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Examining the use of the NeQuick bottomside and topside parameterizations at high latitudes

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Abstract

The NeQuick electron density model, similarly to the IRI, provides a global 3D representation of ionospheric electron density. This study addresses the high latitude representation of the F2 bottomside and topside by the NeQuick model; specifically, this study looks at the method used to parameterize the thickness of the bottomside and topside of the F2 peak, focusing on the use of the NeQuick topside parametrization for the topside extrapolation of ionosonde-derived bottomside profiles and its use in the IRI model.

For the bottomside, we present a comparison between modelled and measured B2Bot thickness parameter. In this comparison, we show that the use of the NeQuick parameterization at high latitudes results in significantly underestimated bottomside thicknesses, regularly exceeding 50%. We show that these errors can be attributed to two main issues in the NeQuick parameterization: 1) through the relationship relating foF2 and M3000F2 to the maximum derivative of F2 electron density, which is used to derive the bottomside thickness, and 2) through a fundamental inability of a constant scale thickness, semi-Epstein shape function to fit the curvature of the high latitude peak electron density region.

For the topside, a comparison is undertaken between the NeQuick topside thickness parameterization, using measured and IRI-modelled ionospheric parameters, and that derived from fitting the NeQuick topside function to Incoherent Scatter Radar-measured topside electron density profiles. Through this comparison, we show that using CCIR-derived foF2 and M3000F2, used in both the NeQuick and IRI, results in significantly underestimated topside thickness during summer periods, overestimated thickness during winter periods, and an overall tendency to underestimate diurnal, seasonal, and solar cycle variability. These issues see no improvement through the use of measured foF2 and M(3000)F2 values. Such measured parameters result in a significant tendency for the parametrization to produce a declining trend in topside thickness with increasing solar activity, to produce damped seasonal variations, and to produce significantly overestimated topside thickness during winter periods.

1. Introduction

The NeQuick electron density model, similarly to the International Reference Ionosphere (IRI), provides a global 3D representation of ionospheric electron density [1]. The model uses a series of semi-Epstein layers with single thickness parameters to represent electron density from the lower E-region up to the upper topside at 2000km. These layers are represented by the following parameterization

$$N(h) = \frac{4N_{max}}{(1+\exp(z))^2}\exp(z) \tag{1}$$

$$z = \frac{h-hmax}{H} \tag{2}$$

where $N(h)$ is the electron density at height h, H is the layer thickness parameter, N_{max} is the peak ionospheric electron density of the layer, and $hmax$ is the layer peak height.

While, like the IRI, the NeQuick model can be considered reasonably accurate at mid latitudes, its application at high latitudes remains untested. That said, it is expected that the NeQuick model suffers similar limitations as those of the IRI [2,3] due to their common use of the same critical frequency (foF2) maps, their similar hmF2 parameterizations, their common use of the CCIR Maximum Usable Frequency (MUF) maps, and their shared use of the NeQuick topside parameterization.

The present study focuses on the NeQuick's representation of the F-layer, particularly the topside thickness parameter, as it is an integral part of both the NeQuick and IRI topside parameterizations.

2. Bottomside Thickness

Despite our focus on the topside thickness, the NeQuick topside parameterization is highly reliant on the calculated bottomside thickness. The NeQuick F2 bottomside thickness parameter is given by the following relationship

$$\ln\left(\left(\frac{dN}{dh}\right)_{max}\right) = -3.467 + 1.714\ln(foF2) + 2.02\ln(M(3000)F2) \tag{3}$$

$$B2_{Bot} = \frac{0.365NmF2}{(dN/dh)_{max}} \tag{4}$$

Where foF2 is the peak critical frequency of the F-layer, M(3000)F2 is the propagation factor, and B2Bot is the bottomside thickness parameter The first of the above parameterizations is empirically derived based on the work of [4]. The second relationship is analytically derived assuming that the semi-epstein function can properly represent the shape of the F-region bottomside.

To evaluate the use of these parameterizations at high latitudes, we make use of a Canadian Advanced Digital Ionosonde (CADI) operated by the Canadian High Arctice Ionospheric Network (CHAIN) at Resolute, Canada (74.75N, 265.00E) [5]. From this ionosonde, we can calculate the expected B2Bot from measured foF2 and M(3000)F2 values, analytically calculate the maximum derivative of the vertical electron density profile to ultimately derive B2Bot from the NeQuick parameterization function, or use a least squares fit of the semi-epstein layer function to the ionosonde-derived electron density to derive a measured B2Bot value. In Figure 1, we undertake all three of the above evaluations of B2Bot and plot the resulting monthly median values for all available data at Resolute. We also using IRI-derived foF2 and M(3000)F2 to come to a modeled B2Bot estimate.

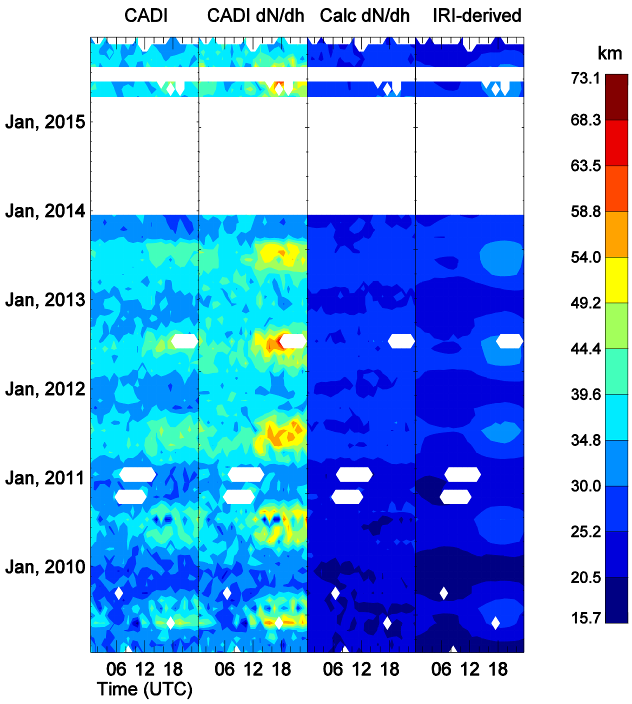

Figure 1. Monthly median B2Bot calculated by fitting to ionosonde electron density profiles (left column), using Equation (4) with ionosonde-calculated $(dN/dh)_{max}$ (center-left column), using the full NeQuick relationship with ionosonde measured foF2 and M(3000)F2 (center-right column), and using the NeQuick relationship with IRI derived parameters (right column)

From this figure, it becomes very clear that the B2Bot values that are calculated using Equation (3) and (4) lead to significantly underestimated B2Bot values regardless of the source of foF2 and M(3000)F2 values. Interestingly, even the use of ionosonde-derived $(dN/dh)_{max}$ exhibits some appreciable errors, particularly during the summer. These errors imply that the high latitude daytime F-layer does not adequately follow a semi-epstein shape to ensure the validity of Equation (4). This is further illustrated in Figure 2, where we present the fitted B2Bot plotted against the variable term on the right hand side of Equation (4).

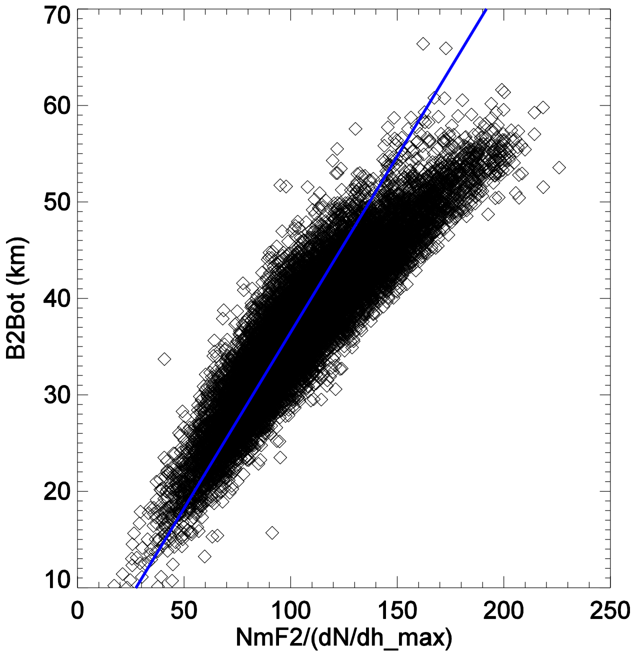

Figure 2. Plot of fitted B2Bot vs. the NmF2 to $(dN/dh)_{max}$ ratio (black points). The blue line represents the expected relationship given Equation (4).

As you can see, there is a significant departure from expectation at high thicknesses. This difference could result from the fact that the F1-ledge is not well defined at these latitudes.

Overall, the above results suggest that Equation (3) should be revised to account for potential regional variations in such a relationship. The question remains, do these issues materialize in the topside thickness as well?

3. Topside Thickness

Similar to the bottomside, the topside is modeled by a simple semi-epstein layer with a single thickness parameter [6]. The topside thickness is directly related to that of the bottomside via the following relationship

$$H_0 = k \cdot B2Bot \quad (5)$$

The k parameter in the above relationship is given by

$$k = 3.22 - 0.0538 foF2 - 0.00664 hmF2 + 0.113 \frac{hmF2}{B2_{Bot}} + 0.00257 R12 \quad (6)$$

To examine the performance of the above relationships as they apply to the high latitude ionosphere, we make use of Incoherent Scatter Radar (ISR) data from the Resolute (RISR-N) and Poker Flat (PFISR) ISRs. The topside thickness from these ISRs is calculated by fitting ISR electron density profiles to the NeQuick topside function, fitting for H_0. In Figure 3, we present the monthly median

H_0 values at RISR-N calculated from directly fitting the electron density profile, by using ISR-measured $(dN/dh)_{max}$ and NmF2, and by using the full NeQuick parameterization with IRI values of foF2, M(3000)F2, and hmF2.

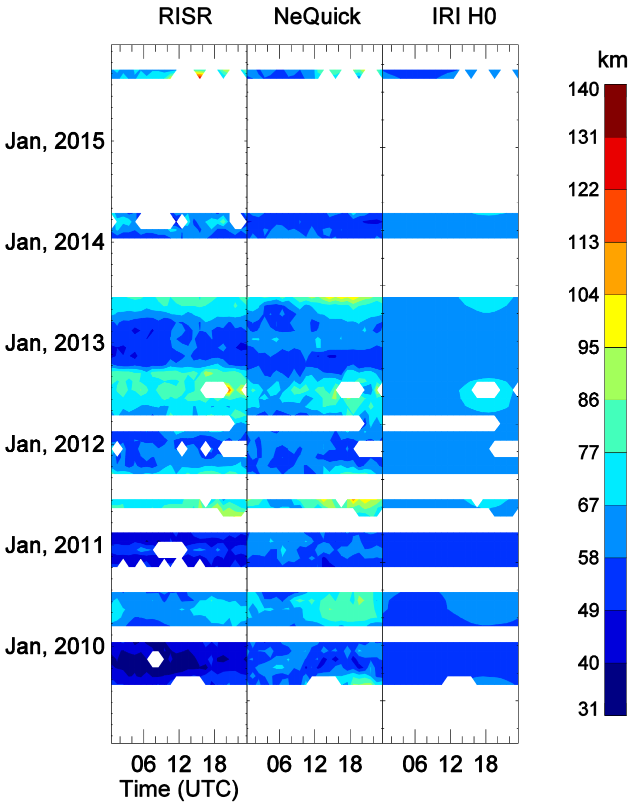

Figure 3. Monthly median topside thickness at RISR-N as fitted from electron density profiles (left column), derived using measured bottomside parameters (center column), and derived using IRI-derived bottomside parameters (right column).

As you can see in Figure 3, the use of IRI-derived parameters with the full NeQuick parameterization results in significantly underestimated H_0 values during summer periods and a very damped seasonal variation, as compared to observation. The use of measured $(dN/dh)_{max}$ results in a much more realistic seasonal variation in H_0; however, it also results in a more significant overestimation of winter thickness. This result is somewhat interesting for ionosonde users who intend to use the NeQuick topside function to extrapolate the topside from bottomside ionograms at high latitudes; however, despite the improved seasonal variability, measured $(dN/dh)_{max}$ still appears to significantly overestimate H_0 during winter periods, performing worse than the IRI.

In Figure 4, we present the results for the PFISR system, which is located within the auroral oval region. The larger and more continuous dataset at PFISR allows us to further examine the performance of the NeQuick topside for ionogram-derived topside electron density extrapolation, as well as assess the performance of the parameterization in the auroral oval region. This larger dataset highlights some remaining issues with the use of the NeQuick topside profile function for bottomside extrapolation: 1) we see an opposite solar cycle variation in the NeQuick-calculated H_0, which culminates in an overestimation of daytime H_0 at solar minimum, 2) seasonal variability in NeQuick-derived H_0 is damped with respect to that fitted from ISR topside profiles, and 3) NeQuick-derived H_0 is significantly overestimated during winter periods. These results are all consistent with the observations of RISR-N; however, the IRI appears to perform better within the auroral oval region.

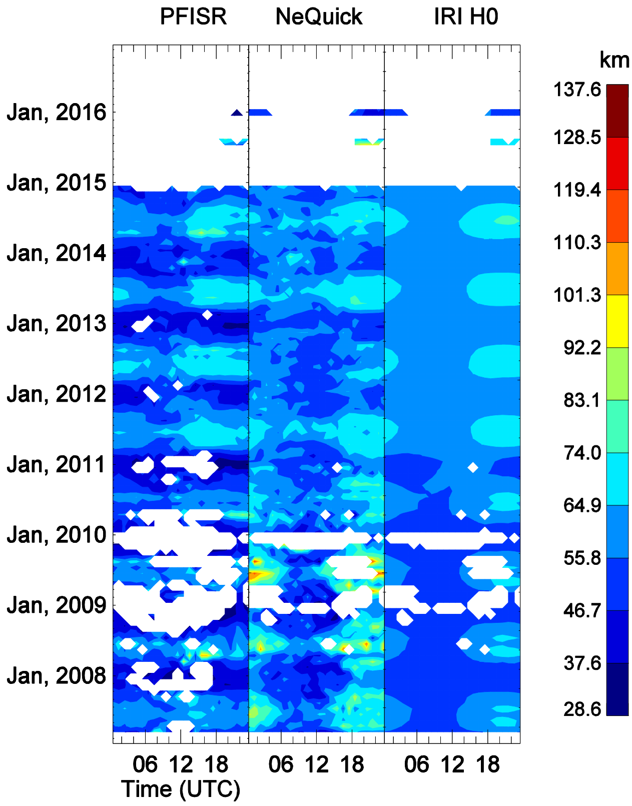

Figure 4. Same as Figure 3 but for PFISR.

Figure 4 also provides a clearer picture of the trends in IRI-derived H_0 that are difficult to fully grasp in Figure 3 at Resolute. From this figure, we see that daytime topside thickness is actually well matched by the IRI during summer periods while topside thickness is overestimated during virtually all other periods.

In Figure 5, we present the monthly RMS errors in topside thickness as derived using measured and IRI parameters. Despite the tendency for the IRI to underestimate diurnal and seasonal variability, we see in Figure 5 that the IRI, in fact, outperforms the use of measured bottomside parameters by a significant margin, particularly during solar minimum. This, however, by no means implies that the IRI parameters produce good agreement with observation, as it is still producing errors of 10% - 35%. Rather, these results imply that not only does the bottomside $(dN/dh)_{max}$ parameterization need to be adjusted for regional variations, the NeQuick topside parameterization itself needs to be adjusted to address its aforementioned shortcomings.

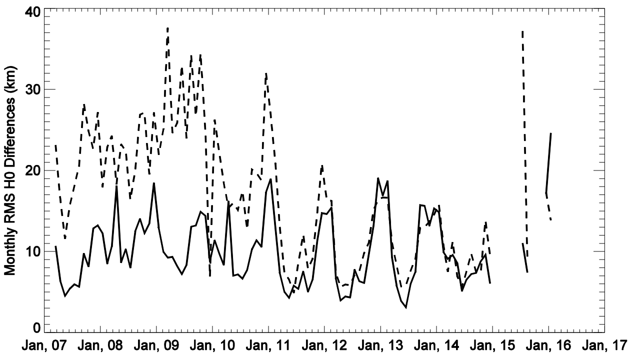

Figure 5. Monthly RMS errors in topside thicknesses derived using IRI bottomside parameters (solid line) and using measured bottomside parameters (dashed line) at PFISR.

4. Conclusions

In this study, we examine the performance of the NeQuick bottomside and topside parameterizations in their application at high latitudes. Through this study, we have shown that errors in the NeQuick's $(dN/dh)_{max}$ parameterization are producing significant errors in bottomside thickness, whereby this thickness can be underestimated by more than 50%. On top of this, even the use of measured $(dN/dh)_{max}$ produced measurable errors in bottomside thickness, particularly for periods with high thickness.

These errors in bottomside thickness, although expected to result in significant topside thickness underestimation, did not appear to be the dominant driver in observed topside thickness errors; in fact, topside errors were significantly lower in the case of using IRI bottomside parameters with the full NeQuick parameterization rather than that which used measured bottomside parameters and bypassed the NeQuick's $(dN/dh)_{max}$ parameterization. This was particularly true for the PFISR system, located within the auroral oval, during solar minimum periods.

Despite the IRI performing better than bottomside extrapolation, it still produced errors in topside thickens of between 10% and 35%, particularly during winter periods. These results imply that not only does the bottomside $(dN/dh)_{max}$ parameterization need to be adjusted for regional variations, the NeQuick topside parameterization itself needs to be adjusted to address its aforementioned shortcomings.

5. Acknowledgements

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