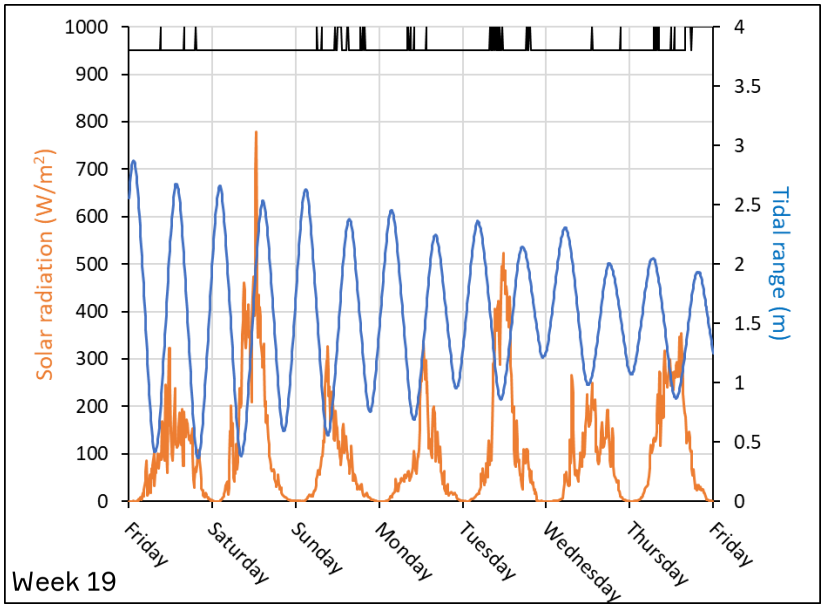
Solar radiation (W/m²)
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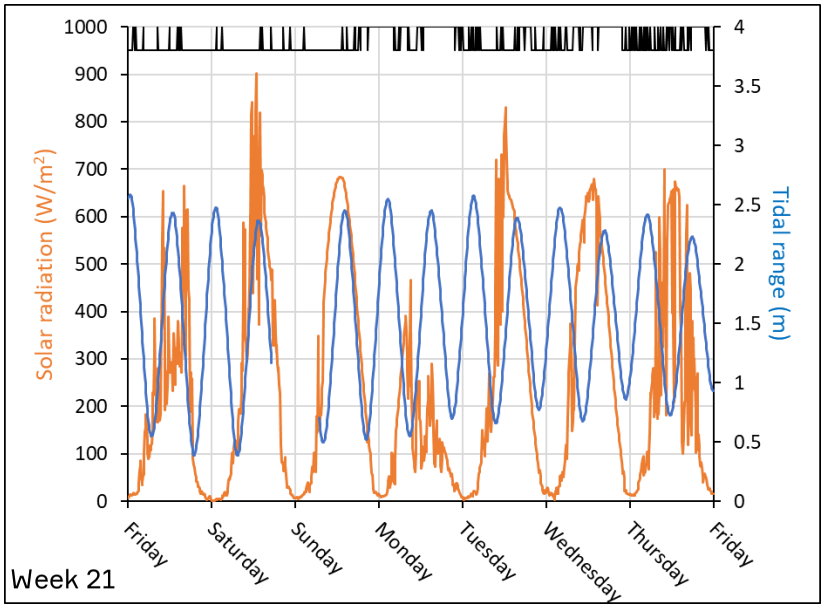
Solar radiation (W/m²)
Tidal range (m)
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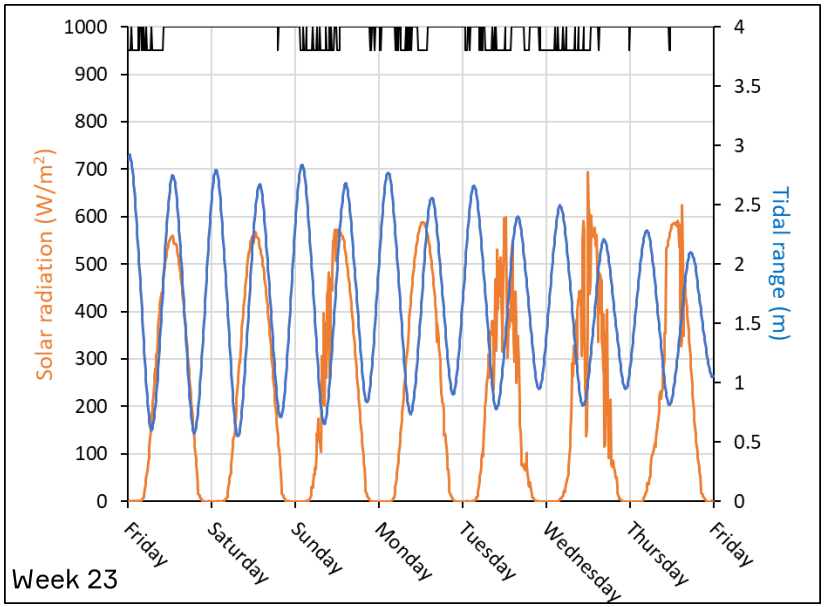
Week 21


Solar radiation (W/m²)
Tidal range (m)
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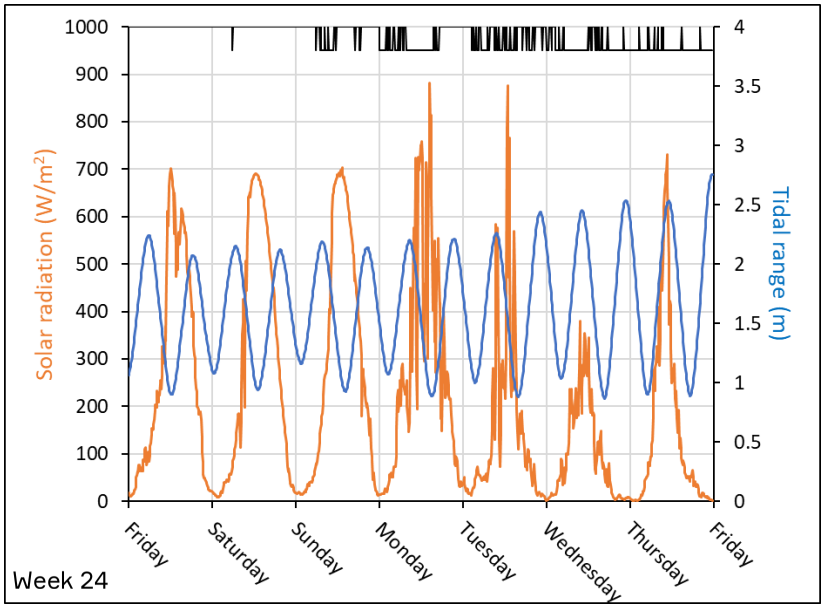
Week 23



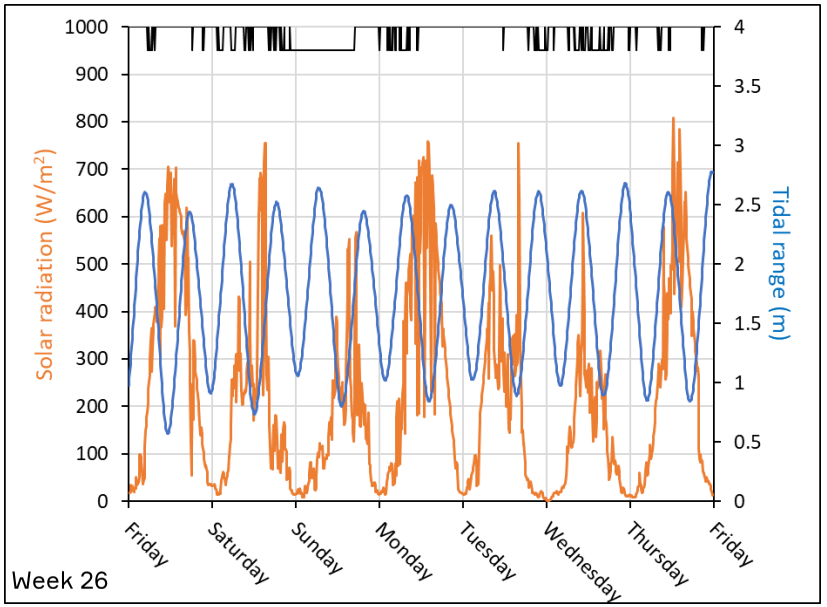


Figure 25. Comparison of changes in solar radiation (W/m²) (orange trend lines) and tidal height (m) (blue trend lines) for selected weeks (all in 2024) that included weekends when patients underwent thyroid ablation therapy at UNN. Solar radiation data represents the mean of observations recorded every minute in consecutive 10-minute periods. Figures also show temporal trends (black trend lines) for any winds from the North, North-Northeast or Northeast (Up) for 1 minute or more in any consecutive 10-minute period or when the wind was from any other direction in any consecutive 10-minute period (Down) for the respective weeks. I-131 was detected at the high-volume air sampling station in Tromsø for all the above weeks with the exception of week 19. Solar radiation and wind direction observations were taken at the University of Tromsø weather station (https://weather.cs.uit.no/). Tidal height observations were taken from the Intergovernmental Oceanographic Commission tidal station in Tromsøysundet (https://www.ioc-sealevelmonitoring.org/station.php?code=trom).

6. Conclusions

It is possible to establish a direct link between the use of I-131 at UNN for thyroid ablation therapy and the occurrence of I-131 in indoor air in the filtration room at the Breivika WTP. Further, although the level of I-131 in indoor air at the Breivika WTP is related to the activity of I-131 that a patient receives, it would appear that this is ultimately dependent on the degree of dilution that any I-131 in sewage from UNN undergoes when mixing with other wastewater streams prior to filtration. Further monitoring of indoor air in the filtration room at the Breivika WTP at different times of year may help better understand the impacts of different flow rates of wastewater on the dilution of I-131 and any other medical radioisotope in sewage from UNN.

When considering the inhalation doses derived in this study as well as the external exposure doses derived in previous studies, it can be concluded that use of GBq activities of I-131 at UNN for thyroid ablation therapy does not lead to any human health risk to workers at the Breivika WTP and pump station.

The detection of I-131 at the high-volume air sampling station in Tromsø can also be linked to the use of I-131 at UNN for thyroid ablation therapy. The levels of I-131 detected at the high-volume air sampler in Tromsø were lower than those detected in indoor air at the Breivika WTP and do not pose any risk to human health. It is possible that the source of I-131 that has been detected at the high-volume air sampling station in Tromsø arises from the venting of I-131 from the filtration room at the Breivika WTP.

This study raises a number of further research questions. Firstly, what are the chemical forms of I-131 that are generated in indoor air in the filtration room at the Breivika WTP and what are their fate (i.e. further chemical conversion) when released to the air over Tromsø. Secondly, how does the chemical form and local environmental conditions affect the subsequent airborne transport of any releases I-131. Such work should take into consideration the local topography and urban setting of the releases, the impact of wet and dry deposition and the latitudinal seasonal light variations in Tromsø. Thirdly, further work should also be carried to out to understand the potential for additional sources of I-131 to the air over Tromsø from seawater and intertidal seaweeds following any discharges of I-131 to Tromsøysundet. As I-131 can be an important radionuclide in terms of public exposure doses during the initial phase of nuclear accident scenarios, answers to these further research questions may provide important insights into the understanding of the impact of any large-scale accidental release of I-131, and in particular if such events were to occur at higher latitudes.

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8. References

Audunson, T., Næser, H., 1975. Resipientundersøkelser ved Tromsø. Vann 4, 277-290.

Demir, M., Parlak, Y., Çavdar, I., Yeyin, N., Tanyildizi, H., Gümüşer, G., Sayit, E., Erees, S., Sayman, H., 2013. The evaluation of urine activity and external dose rate from patients receiving radioiodine therapy for thyroid cancer. Radiation Protection Dosimetry 156(1), 25-29.

Baker, A.R., Tunnicliffe, C. and Jickells, T.D., 2001. Iodine speciation and deposition fluxes from the marine atmosphere. Journal of Geophysical Research: Atmospheres, 106(D22), pp.28743-28749.

Gwynn, J.P., Kiel-Jensen, L. (2019). Iodine-131 and other medical radioisotopes in Fucus vesiculosus in the marine environment around Tromsøya and in sewage from the University Hospital of North Norway in Tromsø. Technical Document No.15. Østerås, Norwegian Radiation Protection Authority.

Huang, R.J., Thorenz, U.R., Kundel, M., Venables, D.S., Ceburnis, D., Ho, K.F., Chen, J., Vogel, A.L., Küpper, F.C., Smyth, P.P.A. and Nitschke, U., 2013. The seaweeds Fucus vesiculosus and Ascophyllum nodosum are significant contributors to coastal iodine emissions. Atmospheric Chemistry and Physics, 13(10), pp.5255-5264.

IAEA, 2004. Sediment distribution coefficients and concentration factors for biota in the marine environment. Technical Report Series No. 422. International Atomic Energy Agency, Vienna.

ICRP (2004). Release of Patients after Therapy with Unsealed Radionuclides. ICRP Publication 94. Ann. ICRP 34 (2).

ICRP (2012). Compendium of Dose Coefficients based on ICRP Publication 60. ICRP Publication 119. Ann. ICRP 41(Suppl.).

ICRP (2015). Occupational Intakes of Radionuclides: Part 1. ICRP Publication 130. Ann. ICRP 44(2).

IPEM, 2018. Institute of Physics and Engineering in Medicine. Advice notice on excretion factors: the percentage of administered radioactivity released to sewer for routinely used radiopharmaceuticals. https://www.ipem.ac.uk/Portals/0/Excretion%20factors%20Sept%202018.pdf?ver=2018-10-03-150031-463

Leblanc, C., Colin, C., Cosse, A., Delage, L., La Barre, S., Morin, P., Fiévet, B., Voiseux, C., Ambroise, Y., Verhaeghe, E. and Amouroux, D., 2006. Iodine transfers in the coastal marine environment: the key role of brown algae and of their vanadium-dependent haloperoxidases. Biochimie, 88(11), pp.1773-1785.

Mettler, F.A., Guiberteau, M.J. 2012. Radioactivity, Radionuclides, and Radiopharmaceuticals. In: Essentials of Nuclear Medicine Imaging (Sixth Edition), Elsevier pp.1-13.

Statens Kartverk, 2008. Den Norske Los, Bind 6, Farvannsbekrivelse: Lødingen og Andenes - Grense Jakobselv. Sjøkartverket, Stavanger.

Prados-Roman, C., Cuevas, C.A., Hay, T., Fernández, R.P., Mahajan, A.S., Royer, S.J., Galí, M., Simó, R., Dachs, J., Großmann, K. and Kinnison, D.E., 2015. Iodine oxide in the global marine boundary layer. Atmospheric Chemistry and Physics, 15(2), pp.583-593.

Saiz-Lopez, A. and Plane, J.M., 2004. Novel iodine chemistry in the marine boundary layer. Geophysical research letters, 31(4).

Saiz-Lopez, A., Plane, J.M., Baker, A.R., Carpenter, L.J., Von Glasow, R., Gómez Martín, J.C., McFiggans, G. and Saunders, R.W., 2012. Atmospheric chemistry of iodine. Chemical reviews, 112(3), pp.1773-1804.

Tinel, L., Adams, T.J., Hollis, L.D., Bridger, A.J., Chance, R.J., Ward, M.W., Ball, S.M. and Carpenter, L.J., 2020. Influence of the sea surface microlayer on oceanic iodine emissions. Environmental Science & Technology, 54(20), pp.13228-13237.

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