Radio Science

RESEARCH ARTICLE
10.1029/2020RS007060

Key Points:

- The study shows that the dry N_d and wet N_w components of the surface refractivity have different mean monthly variability in north and south of Quebec. For all months, the values of N_d are higher in the northern part, whereas the values of N_w are higher in the southern part
- Since the water vapor pressure in Montreal undergoes more significant variation than in Kuujjuaq, for the wet component, there is a significant difference between the variations observed in Montreal than in Kuujjuaq
- The direct smoothing, a forecasting technique which is efficient computationally has been used to estimate the future values of N in Kuujjuaq

Correspondence to:
H. A. Obeidat,
h.obeidat@jpu.edu.jo

Citation:
Bettouche, Y., Obeidat, H. A., Agba, B. L., Kouki, A. B., Mosleh, M. F., AlAbdullah, A. M., & Abd-Alhameed, R. A. (2020). Comparison of surface radio refractivity variability in the northern and southern parts of Quebec, Canada. *Radio Science*, *55*, e2020RS007060. https://doi.org/10.1029/2020RS007060

Received 14 JAN 2020
Accepted 13 APR 2020
Accepted article online 20 MAY 2020

Comparison of Surface Radio Refractivity Variability in the Northern and Southern Parts of Quebec, Canada

Y. Bettouche[1], H. A. Obeidat[2], B. L. Agba[1], A. B. Kouki[1], M. F. Mosleh[3], A. M. AlAbdullah[4], and R. A. Abd-Alhameed[4,5]

[1]Lacime, École de Technologie Supérieure, Montréal, Quebec, Canada, [2]Faculty of Engineering, Jerash University, Jerash, Jordan, [3]College of Electrical Engineering Techniques, Middle Technical University, Baghdad, Iraq, [4]Faculty of Engineering and Informatics, University of Bradford, Bradford, UK, [5]Basra University College of Science and Technology, Basra, Iraq

Abstract Thirty-nine years of archived meteorological data measured at two stations located in the northern and southern parts of Quebec, Canada are used to estimate the surface refractivity and its dry and wet components. The results of the comparison of the obtained estimates showed that for all months the values of the dry component are higher in the northern part, whereas the values of the wet component are higher in the southern part. Due to this, for several months of the year, the values of the surface refractivity are higher in the northern part and for the remaining months in the southern part. Moreover, in both parts, August is the month where the highest values of the surface refractivity were recorded. In this particular month, the slope of the surface refractivity trend in the northern part is several times higher than that in the southern part. The obtained results show that the performance of the used direct smoothing forecasting technique depends on the deviation between the values of N in the current year and the previous year.

1. Introduction

For transmitting audio or/and video data from the transmitter to receiver the terrestrial fixed radio links operating at microwave frequencies on line-of-sight (LOS) are frequently used (Bean, 1962; Bogucki & Wielowieyska, 2009; Grabner et al., 2010). However, the performance of the transmission depends on the equipment used, as well as the values of the meteorological parameters present in the transmission medium (troposphere in this case). The troposphere is the region of the atmosphere that extends from the surface of the Earth up to a height of 8–10 km at polar altitudes, 10–12 km at moderate latitudes, and up to 18–19 km at the equator (Adediji et al., 2007; Grabner et al., 2012). The temperature, pressure, and relative humidity are the main parameters whose variability has an important impact on the quality of the propagation of radio waves (Ali et al., 2012; Grabner & Kvicera, 2003; ITU, 2015; Kablak, 2007; Priestley & Hill, 1985). Therefore, in the design of communication systems, it is necessary to consider this variation. The atmospheric refractivity N is generally used as a metric for this purpose. The International Telecommunication Union (ITU) provides a procedure to find the value of N (ITU, 2015) when the correspondent meteorological parameters are known.

Authors in Bean and Cahoon (1961) and Adediji et al. (2017) showed that there is a high correlation between the surface refractivity and the field strength; through the magnitude of the electromagnetic field which will induce a voltage that will be the input signal for the receiver. In AbouAlmal et al. (2015) authors used local surface meteorological data measured over 17 years from six stations and one radiosonde to estimate and compare the surface refractivity profiles in the United Arab Emirates (UAE). The obtained results were different from the values provided by the ITU. Hence, there is a need to explore always locally measured data as recommended by the ITU. However, this study did not analyze the trend of the surface refractivity over the considered period. In Adediji (2017) the author presented the obtained results of the variability of surface refractivity estimated based on 2 years measured meteorological data at three stations located at the southwestern, north central, and southeastern of Nigeria. However, this is not enough to draw general conclusions since the analyzed period was limited to 2 years only. In Ayantunji et al. (2011) authors presented

Table 1
A Sample of The Collected Data for 2013

Date	Time	Temperature, t (°C)	Dew temperature, tr (°C)	Relative humidity, H (%)	Pressure, P (kPa)
1-8-2013	00:00	11.5	9.1	85	100.74
	01:00	11.2	9.2	87	100.72
	—	—	—	—	...
	23:00	8.5	6.9	90	100.66
—	—	—	—	—	—
31-8-2013	00:00	3.2	0.3	81	100.12
	01:00	2.9	−0.6	78	100.11
	02:00	1.8	0	88	100.12
	—	—	—	—	—
	23:00	4.3	0.2	75	100.89

Note. Dates are formated as day-month-year.

an analysis of seasonal variation of surface refractivity over Nigeria; however, data of only 2 years had been used.

Other metrics are used to evaluate the quality of the propagation, including refractivity gradient dN in the first 1 km above the surface (Bean et al., 1963; Lane & Bean, 1963; Valma et al., 2011) and the equivalent gradient G_e (Misme, 1960). Authors in Valma et al. (2011) studied the variations of radio refractivity and its vertical gradient in Lithuania, they found that the radio refractivity and its vertical gradient could change as the weather suddenly becomes significantly colder. In Lane and Bean (1963) there is a correlation coefficient of 0.7 between dN and the field strength while propagating at VHF (very high frequency) band.

In order to ensure the accuracy of these approaches, it is required to use radiosonde data. In our case only the meteorological data measured at the surface are available. The surface refractivity N can be easily evaluated from the measurements of temperature, pressure, and relative humidity. For this reason, here we will use only surface refractivity.

In this study, the meteorological data collected over the last 39 years from one station located at the northern part and another at the southern part of Quebec are used in the formulae provided by the ITU recommendations to estimate the surface refractivity. The main contributions of this paper are as follows:

1. To give a detailed comparison of the variability of surface refractivity in the northern and southern parts of Quebec. This is motivated by the fact that the two parts are located in different climatic zones.
2. To propose a forecasting technique which has a good performance as well as it requires little calculations.

The organization of the paper is as follows: Section 2 describes the used approach to estimate surface refractivity. While section 3 presents an analysis of the obtained results. Finally, conclusions are drawn in section 4 .

2. Used Approach

2.1. Data

The used meteorological data are measured from the Kuujjuaq and Montreal stations. The Kuujjuaq station is located in the northeast of Quebec at 58.1° latitude and −68.42° longitude, with an altitude of 39.9 m above sea level. The Montreal station is located in the southeast of Quebec at 45.7° latitude and −73.74° longitude, with an altitude of 32.1 m above sea level. The government of Canada provides local climatic parameters (temperature, dew temperature, humidity, pressure, etc.) stored in raw CSV format (Government of Canada, 2019). These files are converted into Excel files for further processing. A sample of the collected data is shown in Table 1.

2.2. Methodology

It is well known that the surface refractivity has dry N_d and wet N_w components. These components are determined by (ITU, 2015)

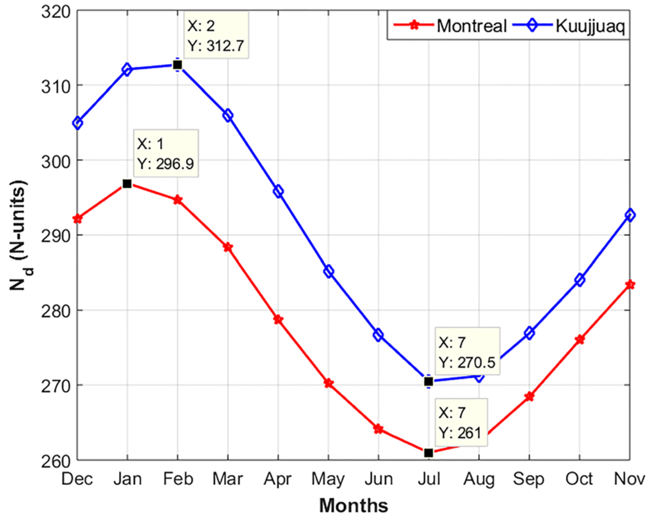

Figure 1. Mean monthly variations of dry components.

$$N_d = 77.6\frac{P_d}{T} \tag{1}$$

where T is the absolute temperature (K), P_d is the dry atmospheric pressure (hPa) which is given by

$$P_d = P - e \tag{2}$$

where P is the total atmospheric pressure (hPa) and e is the water vapor pressure (hPa).

$$N_w = 72\frac{e}{T} + 3.75\frac{e}{T^2} \tag{3}$$

As seen in Equations 1 and 3, the dry component varies with both pressure and temperature, while the wet component depends on the values of humidity and temperature. The water vapor pressure in hPa is determined by (ITU, 2015)

$$e = \frac{He_s}{100} \tag{4}$$

where H is the relative humidity (%), and e_s is the saturation vapor pressure (hPa) determined by

$$e_s = EF_{\mathrm{water}} \cdot a \cdot \exp\left[\frac{bt - \frac{t^2}{d}}{t + c}\right] \tag{5}$$

where t is the temperature (°C), $a = 6.1121$; $b = 18.678$; $c = 257.14$; $d = 234.5$, and

$$EF_{\mathrm{water}} = 1 + 10^{-4}\left[7.2 + P\left(0.032 + 5.9 \times 10^{-6}t^2\right)\right] \tag{6}$$

3. Results and Analysis

The available measured data at Kuujjuaq and Montreal stations are used to estimate the surface refractivity and its dry and wet components. Note that in reference (Bettouche et al., 2019) the authors have used only data collected at the Kuujjuaq. This manuscript completes the previous work by comparing the variations of N in northern (Kuujjuaq) and southern (Montreal) parts of Quebec. We also use a forecasting technique to estimate future values of N in Kuujjuaq. Which had not been done in the previous paper.

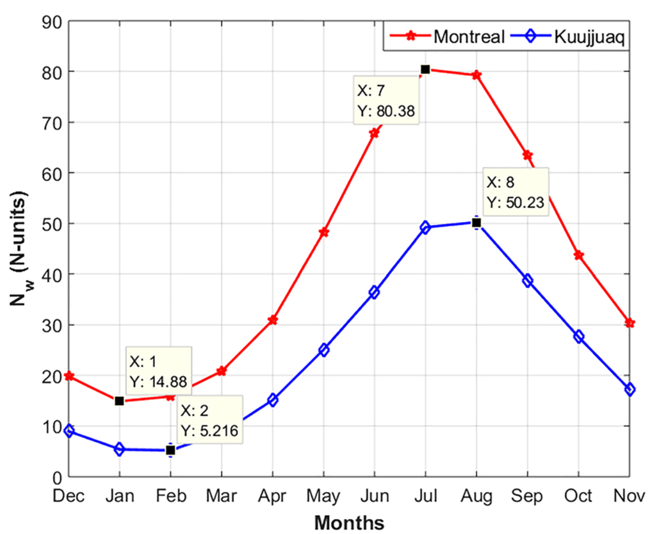

Figure 2. Mean monthly variations of wet components.

3.1. Analysis of the Surface Refractivity (N)

The refractivity N at some altitude h above the sea level, and the sea level refractivity N_0 are related by (Adediji, 2017)

$$N = N_0 e^{\left(\frac{-h}{h_0}\right)} \tag{7}$$

where h is the height of the earth's surface above sea level and $h_0 = 9.5$ km. Considering the altitudes of Kuujjuaq and Montreal stations and Equation 7 there will not be a significant difference between the values of N and N_0. For this reason, our analysis will be based on the values of N.

Figure 1 shows the mean monthly variations of N_d for the considered stations. From this figure, it is clear that the values of N_d in Kuujjuaq for all

Table 2
Difference Between the Maximum and Minimum Values of N_d and N_w in Montreal and Kuujjuaq

Station	ΔN_d	ΔN_w
Montreal	35.9	65.5
Kuujjuaq	42.2	45.014

months are higher than the correspondent values in Montreal; this is because the dry atmospheric pressure, which determines the value of the dry component, is always higher in Kuujjuaq than in Montreal. Figure 1 shows that the values of N_d are higher in the winter season compared to other seasons because in winter the dry atmospheric pressure which determines the value of the dry component is always higher than in other seasons. The maximum and minimum values of N_d are shown in the figure. As seen, in Kuujjuaq the maximum and minimum values are 312.7 N units (in February) and 270.5 N units (in July). It is worth mentioning that the maximum values in Kuujjuaq and Montreal occurred in February and January, respectively. This is mainly because the maximum value of the dry atmospheric pressure occurs in these months.

Figure 2 shows the mean monthly variations of N_w for the two stations. From Figure 2, we see that for N_w the values in Montreal for all months are higher than the corresponding values in Kuujjuaq, the value of the wet component is mainly determined by the water vapor pressure; in Kuujjuaq the value of the water vapor pressure is always lower than in Montreal. The maximum and minimum values of N_w are shown in the figure where values are always higher in summer compared to other seasons since the water vapor pressure, which determines the value of the wet component, is always higher in summer. It is worth mentioning that the minimum values in Kuujjuaq and Montreal occurred in February and January, respectively, this is because the minimum values of the dry atmospheric pressure occur in these months.

Table 2 shows the values of the difference between the maximum and minimum values of N_d and N_w in Montreal and Kuujjuaq. From the table, it can be concluded that in Montreal there is a relatively significant difference between the maximum and minimum values of N_w, this is because the water vapor pressure in Montreal undergoes more significant variation in Montreal than in Kuujjuaq. Table 3 shows the correlation between mean monthly values of N and temperature as well as water vapor.

Analysis of the data shown in Table 3 and the variations of wet components from Figure 2 show that the difference between the values of N_w is particularly important for months (July and August) with a high correlation coefficient between N and e in both locations of Montreal and Kuujjuaq. Therefore, the humidity has more impact on the value of refractivity in the south than in the north. Figure 3 shows the mean monthly variations of N for the two stations.

As seen in Figure 3, the values of N in Kuujjuaq are higher than the values in Montreal for the months: December, January, February, March, and April (these are mainly in winter and spring seasons). While for the majority of summer and autumn months, the values of N tend to be higher in Montreal. These variations are due to the variations of N_w. As it is seen from Figure 2 for the months from May to November the values of N_w in Montreal are much higher than the values for the months from December to April. Also from Figure 4, it is clear that the relative contribution of N_w to N is higher for the months from May to November in both locations. In Montreal, the highest relative contribution of N_w to N lies in July (23.55%), while the lowest contribution (4.773%) is found to be in January. In Kuujjuaq the maximum and minimum relative contributions lie in August (15.63%) and February (1.641%), respectively. However, for a given station the relative contributions of N_w to N for the months of July and August are similar.

Table 3
The Correlation Between Mean Monthly Values of N and Temperature as Well as Water Vapor

	Montreal			Kuujjuaq		
Month	T (K)	e (hPa)	P (hPa)	T (K)	e (hPa)	P (hPa)
Dec	0.13	0.32	0.58	−0.81	−0.65	0.56
Jan	−0.46	−0.28	0.74	−0.92	−0.81	0.71
Feb	−0.07	0.17	0.72	−0.85	−0.70	0.44
Mar	0.06	0.53	0.50	−0.74	−0.65	0.26
Apr	0.14	0.84	0.01	−0.50	−0.27	0.62
May	0.45	0.93	0.14	0.17	0.53	0.22
Jun	0.44	0.97	−0.07	0.44	0.79	0.34
Jul	0.37	0.96	−0.05	0.71	0.96	−0.18
Aug	0.51	0.95	−0.04	0.61	0.95	0.08
Sep	0.84	0.97	0.13	0.59	0.91	0.11
Oct	0.89	0.97	0.22	0.59	0.79	0.39
Nov	0.66	0.85	0.12	−0.23	−0.02	0.70

Figure 5 shows the mean yearly variation of refractivity and its linear trend from 1981 to 2019 in Montreal and Kuujjuaq. Here and in the rest of this document, it is assumed that the variable x represents a specific year in the analyzed period. The linear trend for Montreal follows the model: $0.015x + 320$, while for Kuujjuaq it follows the model: $0.0048x + 310$. These trends are shown in Figure 5. Therefore, starting from 1981, each year, N increases by 0.015 and 0.0048 N unit in Montreal and Kuujjuaq, respectively. Thus, the increase of N trend in Montreal is significantly greater than in Kuujjuaq.

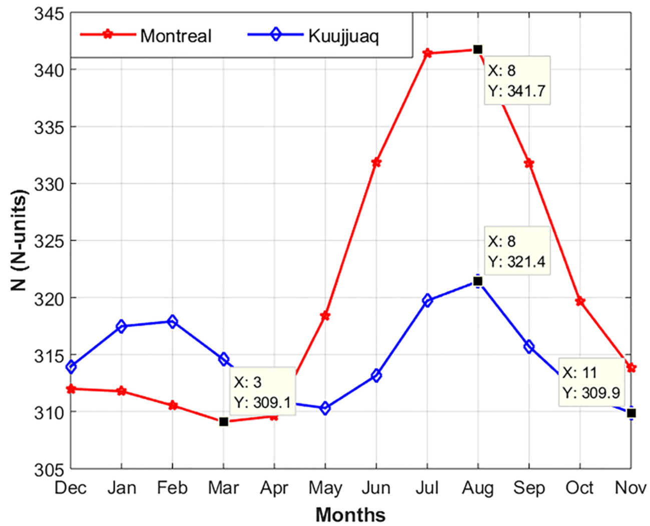

Figure 3. Mean monthly variation of refractivity.

Figure 6 shows the mean yearly cumulative distribution over the analyzed period for the two stations. Analysis of distributions from Figure 6 shows that for a percentage of time less than 10%, the worst location (location with highest values of *N*) is Kuujjuaq. For all remaining time percentages, the worst location is Montreal.

3.2. Analysis of Refractivity for the Worst Month

For each station, we have selected the month with the maximum value of *N* (worst month). This month for both stations is August. Figure 7 shows the corresponding variations of *N* and their trends over the analyzed period.

The values of *N* in Montreal are significantly higher than in Kuujjuaq. Our analysis shows that for both stations the variance has a minimum value when the variation of *N* is modeled as a linear trend process rather than a constant process. The equations for linear trends shown in Figure 7 are $0.1414x + 318.8$ and $0.0348x + 341$ for Kuujjuaq and Montreal, respectively. These equations show that in the northern part of

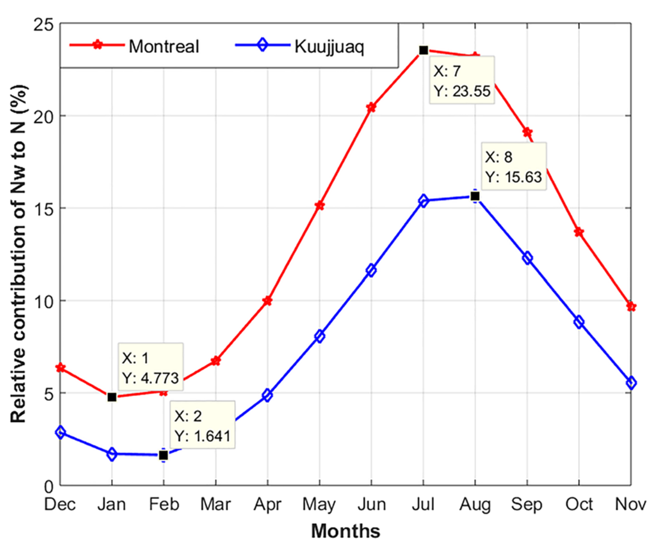

Figure 4. Mean monthly relative contribution of N_w to *N*.

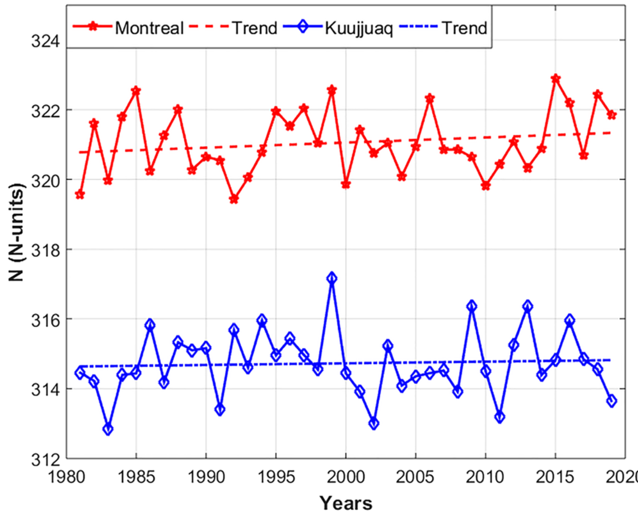

Figure 5. Mean yearly variation of refractivity.

Quebec there is a relatively high increase (0.1414 *N* unit each year) in comparison to the southern part where the increase is only 0.0348 *N* unit each year.

Since the station Kuujjuaq has the highest slope for the variation of *N* in the rest of this section, we propose a procedure to estimate future values of *N*. The procedure is based on the use of the so-called direct smoothing (Douglas et al., 1990). The main advantage of direct smoothing is that it is computationally efficient. According to this forecasting technique, the new model parameters are obtained from the previous parameters by adding the current period's forecast error weighed with some coefficient. The forecast value of *N* at some period *T* is (Douglas et al., 1990)

$$N_f(T) = a_1(T) + a_2(T) \tag{8}$$

where $a_1(T)$ and $a_2(T)$ are the model parameters determined for the period T:

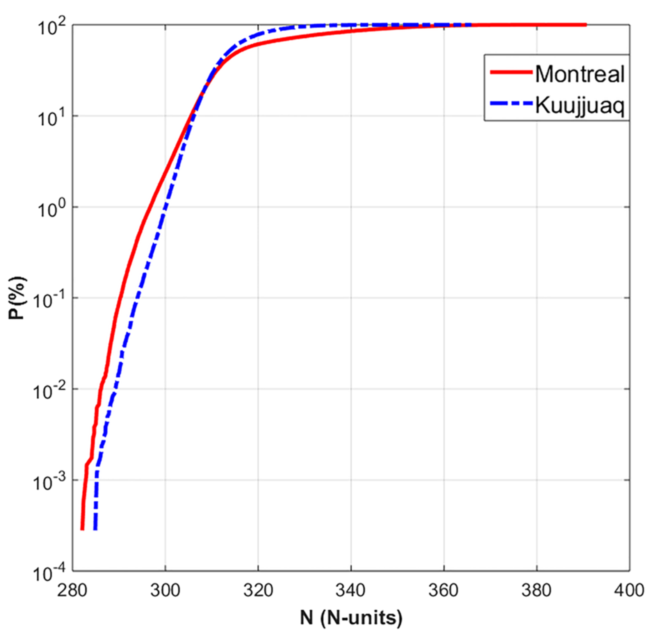

Figure 6. Mean yearly PDF of *N*.

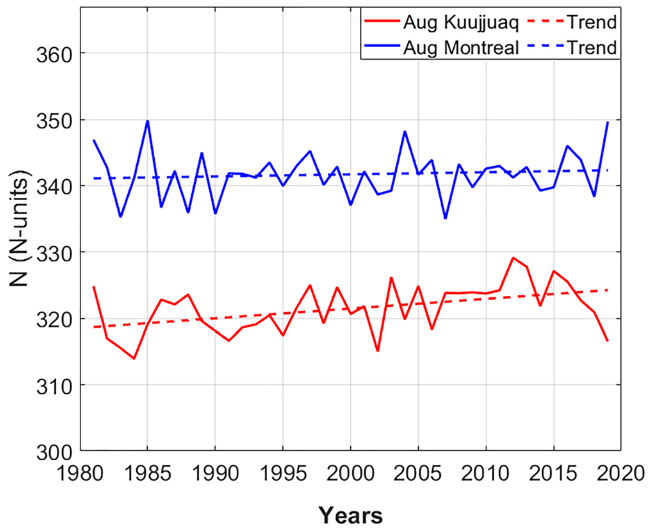

Figure 7. Average yearly variations of N for the worst month.

$$\begin{cases} a_1(T) = a_1(T-1) + a_2(T-1) + \left(1-\beta^2\right)e(T) \\ a_2(T) = a_2(T-1) + (1-\beta)^2 e(T) \end{cases} \tag{9}$$

In Equation 9, $e(T)$ is the forecast error (the difference between the observed value $N(T)$ and the forecast for that value $N_f\,(T)$)

$$e(T) = N(T) - N_f(T) \tag{10}$$

Note that in order to estimate $N_f(T)$, the initial values of $a_1(0)$ and $a_2(0)$ are required. In our case, we consider $a_1(0)$ and $a_2(0)$ as intercept and slope of the obtained linear trend based on the first 25 years historical data of N. We get: $a_1(0) = 318.828$ and $a_2(0) = 0.1263$.

The variable β in Equation 9 is the discount factor, whose value lies in the interval $0 < \beta < 1$. In this case to select the optimal value of β we use the value which yields the minimum value of the sum of the squares of the deviations between the observed values of N and the corresponding forecasts for the remaining 14 years

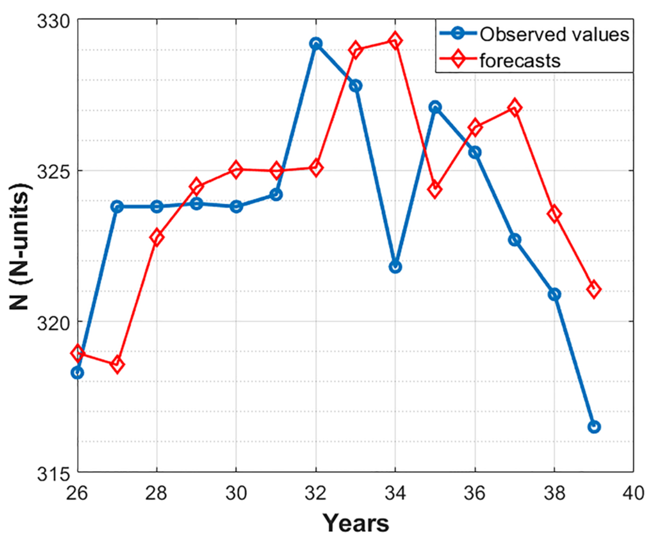

Figure 8. Observed of N and forecasts for the last 14 years of the analyzed period.

historical data when β is set in the interval 0.1 to 0.9 with a step 0.1. Remember that in the analysis data collected over a period of 39 years are used. Since data for the first 25 years have been used for estimating the initial values of the model parameters, it will remain the only data for 14 years. The data for these remaining years are used for estimating the forecast. We found that the optimal value of β is 0.6. For this value of β, Figure 8 shows the observed values and forecasts obtained using the described procedure above for the remaining last 14 years of the analyzed period.

From Figure 8 we can conclude that forecasts are relatively far from the observed values for years where the observed value is far away from the previous year. Thus, the performance of the used forecasting technique depends on the deviation between the values of N of the current year and the previous year.

4. Conclusion

The main findings in the performed study are as follows: The dry component is the main component of N in the north and south of Quebec. For all months, the values of N_d are higher in the northern part. For the wet component N_w, it was found that the values are higher in the southern part for all months. The highest values of N lie in summer, particularly in the month of August in the north, as well as in the south. However, for this month, the slope of the surface refractivity trend in the northern part is several times higher than that in the southern part, whereas the intercept in the south is higher than that in the north. Our results show that although a direct smoothing requires a little computation, it is a relatively good performance.

Acknowledgments

All measured data are available in the following link (https://zenodo.org/record/3607942#.Xh3VScgzbIU).

References

AbouAlmal, A., Alhassan, H., Obeidat, H., Abusitta, M., Abd-Alhameed, R., Jones, S., & Al-Ahmad, H. (2015). Surface refractivity profile and validation of measurements in Arabian Gulf region. Paper presented at the 2015 Loughborough Antennas & Propagation Conference (LAPC).

Adediji, A. (2017). Reduced-to-sea-level value of microwave radio refractivity over three stations in Nigeria. *Nigeria Journal of Pure and Applied Physics*, *7*(1), 19–25.

Adediji, A., Adebusola, S., & Ojo, J. (2017). Variability of microwave radio refractivity and field strength over some selected locations in Nigeria. *Physical Science International Journal*, *14*(3), 1–11. https://doi.org/10.9734/PSIJ/2017/33447

Adediji, A., Ajewole, M., Falodun, S., & Oladosu, O. (2007). Radio refractivity measurement at 150 m altitude on TV tower in Akure, South West Nigeria. *Journal of Engineering and Applied Sciences*, *2*(8), 1308–1313.

Ali, S., Malik, S. A., Alimgeer, K. S., Khan, S. A., & Ali, R. L. (2012). Statistical estimation of tropospheric radio refractivity derived from 10 years meteorological data. *Journal of Atmospheric and Solar-Terrestrial Physics*, *77*, 96–103. https://doi.org/10.1016/j.jastp.2011.12.001

Ayantunji, B., Okeke, P., & Urama, J. (2011). Seasonal variation of surface refractivity over Nigeria. *Advances in Space Research*, *48*(12), 2023–2027. https://doi.org/10.1016/j.asr.2011.08.025

Bean, B., & Cahoon, B. (1961). Correlation of monthly median transmission loss and refractive index profile characteristics. *Journal of Research NBS*, *65*(1), 67–74.

Bean, B., Frank, V., & Lane, J. (1963). A radio meteorological study, part II. An analysis of VHF field strength variations and refractive index profiles. *Journal of Research NBS D*, *67*, 597–604.

Bean, B. R. (1962). The radio refractive index of air. *Proceedings of the IRE*, *50*(3), 260–273. https://doi.org/10.1109/JRPROC.1962.288318

Bettouche, Y., Obeidat, H., Agba, B., Kouki, A., Alhassan, H., Rodriguez, J., et al. (2019). Long-term evolution of the surface refractivity for Arctic regions. *Radio Science*, *54*, 602–611.

Bogucki, J., & Wielowieyska, E. (2009). Empirical season's fadings in radio communication at 6 GHz band. *Journal of Telecommunications and Information Technology*, *2*, 48–52.

Douglas, C. M., Lynwood, A. J., & John, S. (1990). *Forecasting and time series analysis* (2nd ed.). Columbus, OH: McGraw-Hill, Inc.

Government of Canada (2019). Données climatiques historiques. Retrieved from http://climat.meteo.gc.ca/

Grabner, M., & Kvicera, V. (2003). Clear-air propagation modeling using parabolic equation method. *Radioengineering-Prague*, *12*(4), 50–54.

Grabner, M., Kvicera, V., Pechac, P., & Jicha, O. (2012). Parameters of vertical profiles of temperature humidity and refractive index of air in the lowest troposphere. Paper presented at the Proceedings of 9th international symposium on tropospheric profiling (ISTP).

Grabner, M., Kvicera, V., Pechac, P., & Mudroch, M. (2010). Multipath fading measurement and prediction on 10 GHz fixed terrestrial link. Paper presented at the 15th conference on microwave techniques COMITE 2010.

ITU (2015). ITU-R P.453–11: The radio refractive index: its formula and refractivity data. Retrieved from Geneva.

Kablak, N. (2007). Refractive index and atmospheric correction to the distance to the Earth's artificial satellites. *Kinematics and Physics of Celestial Bodies*, *23*(2), 84–88. https://doi.org/10.3103/S0884591307020079

Lane, J., & Bean, B. (1963). A radio meteorological study, part 1. *Existing radio meteorological parameters*, 589–604.

Misme, P. (1960). Models of the atmospheric radio refractive index. *Proceedings of the Institute of Radio Engineers*, *48*(8), 1498–1499.

Priestley, J., & Hill, R. (1985). Measuring high-frequency humidity, temperature and radio refractive index in the surface layer. *Journal of Atmospheric and Oceanic Technology*, *2*(2), 233–251. https://doi.org/10.1175/1520-0426(1985)002<0233:MHFHTA>2.0.CO;2

Valma, E., Tamosiunaite, M., Tamosiunas, S., Tamosiuniene, M., & Zilinskas, M. (2011). Variation of radio refractivity with height above ground. *Elektronika ir Elektrotechnika*, *111*(5), 23–26.