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An improved bottomside for the ionospheric electron density model NeQuick

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Abstract
The ionospheric electron density model NeQuick is a «profiler» which uses the peaks of the *E*-layer, the *F*1-layer and the *F*2-layer as anchor points. In the version prepared for and submitted to the International Telecommunication Union (ITU) the model uses the ITU-R (CCIR) maps for *foF*2 and *M*(3000)*F*2 and adapted maps similar to the ITU-R ones for *foE* and *foF*1. Since users found problematic behaviour of NeQuick under conditions of strong differences of *foE* and *foF*2 map structures, the profiling was adapted by changing the properties of the Epstein layers used for this purpose. The new formulation avoids both strange horizontal structures of the geographic distribution of electron density in fixed heights and unrealistic peculiarities of the height profile which occasionally occurred with the old version of the model. Since the Epstein layer approach allows for 8 parameters only (3 layer amplitudes and 5 semi-thicknesses) the adaptation was no minor task but needed careful planning of suitable strategies.

Key words *ionosphere – electron density models – profilers*

1. Introduction: the NeQuick formulation

The purpose of this paper is to present the reasons for the revision of the bottomside of the three dimensional and time dependent electron density model NeQuick (Radicella and Leitinger, 2001) and to show some of the improvements gained by the revision.

NeQuick was submitted to ITU-R by the European Space Agency and was accepted by the relevant ITU-R authorities in July 2000. Source code, executable and two driver programs are now available on the ITU-R web page <http://www.itu.int/ITU-R/software/study-groups/rsg3/databanks/ionosph>.

NeQuick-ITUR strictly follows relevant ITU-R recommendations and uses the ITU-R relation between average sunspot number (R_{12}) and 10.7 cm solar radio flux ($F_{10.7}$)

$$F_{10.7} = 63.7 + (0.728 + 0.00089\, R_{12})\, R_{12}$$

or

$$R_{12} = [167273 + (F_{10.7\,-\,63.7})\, 1123.6]^{0.5} + -408.99$$

with saturation of the *F*2 layer critical frequency *foF*2 and the transfer parameter *M*(3000)*F*2 at R_{12}=150 (Recommendation ITU-R P.1239, ITU-R, 1997).

The model is formulated in the FORTRAN 77 language, uses a modular design and contains no COMMON blocks.

NeQuick is a «profiler» model which uses the peaks of the *E*-layer, the *F*1-layer and the

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$F2$-layer as anchor points. At any location the anchor points are derived from «maps» for the ionosonde parameters *foE*, *foF*1, *foF*2 and *M*(3000)*F*2. The *foF*2 and *M*(3000)*F*2 maps are from ITU-R (CCIR), the *foE* map is a modified formulation of that due to John Titheridge (see Leitinger *et al*., 1995, 1996) and *foF*1 is taken to be $1.4 \times foE$ (Leitinger *et al*., 1999) during daytime and is set zero during nighttime.

The maps are formulated in «modified dip latitude» μ: $\tan\mu = I/\sqrt{\cos\varphi}$ where μ is (Rawer's) modified dip latitude or «MODIP» (Rawer, 1963); I, the magnetic dip; and φ, the geographic latitude.

The peak of the E-layer has a fixed height of 120 km, the $F2$ peak is constructed from *foF*2 (symbol f_{F2}), M(3000)*F*2 (symbol M_3) and *foE* (symbol f_E) using Dudeney's form of the Bradley and Dudeney (1973) formula (see Dudeney, 1983).

With $\mu = M_3\sqrt{(0.0196M_3^2 + 1)/(1.2967M_3^2 - 1)}$, $\rho = f_{F2}/f_E$, $\Delta = [0.253/(\rho - 1.215)] - 0.012$ (if $f_E = 0$ then $\Delta = -0.012$), we get $h_m = [(1490\mu)/(M_3 + \Delta)] - 176\,\text{km}$.

The height of the $F1$ anchor point was originally modelled as $h_{mF1} = (108.8 + 14 \times N_{mF1} + 0.71 \times |I|)$ km, N_{mF1} being the $F1$ peak electron density in electrons per cubic meter and I being the inclination (dip) of the geomagnetic induction vector in degrees.

For the bottomside of the F-region, anchor point related profiling is realised by means of a sum of three semi-Epstein layers. With $N_{mF2} = 0.124\, f_{F2}^2$, $N_{mF1} = 0.124\, f_{F2}^2$, $N_{mE} = 0.124\, f_E^2$ being the $F2$, $F1$ and E-layer peak electron densities, h_{mF2}, h_{mF1}, h_{mE} being the $F2$, $F1$ and E-layer peak heights, B_{F2}, B_{F1}, B_E the $F2$, $F1$ and E-layer thickness parameters, we get for the bottom side

$$N(h) = N_{F2}(h) + N_{F1}(h) + N_E(h)$$

$$N_{F2}(h) = \frac{4N_{mF2}}{\left[1 + \exp\left(\frac{h - h_{mF2}}{B_{F2}}\right)\right]^2} \exp\left(\frac{h - h_{mF2}}{B_{F2}}\right)$$

$$N_{F1}(h) = \frac{4N_{mF1}}{[1 + \exp(\zeta_{F1})]^2} \exp(\zeta_{F1})$$

$$N_E(h) = \frac{4N_{mE}}{[1 + \exp(\zeta_E)]^2} \exp(\zeta_E)$$

$$\zeta_L = \frac{h - h_{mL}}{B_L} \exp\left(\frac{\varepsilon_1}{1 + \varepsilon_2 d}\right)$$

with $d = |(h - h_{mF2})/B_L|$, $\varepsilon_1 = 10$, $\varepsilon_2 = 2$, index L: or $F1$, or E.

This modification ensures that at the $F2$ peak the lower layers are «faded out» effectively. Examples: if $d = 99$ the argument of the «fading out» exponential is 0.1, if $d = 4.5$ it is 2, if $d = 0.5$ it is 5, if $d = 0$ it is 10.

The thickness parameters take different values for the bottomside and for the topside of the layers ($B_{E\text{bot}}$ and $B_{E\text{top}}$ for the E-layer, $B_{F1\text{bot}}$ and $B_{F1\text{top}}$ for the $F1$-layer)

$$N_{\text{top}}(h) = \frac{4N_{mF2}}{[1 + \exp(z)]^2} \exp(z)$$

$$\text{with} \quad z = \frac{h - h_{mF2}}{H_O\left[1 + \frac{rg(h - h_{mF2})}{rH_O + g(h - h_{mF2})}\right]}$$

where $H_O = B_{\text{top}}/v$; $v = (0.041163x - 0.183981)x + 1.424472$; $x = (B_{\text{top}} - 150)/100$.

The profile for the topside, too, is the upper half of an Epstein layer: g is a height gradient for the scale height H_O, $[rH_O + g(h - h_{mF2})]$ restricts the scale height increase, the factor v was introduced to reduce the vertical electron content to observed values. The topside thickness parameter $B_{\text{top}} = kB_{F2}$, with two different formulations, $k = 6.705 - 0.014R_{12} - 0.008\, h_{mF2}$ (April to September), $k = -7.77 + 0.097\,(h_{mF2}/B_{\text{top}})^2 + 0.153\, N_{mF2}$ (October to March). In both cases k is restricted to $2 \le k \le 8$.

2. Revision of the NeQuick bottomside

2.1. *Reason for the revision*

In «mapping» applications of NeQuick (construction of electron density grids in fixed heights below the $F2$ peak) it became evident that in some cases strong gradients and strange structures appear in E and $F1$-layer heights (see fig. 1a). An investigation demonstrated that a large fraction of the gradient problem cases was coupled to the following behaviour of the *foE* and *foF*2 maps. We found that in the critical regions and time intervals

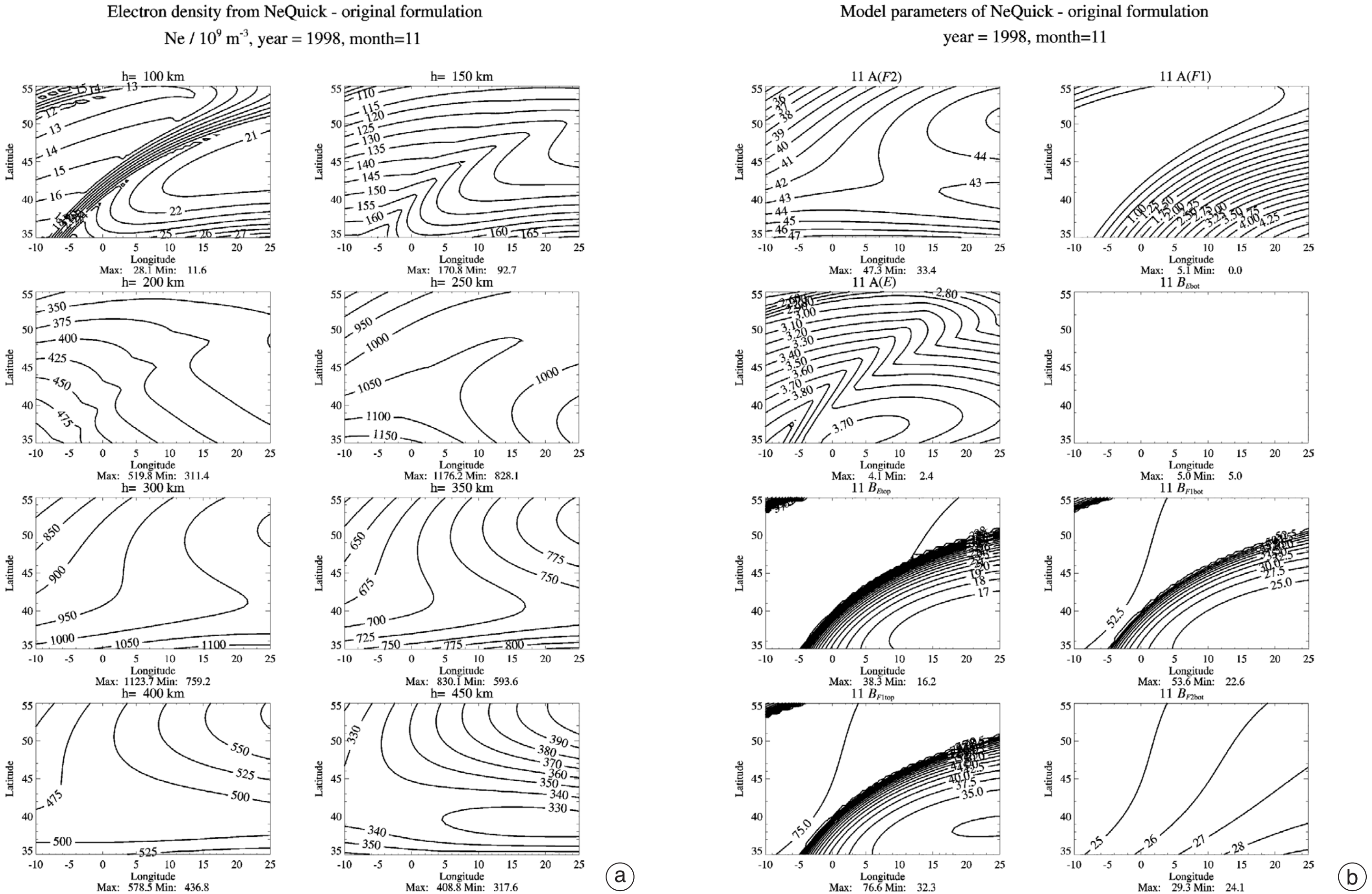

Fig. 1a,b. NeQuick, original formulation. a) Isolines of electron density in units of 109 m^{-3} in a geographic latitude *versus* longitude system. Heights from 100 km (*top left*) to 450 km (*bottom right*) in steps of 50 km. Monthly mean conditions for November 1998, 11 h UT. b) Isolines of model parameters in a geographic latitude *versus* longitude system. Epstein layer amplitudes and thickness parameters. Monthly mean conditions for November 1998, 11 h UT. From top left to bottom right: $F2$ amplitude, $F1$ amplitude, E amplitude, $B_{E\mathrm{bot}}$, $B_{E\mathrm{top}}$, $B_{F1\mathrm{bot}}$, $B_{F1\mathrm{top}}$, $B_{F2\mathrm{bot}}$.

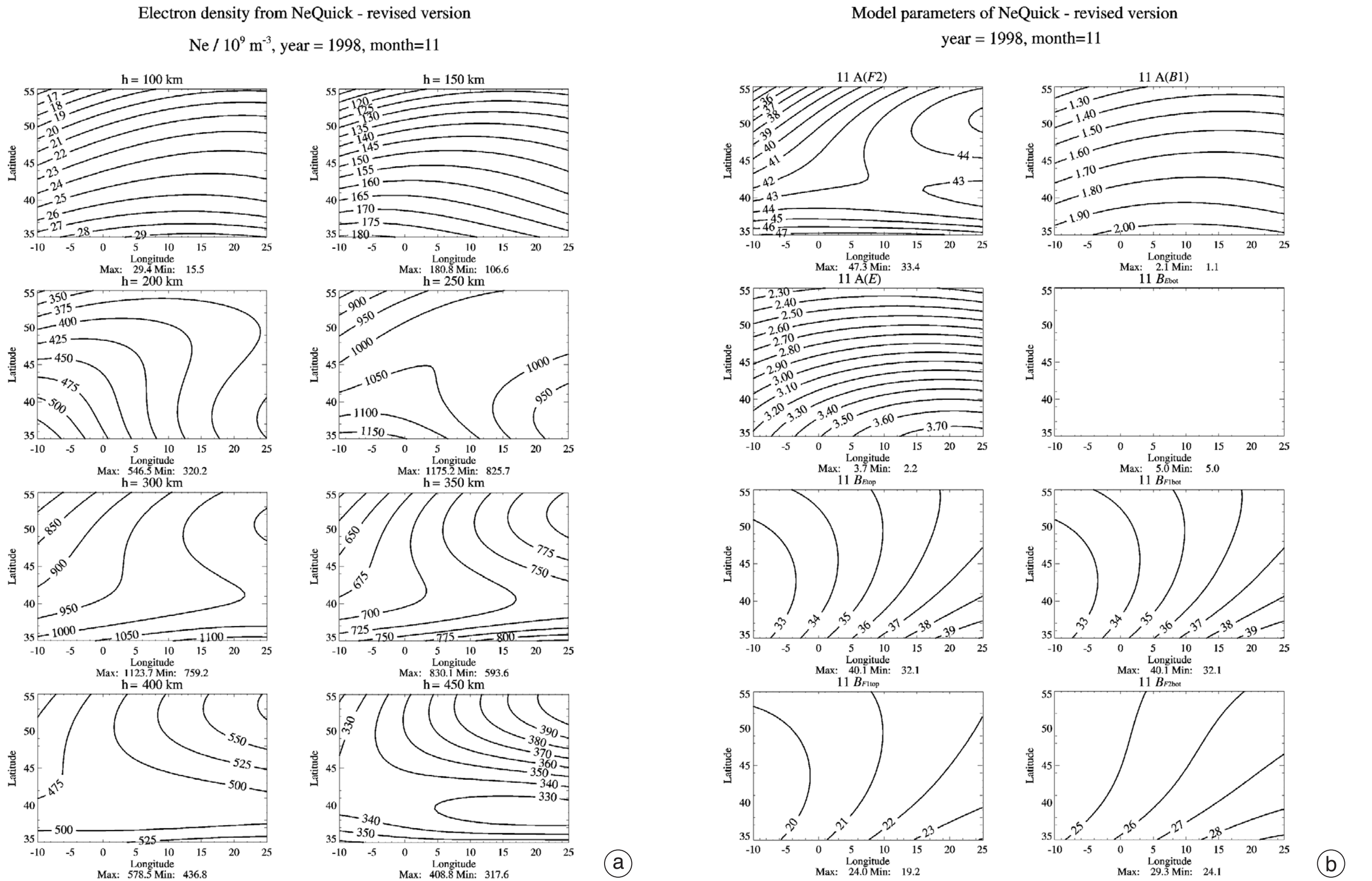

Fig. 2a,b. NeQuick, revised. a) Isolines of electron density in units of 109 m-3 in a geographic latitude *versus* longitude system. Heights from 100 km (*top left*) to 450 km (*bottom right*) in steps of 50 km. Monthly mean conditions for November 1998, 11 h UT. b) Isolines of model parameters in a geographic latitude *versus* longitude system. Epstein layer amplitudes and thickness parameters. Monthly mean conditions for November 1998, 11 h UT. From top left to bottom right: $F2$ amplitude, $F1$ amplitude, E amplitude, B_{Ebot}, B_{Etop}, B_{F1bot}, B_{F1top}, B_{F2bot}.

the isolines of *foF*2 and *foE* are nearly orthogonal to each other leading to difficult profile transitions. Isoline displays of electron density for constant height clearly show that the *foE* structure (isolines nearly parallel to the abscissa) is correctly forced at the *E*-layer peak (at a height of 120 km) but not above and below where the reasonable and expected structure is interrupted by strange features in the diagonal of the display (fig. 1a, isoline displays for 100 km and 150 km). Single parameter adaptations could not solve the problem but a more elaborate revision of the original «Di Giovanni-Radicella» (DGR) modelling approach (Di Giovanni and Radicella, 1990; Radicella and Zhang, 1995) was necessary.

2.2 *The most important revisions*

Following an elaborate parameter adaptation strategy and after many tests we adopted the revisions:

1) Replace the formerly complicated formulation for the height of the $F1$ peak, h_{mF1}, by using $h_{mF1}=(h_{mF2}+h_{mE})/2$.

2) Set $foF1$ to zero if foE is smaller than 2 MHz and avoid that $foF1$ gets too close to $foF2$. The original formulation was $f_{F1}=1.4\ f_E$ under all daytime conditions. Now $f_{F1}=0.85\times 1.4\ f_E$ if $1.4\ f_E>0.85\ f_{F2}$.

3) Introduce simplified formulations for the thickness parameters $B_{F1\mathrm{top}}$, $B_{F1\mathrm{bot}}$ and $B_{E\mathrm{top}}$.

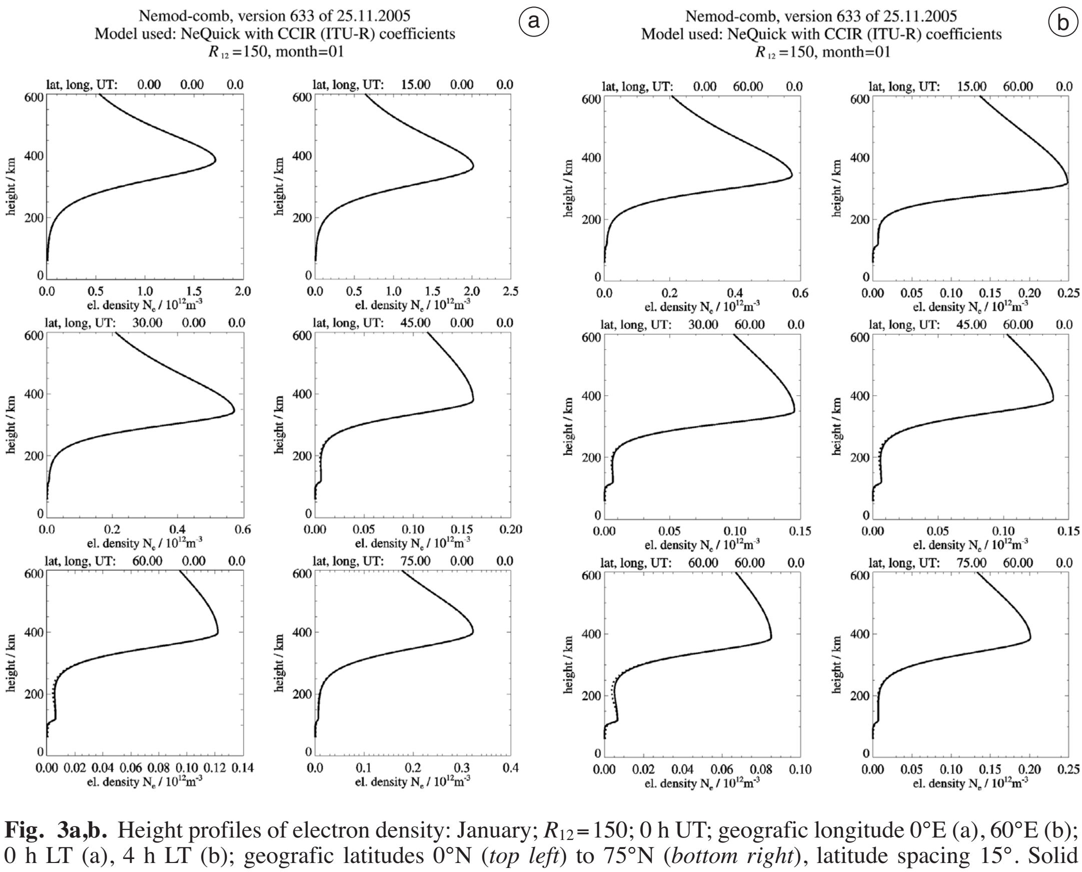

Fig. 3a,b. Height profiles of electron density: January; $R_{12}=150$; 0 h UT; geografic longitude 0°E (a), 60°E (b); 0 h LT (a), 4 h LT (b); geografic latitudes 0°N (*top left*) to 75°N (*bottom right*), latitude spacing 15°. Solid curves: revised NeQuick, dotted curves: NeQuick, old formulation.

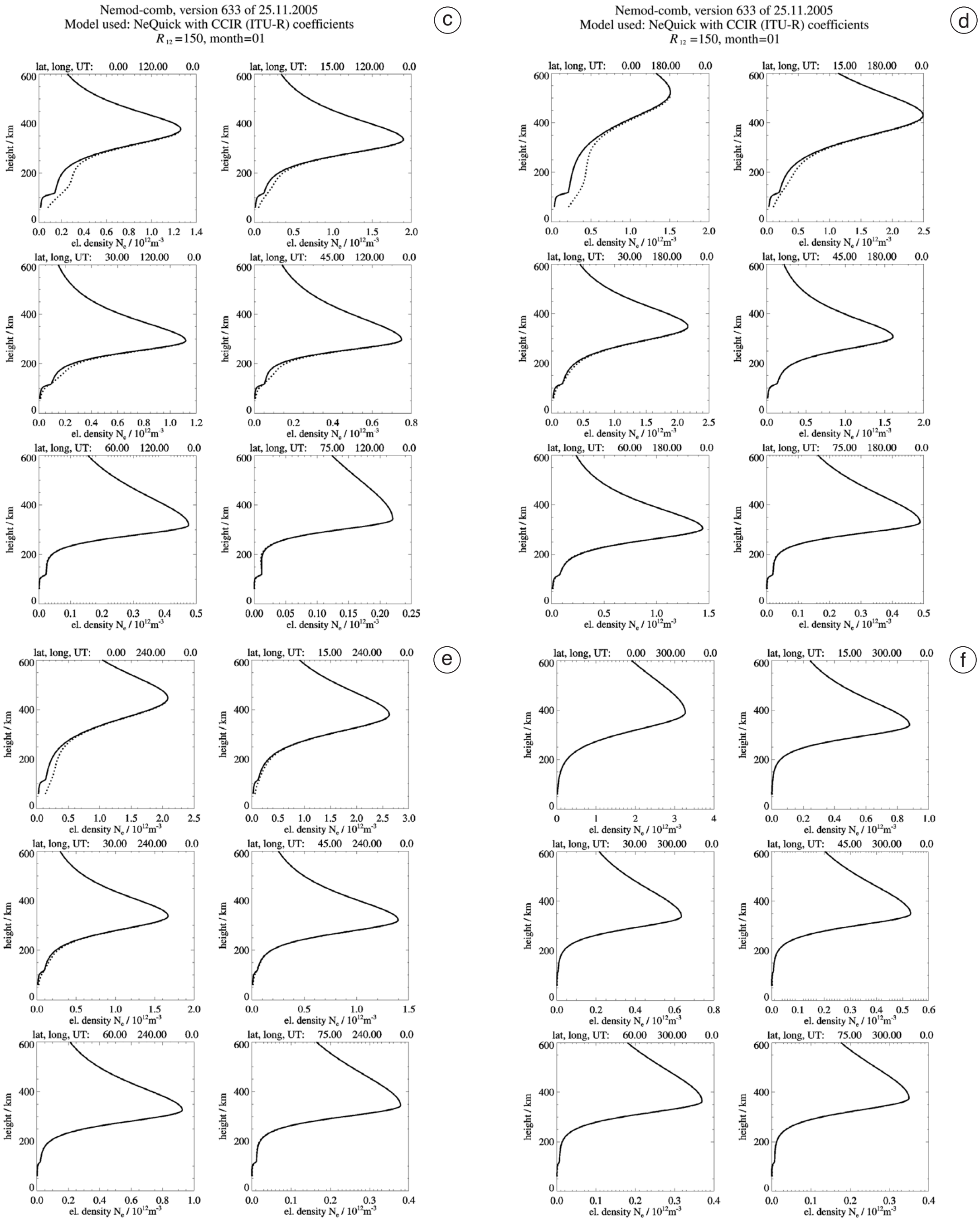

Fig. 3c-f. Height profiles of electron density: January; $R_{12}=150$; 0 h UT; geografic longitude 120°E (c), 180°E (d), 240°E (e), 300°E (f); 8 h LT (c), 12 h LT (d), 16 h LT (e), 20 h LT (f); geografic latitudes 0°N (*top left*) to 75°N (*bottom right*), latitude spacing 15°. Solid curves: revised NeQuick, dotted curves: NeQuick, old formulation.

The complete set of thickness parameters now is $B_{F2}=38.5N_{mF2}/d$ with $d=\exp[(-3.467+0.857\cdot\ln(f_{F2}^2)+2.02\ln(M_3)]$; $B_{F1top}=0.3(h_{mF2}-h_{mF1})$; $B_{F1bot}=0.5(h_{mF1}-h_{mE})$; $B_{Etop}=0.5(h_{mF1}-h_{mE})$ or $B_{Etop}=7$ whatever is larger; $B_{Ebot}=5$.

3. Comparison of NeQuick-ITUR with the revised NeQuick

The following collection of maps and profiles demonstrates the improvement of the NeQuick properties.

The comparison of fig. 2a (revised NeQuick) with fig. 1a (NeQuick before revision) clearly shows that strong gradients and strange structures have disappeared. This is especially true for *E*-layer heights and for the *E*-*F*1 transition region. Figure 1b connects the strong gradients and strange structures to the latitude-longitude distribution of *E* and *F*1 thickness parameters B_{Etop}, B_{F1bot} and B_{F1top} and to the amplitude of the *E*-Epstein layer, $A(E)$. Figure 2b shows that after the revision all these parameters are very well behaved.

The profile comparisons of fig. 3a-f (January, high solar activity) and fig. 4a-f (April, low solar activity) show that two profile peculiarities have disappeared with the revision:

a) A low latitude «contamination» of the *E*-layer by the *F*1-layer leading to electron densi-

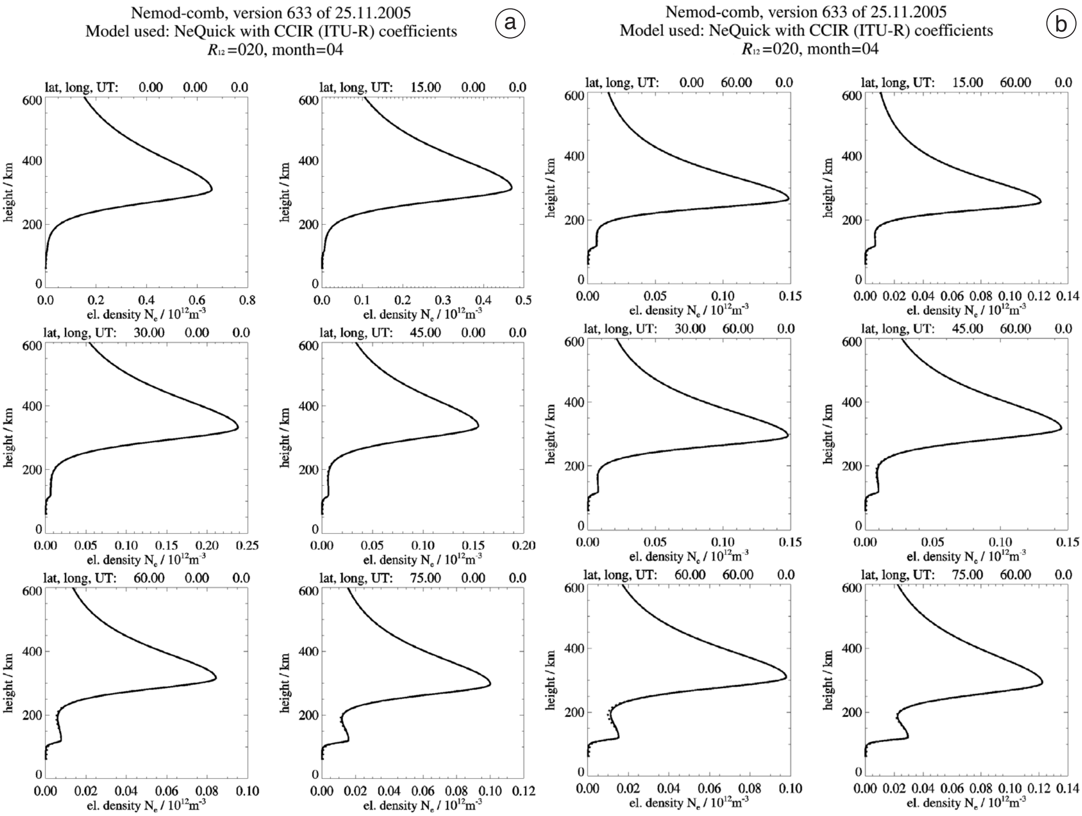

Fig. 4a,b. Height profiles of electron density: April; $R_{12}=20$; 0 h UT; geografic longitude 0°E (a), 60°E (b); 0 h LT (a), 4 h LT (b); geografic latitudes 0°N (*top left*) to 75°N (*bottom right*); latitude spacing 15°. Solid curves: revised NeQuick, dotted curves: NeQuick, old formulation.

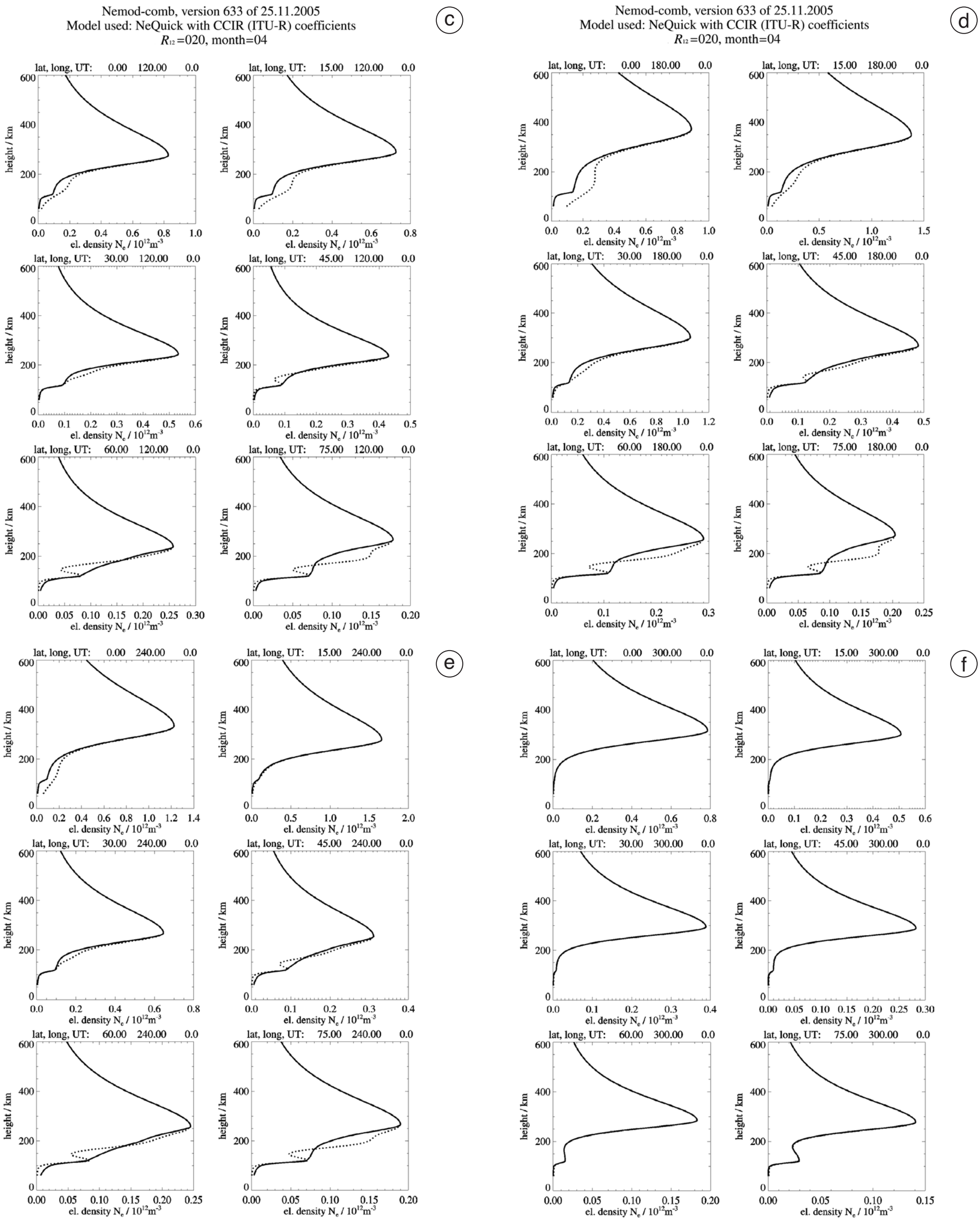

Fig. 4c-f. Height profiles of electron density: April; $R_{12}=20$; 0 h UT; geografic longitude 120°E (c), 180°E (d), 240°E (e), 300°E (f); 8 h LT (c), 12 h LT (d), 16 h LT (e), 20 h LT (f); geografic latitudes 0°N (*top left*) to 75°N (*bottom right*); latitude spacing 15°. Solid curves: revised NeQuick, dotted curves: NeQuick, old formulation.

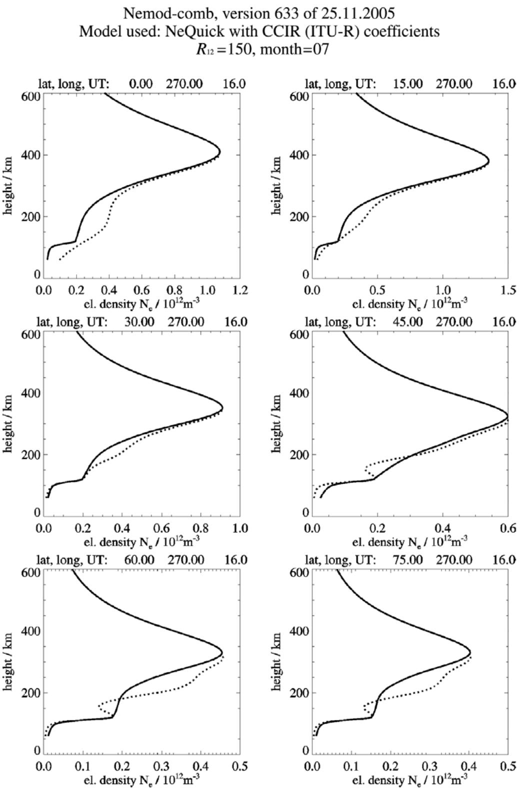

Fig. 5. Height profiles of electron density: July; R_{12}=150; 16 h UT; geografic longitude 270°E; 10 h LT; geografic latitudes 0°N (*top left*) to 75°N (*bottom right*); latitude spacing 15°. Solid curves: revised NeQuick, dotted curves: NeQuick, old formulation.

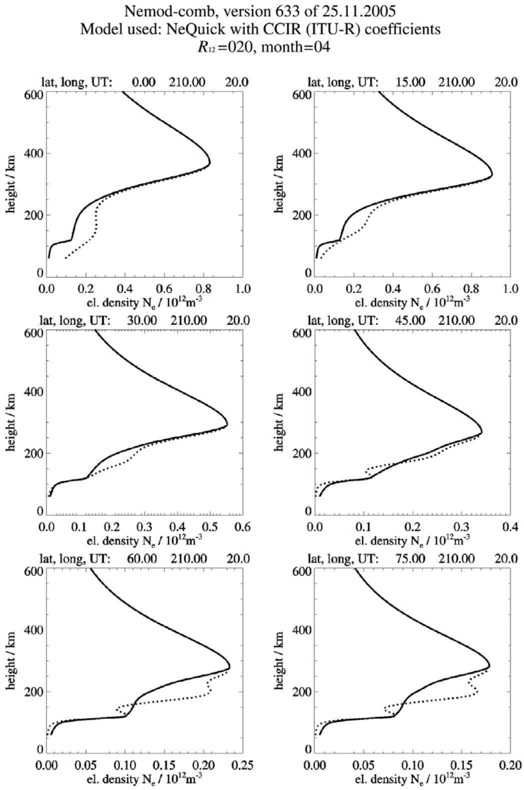

Fig. 6. Height profiles of electron density: April; R_{12}=20; 20 h UT; geografic longitude 210°E; 10 h LT; geografic latitudes 0°N (*top left*) to 75°N (*bottom right*); latitude spacing 15°. Solid curves: revised NeQuick, dotted curves: NeQuick, old formulation.

ties larger than $Nm(E)$ at the presumed E-layer peak of 120 km (top rows of fig. 4c,d).

b) A (upper mid and) high latitude «contamination» of the $F2$-layer by the $F1$-layer leading to secondary maxima somewhere between the $F1$ and the $F2$ peaks (figs. 5 and 6). In some cases the secondary maxima had electron density values larger than $Nm(F2)$ (*e.g.*, bottom of fig. 5). These artifacts tended to appear in the «old» NeQuick around 10 h Local Time (LT) both under high solar activity conditions (fig. 5) and low solar activity conditions (fig. 6).

The revised NeQuick has been released on 25 November, 2002 after automatic checking of about 72000 and systematic visual inspection of hundreds of model profiles gained in all seasons under high, mid and low solar activity conditions and distributed globally in latitude and longitude and distributed over Universal Time (UT) days.

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