Space weather impact in the D-region ionosphere: observations and modelling

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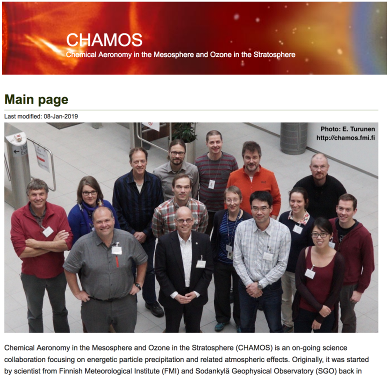
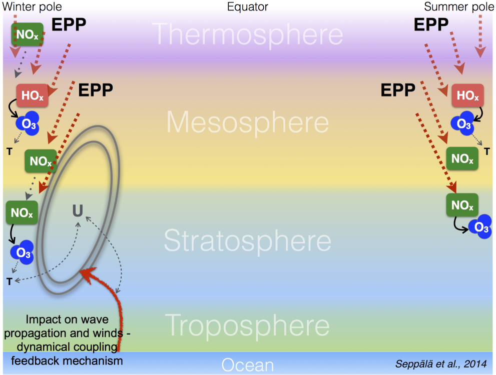
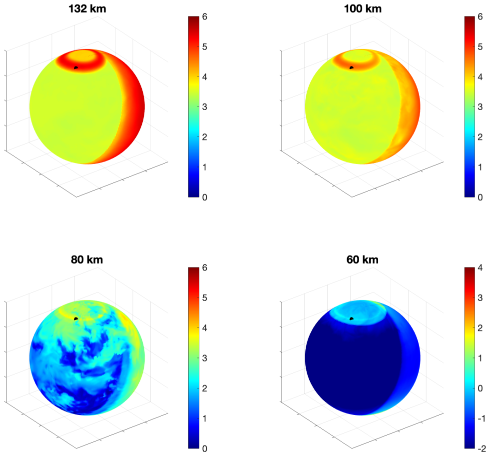
CHAMOS (http://chamos.fmi.fi)



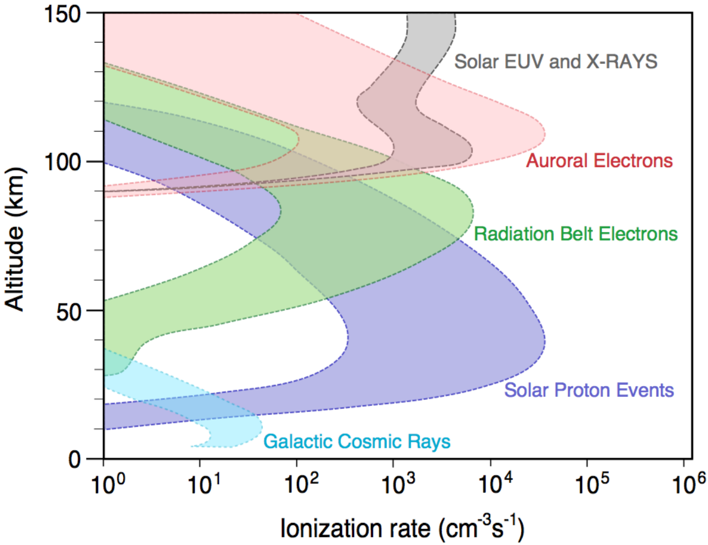


$$NO_x = N + NO + NO_2$$
$$HO_x = H + OH + HO_2$$
$$O_x = O_3 + O$$

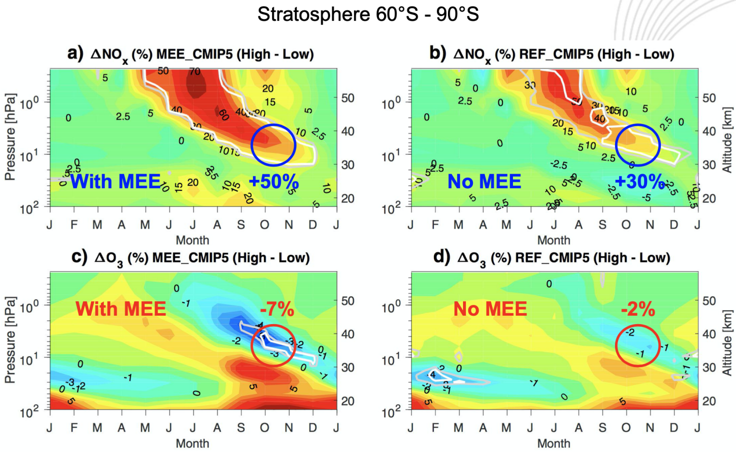
WACCM-D model video



Ionisation sources

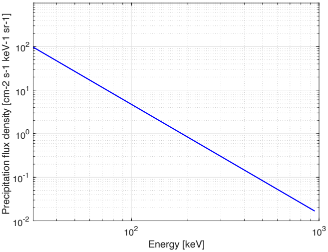


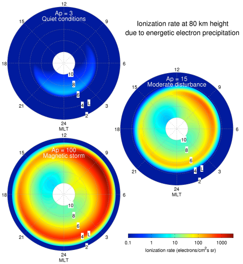
CMIP with (and without) the medium energy electrons (E=30...1000 keV)

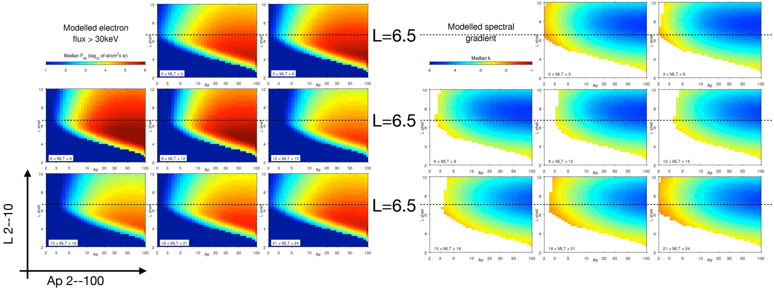


From: Andersson et al., JGR (Atmos.), http://doi.org/10.1002/2017JD027605, 2018

APEEP precipitation model, van de Kamp et al., 2016







Tyssøy et al., 2021: HEPPA III intercomparison experiment on electron precipitation impacts

Journal of Geophysical Research: Space Physics
10.1029/2021JA029128

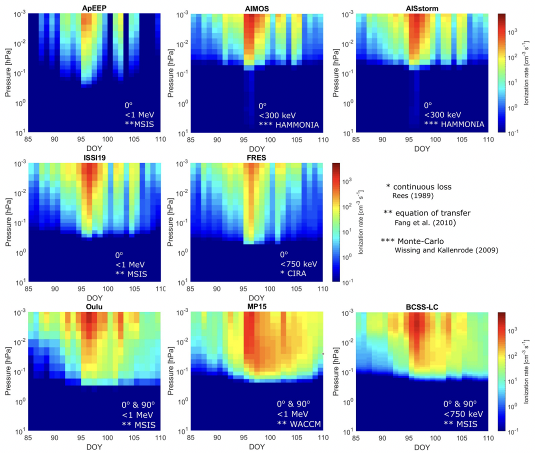
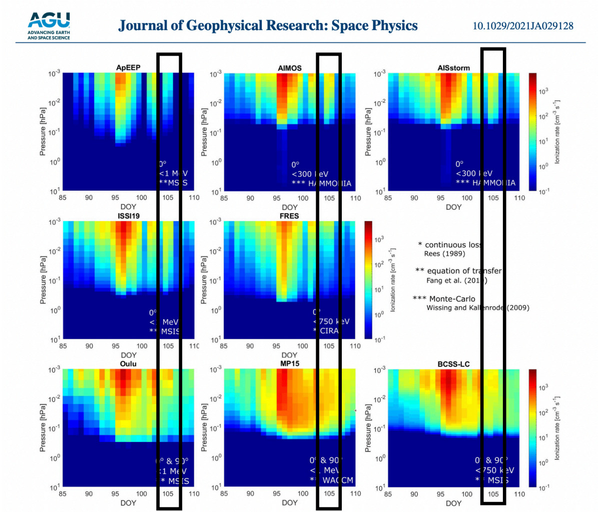


Figure 4. Latitude corrected hemispheric mean poleward of 45°S for the eight ionization rate estimates. The legends list the detector(s), upper energy limit, background atmosphere and ionization rate method applied.

EISCAT data available for 15th April 2010 (doy 105)!



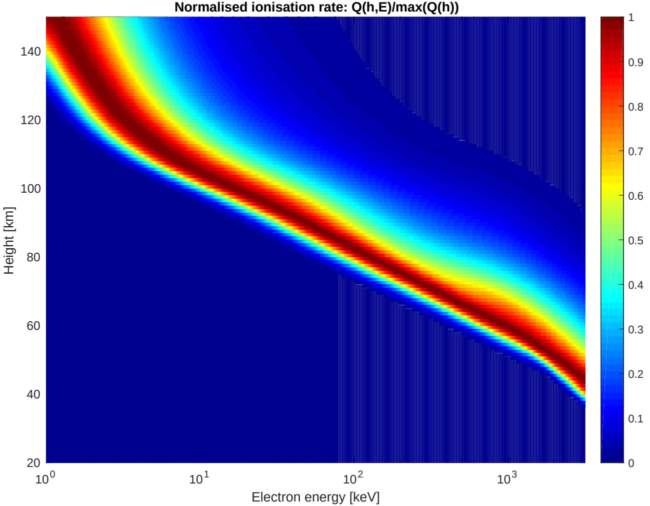
[1]https://doi.org/10.1029/2021JA029128

EPP inversion: $\phi(E) \rightarrow Q(h) \rightarrow N_{\mathrm{e}}(h)$

1. $\phi(E) \rightarrow Q(h)$
   - Calculate $Q(h) = \int A(h, E)\phi(E)dE$
   - Matrix $A(h, E)$ contains the atmospheric response[1]
2. $Q(h) \rightarrow \mathrm{SIC} \rightarrow N_{\mathrm{e}}(h)$
   - Pre-calculate N_e at a sufficiently fine grid of Q and interpolate $Q \rightarrow N_e$
3. Inversion
   - Proposal $\phi(E)$ is an arbitrary piece-wise log-log (here: 7 nodes)
   - Minimise in MCMC chain (N=100 000):
     $\chi^2 = \sum_h ((\log(N_e(h)) - \log(N_{\mathrm{e:data}}(h)))/W)^2$

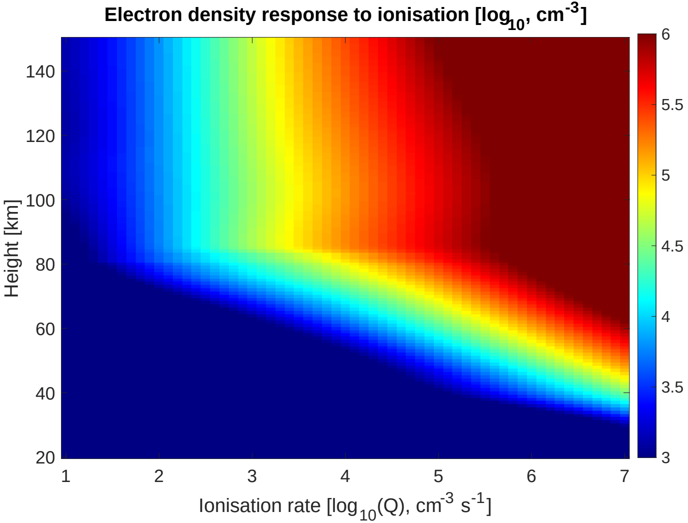
[1]Fang, X., C. E. Randall, D. Lummerzheim, W. Wang, G. Lu, S. C. Solomon, and R. A. Frahm (2010), Parameterization of monoenergetic electron impact ionization, Geophys. Res. Lett., 37, L22106, doi:10.1029/2010GL045406.

EPP: energy vs. ionisation

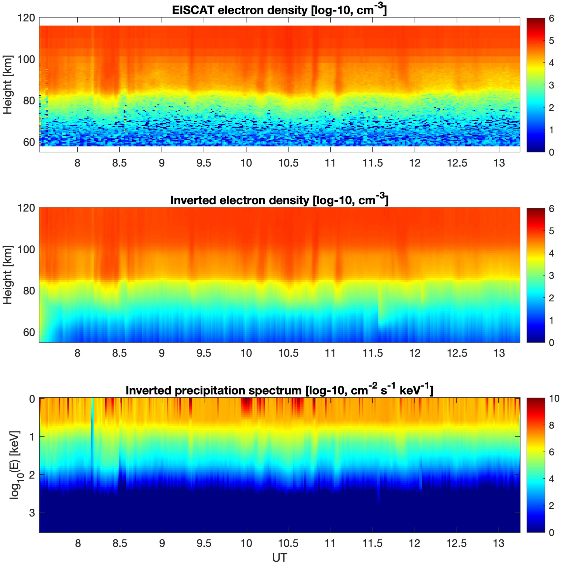


[1] Fang et al., Parameterization of monoenergetic electron impact, GRL, 2010

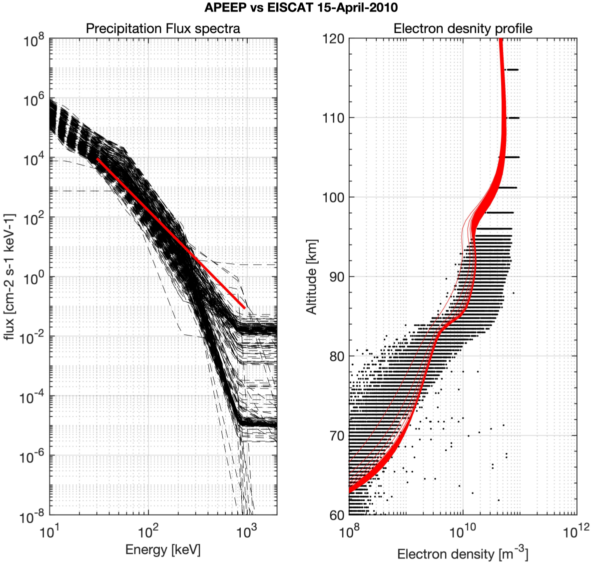
Ionisation impact on electron density (SIC model)



Inversion analysis of EISCAT VHF, 15 April 2010



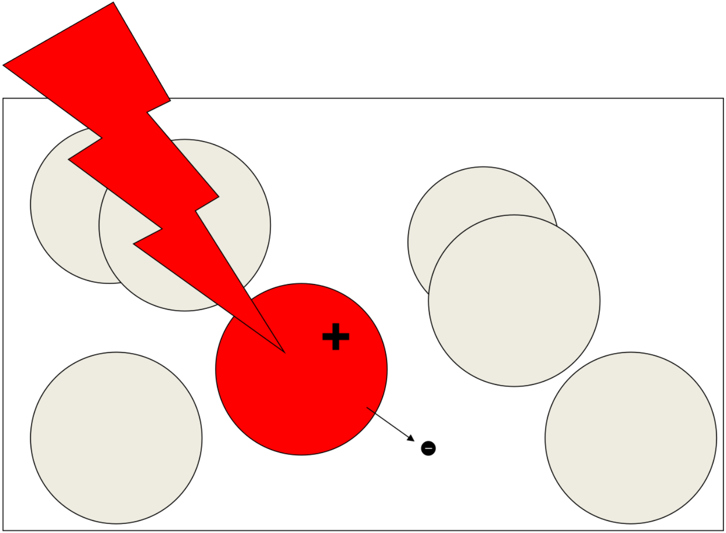
Comparison: EISCAT vs. APEEP



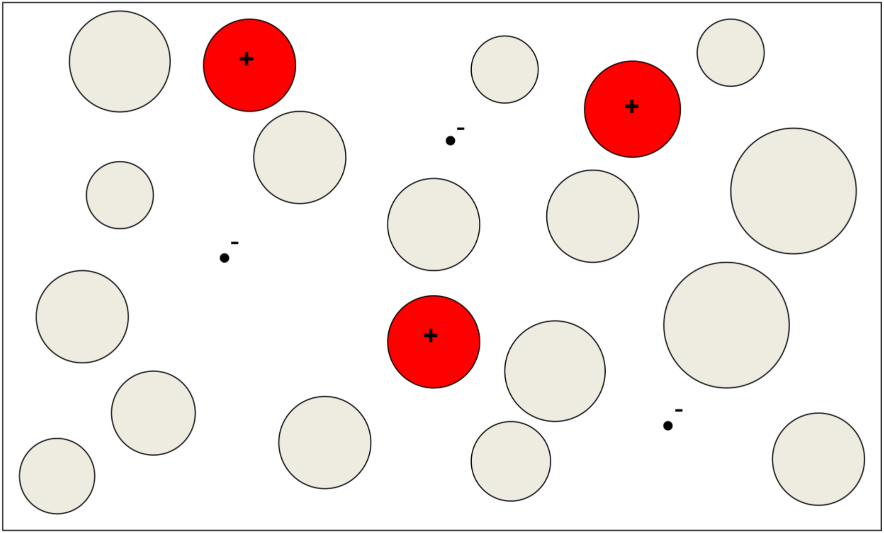
Summary of part 1/3

- APEEP seems to be in *the right ballpark* with the EISCAT data
- Slight overestimation at the relativistic fluxes is likely due to "stiffness" of the spectral shape
- This case study does not seem to provide an easy solution for the NOx dilemma, i.e., there's *no drastic underestimation* of the ionisation.
- All EISCAT D-region data available for similar comparisons to validate & improve the model.

Part 2/3: Modelling of consequences of ionisation



Ionisation → plasma



Building a chemistry model

Chemical reactions introduce a set of differential continuity equations:
The most simple: just 1 positive ion type N_{ip}:

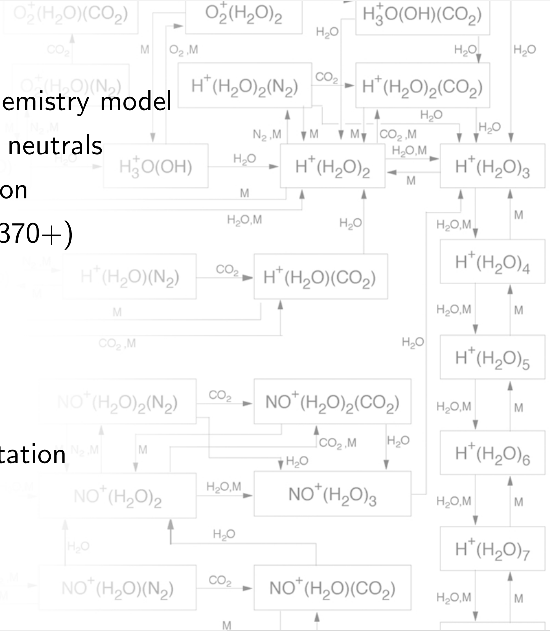
$$\frac{dN_e}{dt} = Q - k_1 N_e N_{ip} = Q - k_1 N_e^2 \quad (1)$$

For one type of positive N_{ip} and one type of negative N_{in} ions:

$$\frac{dN_e}{dt} = Q - k_1 N_e N_{ip} - k_2 N_e + k_3 N_{in} \quad (2)$$

And so forth ...

Sodankylä Ion (and neutral) Chemistry model (SIC)



Detailed 1-D time dependent chemistry model

- 63 ions (27 negative) & 13 neutrals
- 20-150 km in 1 km resolution
- several hundred reactions (370+)
- vertical transport

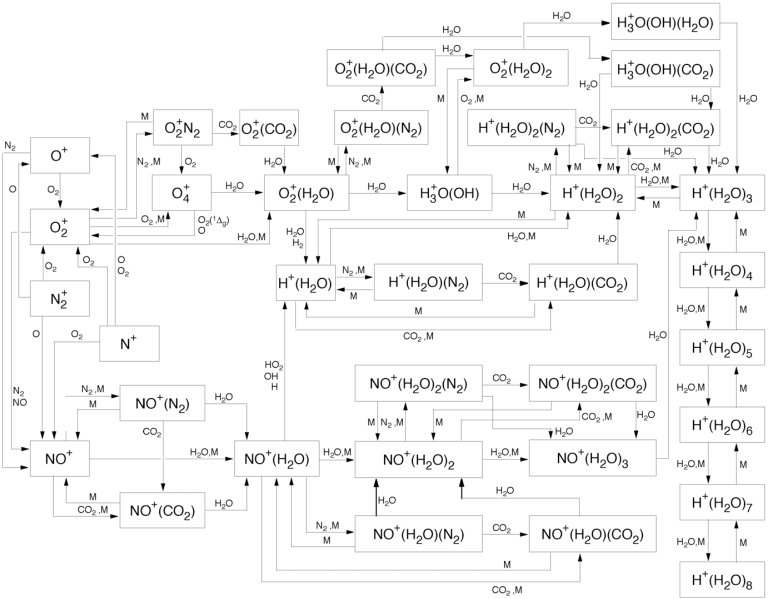
Input

- MSIS
- solar EM flux
- proton and electron precipitation
- cosmic rays

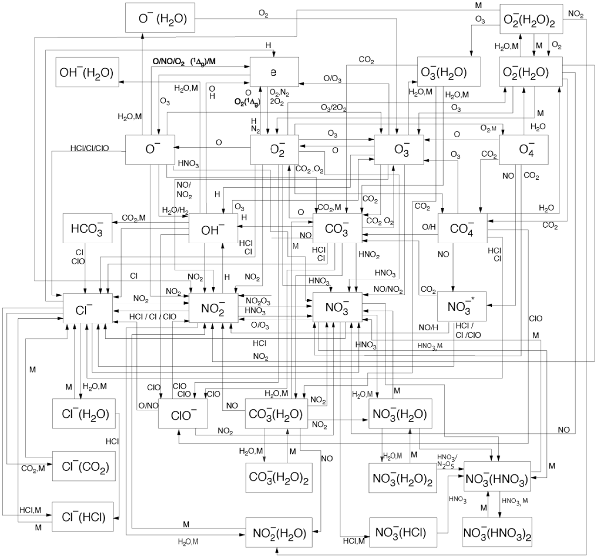
SIC species

	POSITIVE IONS		NEGATIVE IONS		NEUTRALS
1	O^+	1	O^-	1	N_2
2	O_2^+	2	O_2^-	2	O_2
3	O_4^+	3	O_3^-	3	O
4	N^+	4	O_4^-	4	Ar
5	N_2^+	5	OH^-	5	He
6	NO^+	6	CO_3^-	6	NO
7	$NO^+(N_2)$	7	CO_4^-	7	$O_2(^1D_g)$
8	$NO^+(CO_2)$	8	NO_2^-	8	H_2O
9	$NO^+(H_2O)$	9	NO_3^-	9	N
10	$NO^+(H_2O)_2$	10	NO_3^{*-}	10	H
11	$NO^+(H_2O)_3$	11	HCO_3^-	11	CO_2
12	$NO^+(H_2O)(N_2)$	12	$O_2^-(H_2O)$	12	O_3
13	$NO^+(H_2O)(CO_2)$	13	Cl^-	13	OH
14	$NO^+(H_2O)_2(N_2)$	14	$OH^-(H_2O)$	14	NO_2
15	$NO^+(H_2O)_2(CO_2)$	15	$O_3^-(H_2O)$	15	HO_2
16	$O_2^+(H_2O)$	16	$NO_3^-(H_2O)$	16	NO_3
17	$H_3O^+(OH)$	17	$CO_3^-(H_2O)$	17	HNO_2
18	$H^+(H_2O)$	18	$Cl^-(H_2O)$	18	CO_3
19	$H^+(H_2O)_2$	19	ClO^-	19	M
20	$H^+(H_2O)_3$			20	H_2
21	$H^+(H_2O)_4$			21	HCl
22	$H^+(H_2O)_5$			22	HNO_3
23	$H^+(H_2O)_6$			23	Cl
24	$H^+(H_2O)_7$			24	ClO
25	$H^+(H_2O)_8$			25	CH_4
26	$O_2^+N_2$			26	CH_3
27	$H^+(H_2O)_2(CO_2)$			27	$O(^1D)$
28	$H^+(H_2O)_2N_2$			28	N_2O
29	$H^+(H_2O)CO_2$			29	$N(^2D)$
30	$H^+(H_2O)N_2$			30	H_2O_2
31	$O_2^+CO_2$			31	CO
32	$O_2^+(H_2O)N_2$			32	CH_2O
33	$O_2^+(H_2O)CO_2$				
34	$O_2^+(H_2O)_2$				
35	$H_3O^+(OH)H_2O$				
36	$H_3O^+(OH)CO_2$				

Positive ion chemistry scheme



Negative ion chemistry scheme



Solving an arbitrary chemistry scheme

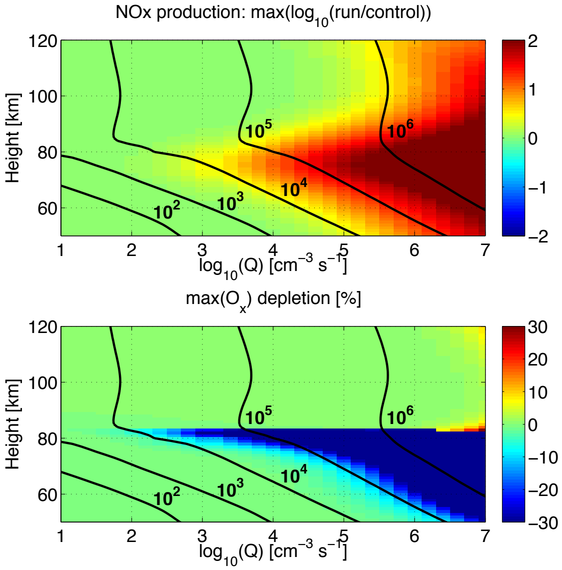
$$\frac{\partial \bar{N}}{\partial t} = \mathbf{B}\bar{N} + \bar{Q} = \begin{pmatrix} -\Lambda_1 & +\Pi_{12} & \dots & +\Pi_{1n} \\ +\Pi_{21} & -\Lambda_2 & & \\ \vdots & & \ddots & \\ & & & \\ +\Pi_{n1} & & & -\Lambda_n \end{pmatrix} \begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ \vdots \\ n_n \end{pmatrix} + \begin{pmatrix} q_1 \\ q_2 \\ q_3 \\ \vdots \\ q_n \end{pmatrix}. \quad (4.9)$$

[1] Courtesy of Verronen, 2006

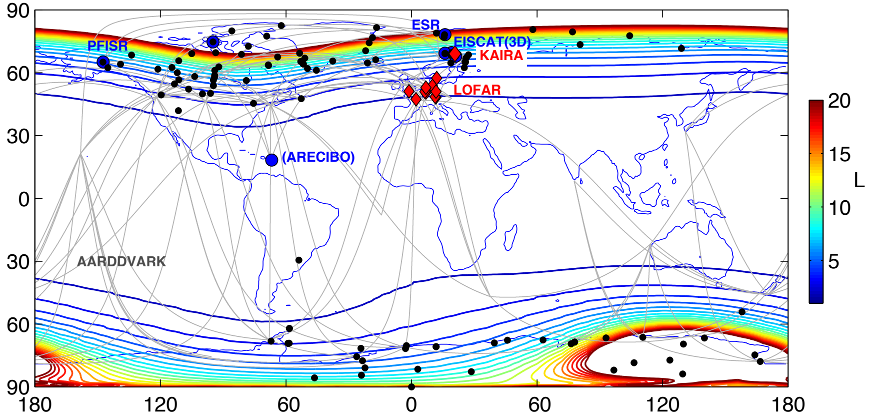
From EPP to NOx and HOx

- EPP produces O_2^+ (also: $N_2^+ + O_2 \rightarrow O_2^+ + N_2$)
- NO_x is produced e.g., via: $O_2^+ + N_2 \rightarrow NO^+ + NO$
- HO_x: O_2^+ turns into water clusters $O_2^+(H_2O)$
- Recombination with electrons turn $O_2^+(H_2O)$ into OH
- Recombination with negative ions turn $O_2^+(H_2O)$ into HNO_3, which is photodissociated into OH

The end of part 2/3: Sensitivity to ionisation (30 minutes)



Part 3/3: Radio wave methods for observing the ionisation (=electron density)?

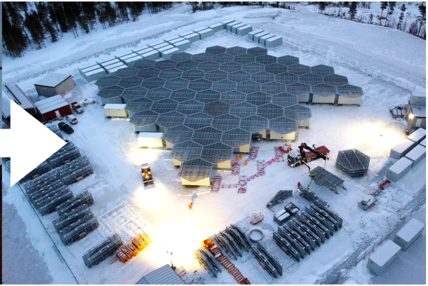


Incoherent scatter radars: paradigm change

Current EISCAT

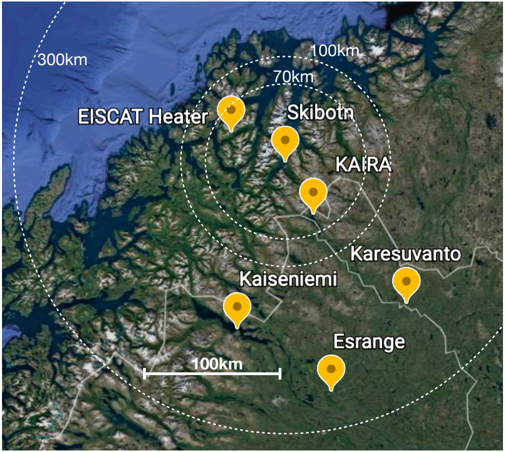
UHF-radar at Tromsø, Norway

EISCAT_3D

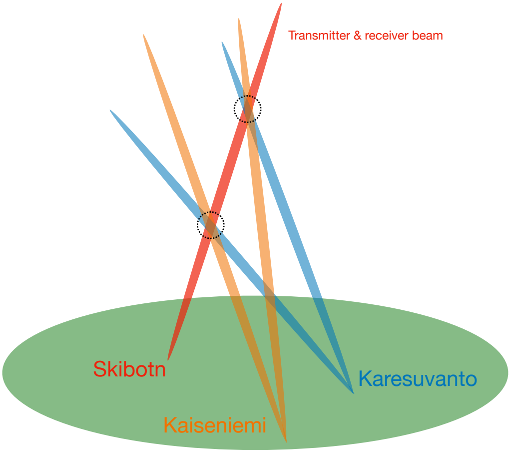


EISCAT_3D transmitter site
Skibotn, Norway

EISCAT_3D geography



EISCAT_3D concept



HPC-approach needed!

Data available:

- "cp6" — from 1990-06-13 to 1998-09-24, 76 experiments, ~52 full days (full day = 24h)
- "arcd" —from 2003-05-29, 183 experiments, ~110 full days
- "manda" — from 2005-04-14, more than 411 experiments, ~202 full days

Total duration of data available = **364 full days**

Full computational cost

- ➢ MCMC run time for each altitude = ~**3.5 sec**
- ➢ No of altitude steps = **250**
- ➢ Computational time for each 5 min average profile = 3.5 x 250 = **875 sec (~ 15 min)**
- ➢ 5 min-integrated profiles in 24 hr = **288**

Estimated computational time :
364 full days x 288 5-min-integrated profiles x 15 minutes per one profile = 1572480 minutes = ~ **3 years of computational time!).**

Incoherent scatter radar data levels

- Level 0: raw voltage samples
- Level 1: lag-profiles
- Level 2: plasma parameters (density, temperature, composition)
- Level 3: particle precipitation, conductivities, currents ...

Step 1: Lag-profiles to plasma parameters (level 1 to 2)

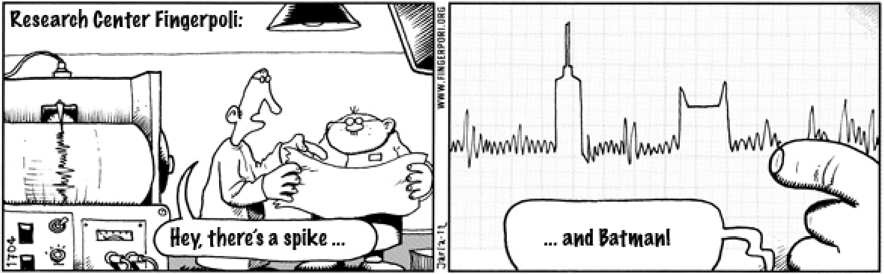


Figure: Fingerpori, HS, 7 September 2012

Incoherent scatter spectrum

The spectral density of the incoherent scattering is

$$\sigma(\omega_0+\omega)d\omega = \frac{N_e r_e^2 d\omega}{\pi}\frac{\left(\left|y_e\right|^2 \frac{\sum_j n_j \Re(y_j)}{\omega-\mathbf{k}\cdot\mathbf{v}_{dj}} \left|\sum_j \mu_j y_j + i\lambda_D^2 k^2\right|^2 \frac{\Re(y_e)}{\omega-\mathbf{k}\cdot\mathbf{v}_{de}}\right)}{\left(\left|y_e + \sum_j \mu_j y_j + i\lambda_D^2 k^2\right|^2\right)}.$$

Here

- $n_j = N_j/N_e$ and $\mu_j = n_j T_e/T_j$ (densities and temperatures),
- $\lambda_D = (\epsilon_0 k_B T_e/N_e e^2)^{1/2}$ (Debye length)
- $k = 2\pi/\lambda$ (wave number).

Incoherent scatter spectrum: Inputs

What is needed for calculating the IS spectrum?

- Radio wave parameters: ω, $\mathbf{k}$
- Plasma composition, temperatures, ion masses, coll. frequencies and drift velocities: N_j, T_j, m_j, ν_j and $\mathbf{v_j}$
- Magnetic field $\mathbf{B}$

Sodankylä Ion (and neutral) Chemistry model (SIC)

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Input

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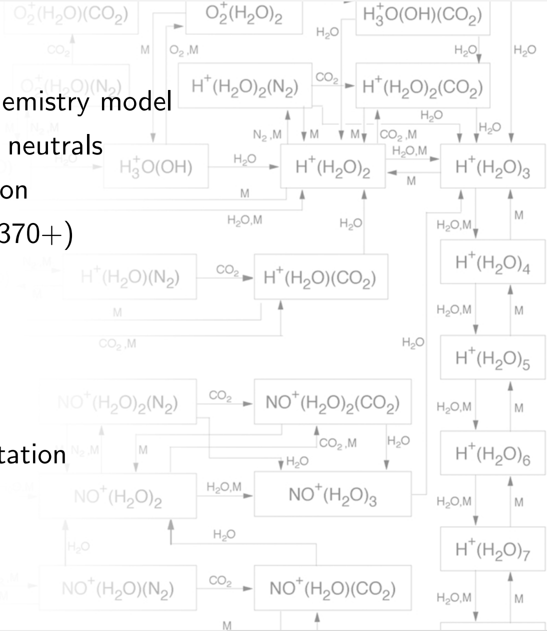
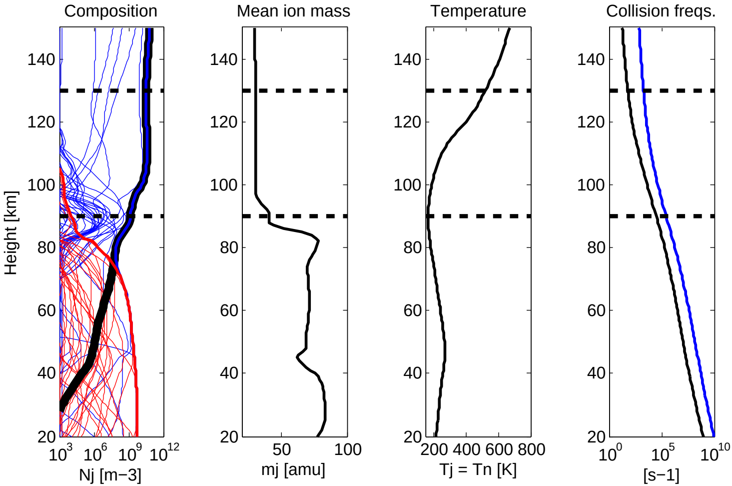
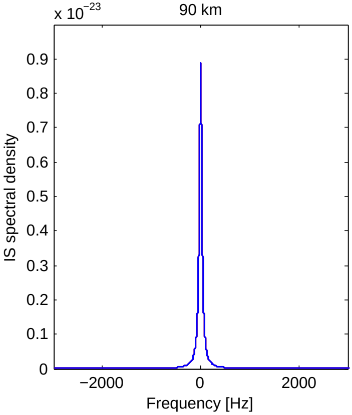


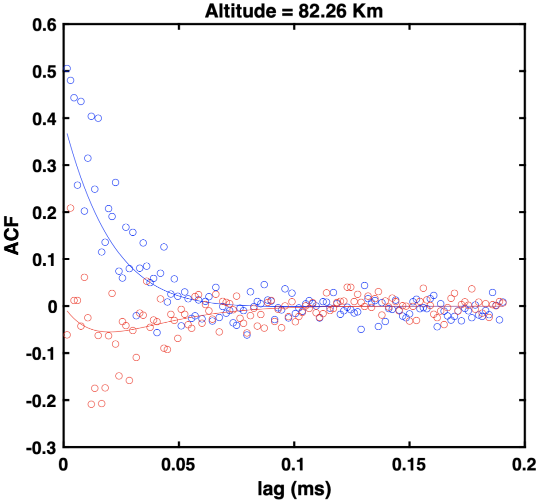
Input profiles (based on the SIC model)



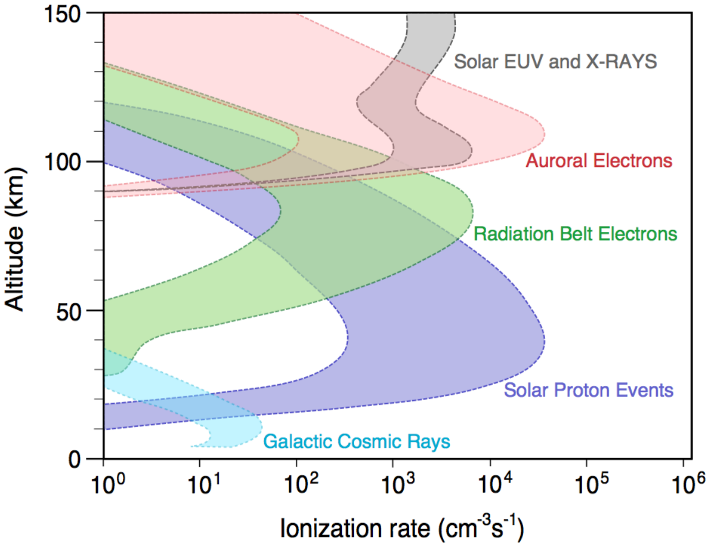
Incoherent scatter ion line: 90 and 130 km



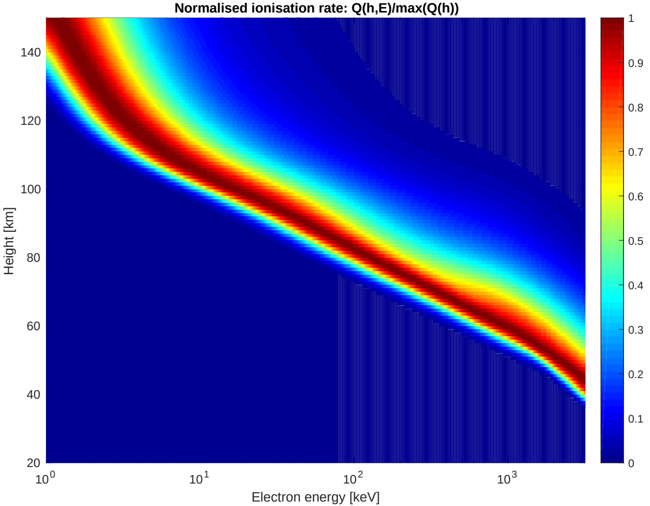
Plasma parameter fit to the ACFs measured



Step 2: Energetic particle precipitation inversion

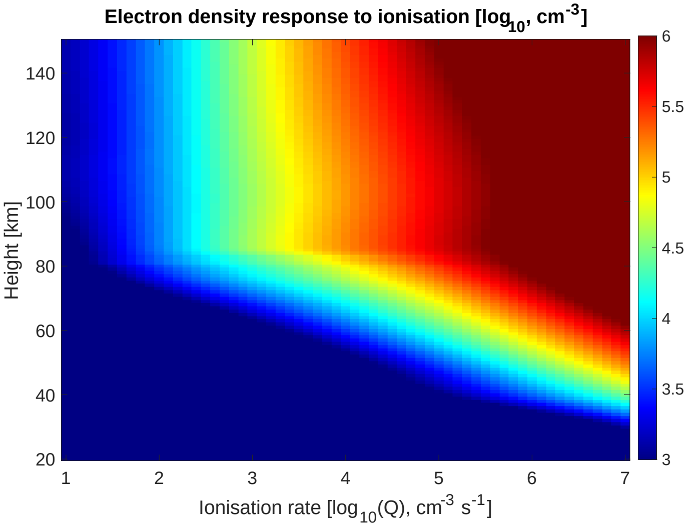


Electron precipitation driven ionisation: height vs. altitude



[1] Fang et al., Parameterization of monoenergetic electron impact, GRL, 2010

Ionisation impact on electron density (SIC model)



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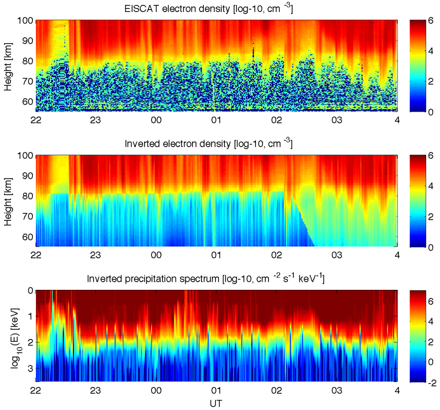
[1]Fang, X., C. E. Randall, D. Lummerzheim, W. Wang, G. Lu, S. C. Solomon, and R. A. Frahm (2010), Parameterization of monoenergetic electron impact ionization, Geophys. Res. Lett., 37, L22106, doi:10.1029/2010GL045406.

Why MCMC inversion?

- A non-linear problem
- Easy to construct the χ^2 error function (e.g., in log-scale)
- Easy to limit the solution (e.g., only positive fluxes are allowed)
- Kick-ass MCMC toolbox available[1]

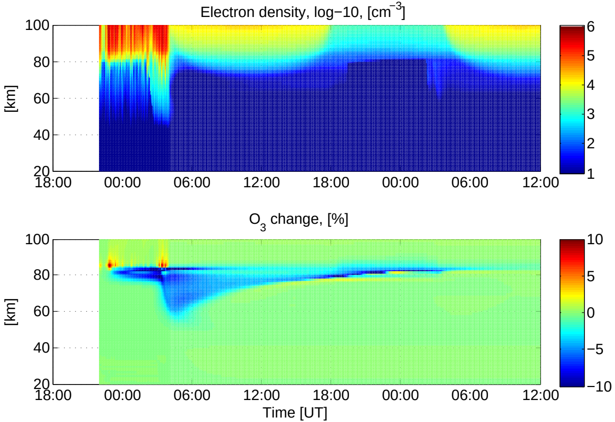
[1] Search: 'Marko Laine + MCMC' → http://helios.fmi.fi/~lainema/mcmc/

Example case: 28–29 March 2017



[1]Miyoshi et al. (2021), Penetration of MeV electrons into the mesosphere accompanying pulsating aurorae, Scientific Reports (Springer-Nature). https://doi.org/10.1038/s41598-021-92611-3

Example case: 28–29 March 2017



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Summary of part 3/3

- Inversion of the precipitation characteristics (ϕ, Q, N_e) from the incoherent scatter radar data
- Full time-dependent ion chemistry of the SIC model is used in the forward model $\rightarrow$ chemical consequences
- Results provide means to constrain better the particle forcing input to the climate models (such as WACCM-D)