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Canadian Ionosphere and Atmosphere Model: model status and applications

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Outline

1. C-IAM project: Goals and motivation
2. Model description
3. First published results:
   - 135.6 nm $O(^5S - ^3P)$ nighttime ionospheric emission
   - 732 nm $O^+(^2P – ^2D)$ daytime ionospheric emission
4. Further model development and applications

The C-IAM is a first principles whole atmosphere model extending from the surface to the inner magnetosphere.

This type of model allows the whole atmosphere and ionosphere to be considered as a single system with all internal interactions described in a self-consistent manner. In particular, it is able to describe in a self-consistent way the impact of lower atmosphere dynamical variability on the upper atmosphere and ionosphere and vice versa.

Internationally, similar models have been developed in the USA (IDEA, NOAA; WACCM-X, NCAR) and Japan (GAIA, Kyushu University), and are planned to be developed in the UK (MetOffice).

Motivation:

1. To provide model support for satellite missions and ground-based observations.

2. To improve space weather forecasting by taking into account the perturbations originating in the lower atmosphere.

3. To estimate the impact of the upper atmosphere on the lower atmosphere (mesosphere, stratosphere and, possibly, troposphere).

4. To potentially improve weather forecasting and, in particular climate studies, by removing effects of the artificial upper boundary conditions.

Model description:

<u>Interactive neutral atmosphere and ionosphere</u>

The C-IAM has been developed on the basis of two existing state-of-the-art first principles global models:

- The atmospheric part of the C-IAM is based on the extended Canadian Middle Atmosphere Model (CMAM) which describes the neutral atmosphere from the surface up to ~200-350 km (depending on solar activity level);
- The ionospheric part of the C-IAM is based on the Upper Atmosphere Model (UAM) which describes the ionosphere and inner magnetosphere, and includes the electric fields of both magnetospheric and dynamo origin.

Atmospheric part of the C-IAM (eCMAM):

A vertically extended GCM with interactive chemistry.

- spectral resolution: T31 (horizontal resolution 6 degrees)
- vertical domain: from the surface up to 2×10^{-7} hPa, ~250-300km, $\Delta z \leq 0.35$ H
- comprehensive troposphere and middle atmosphere
- full expanded chemistry from 400 hPa up to the model top (99% of the atmosphere is actively simulated, the remaining ~1% being noble gases)

Upper atmosphere features:

- molecular diffusion is active on momentum, heat and species. It produces species separation above the homopause
- eddy diffusion generated by the GWD scheme (Hines, 1997)
- non-LTE effects in radiative heating and cooling

Ionospheric part of the C-IAM:

Lower Ionosphere block

$n(XY^+)$ photochemical equilibrium

T_i, T_e — energy balance equation

$\vec{v}_i$ — momentum equation

Ionization rates: $q(O_2^+)$, $q(NO^+)$, $q(N_2^+)$, $q(O^+)$

Upper Ionosphere and Inner Magnetosphere block

$n(O^+)$, $n(H^+)$ — continuity equation

$v_{\|}(O^+)$, $v_{\|}(H^+)$ — momentum equation

T_i T_e — energy balance equation

Electric field block

$\varphi(\vec{E})$ - magnetospheric and dynamo

FAC (field aligned currents)

Pedersen and Hall conductivities

Covers the altitude range from 80 km to 15 Earth radii and takes into account the offset between the geomagnetic and geographic axes of the Earth. The quasi-hydrodynamic equations of continuity, motion and heat balance for ions and electrons, and the Poisson equation for the electric field potential are solved numerically.

Being based on a comprehensive GCM (CMAM), C-IAM is able to self-consistently produce a realistic spectrum of atmospheric waves in the lower atmosphere, generated by solar heating, hydro cycle, orography etc. CMAM has been validated through numerous comparisons of the CMAM results with satellite observations (e.g., WINDII and SABER).

This model feature is crucial for the ionospheric part of the C-IAM: model studies and observations (e.g., Rishbeth and Mendillo, 2001; Liu et al., 2013) have shown that under moderate solar and geomagnetic activity not less than 50% of the day-to-day variability in the ionosphere/thermosphere is caused by the perturbations originating in the lower atmosphere and propagating upward.

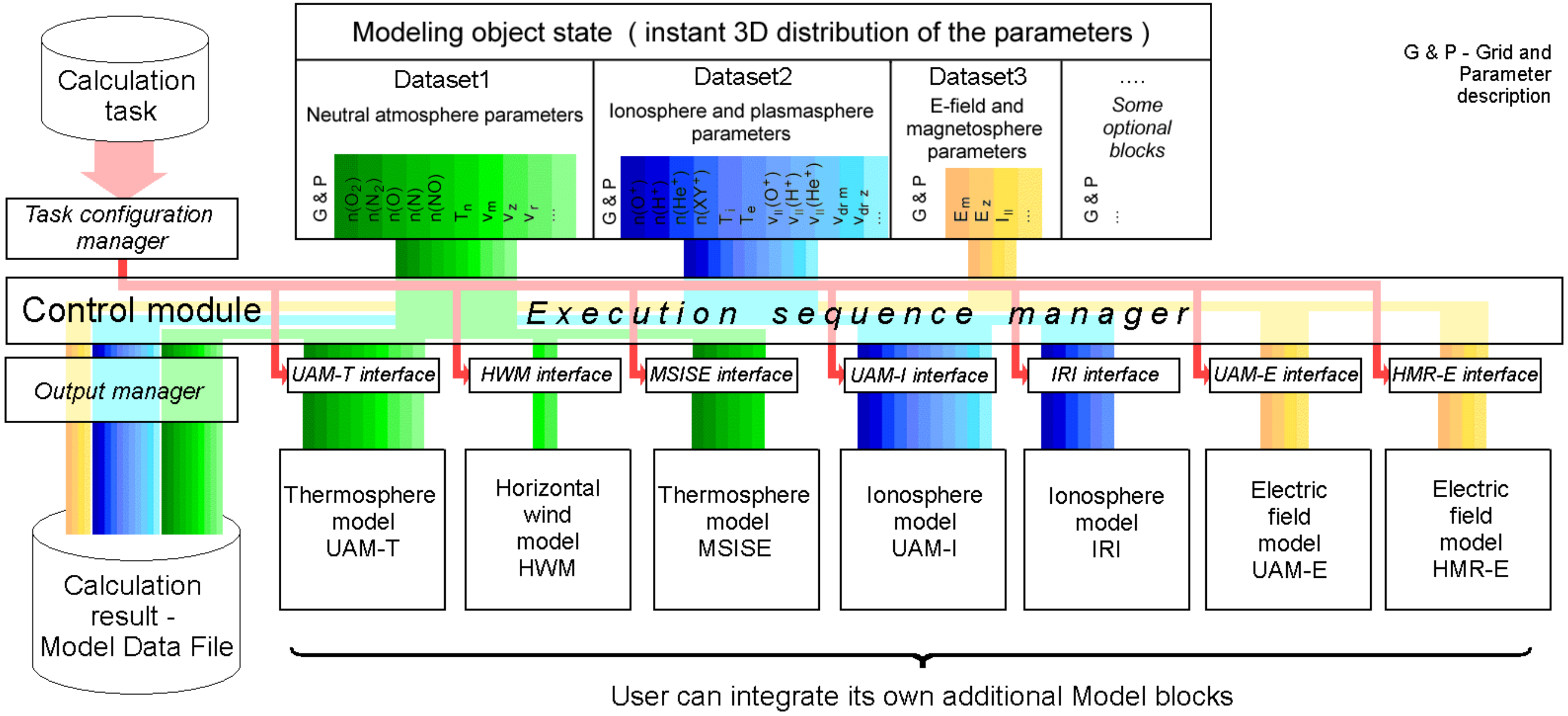
The C-IAM is not just “a self-consistent atmosphere model”. In addition to interactive physics based blocks, it includes a few alternative empirical models, which can be used in any combination. Such architecture provides much more flexibility.

This approach is based on the object-oriented programing ideology. The models to be integrated are considered as “black boxes”. They need some input, which provided by other models included into the system, and return some output – numerical values of some physical fields in some spatial points. How exactly they do it is not important.

Simply, the model integration task here is not about physical equations but about data flows control.

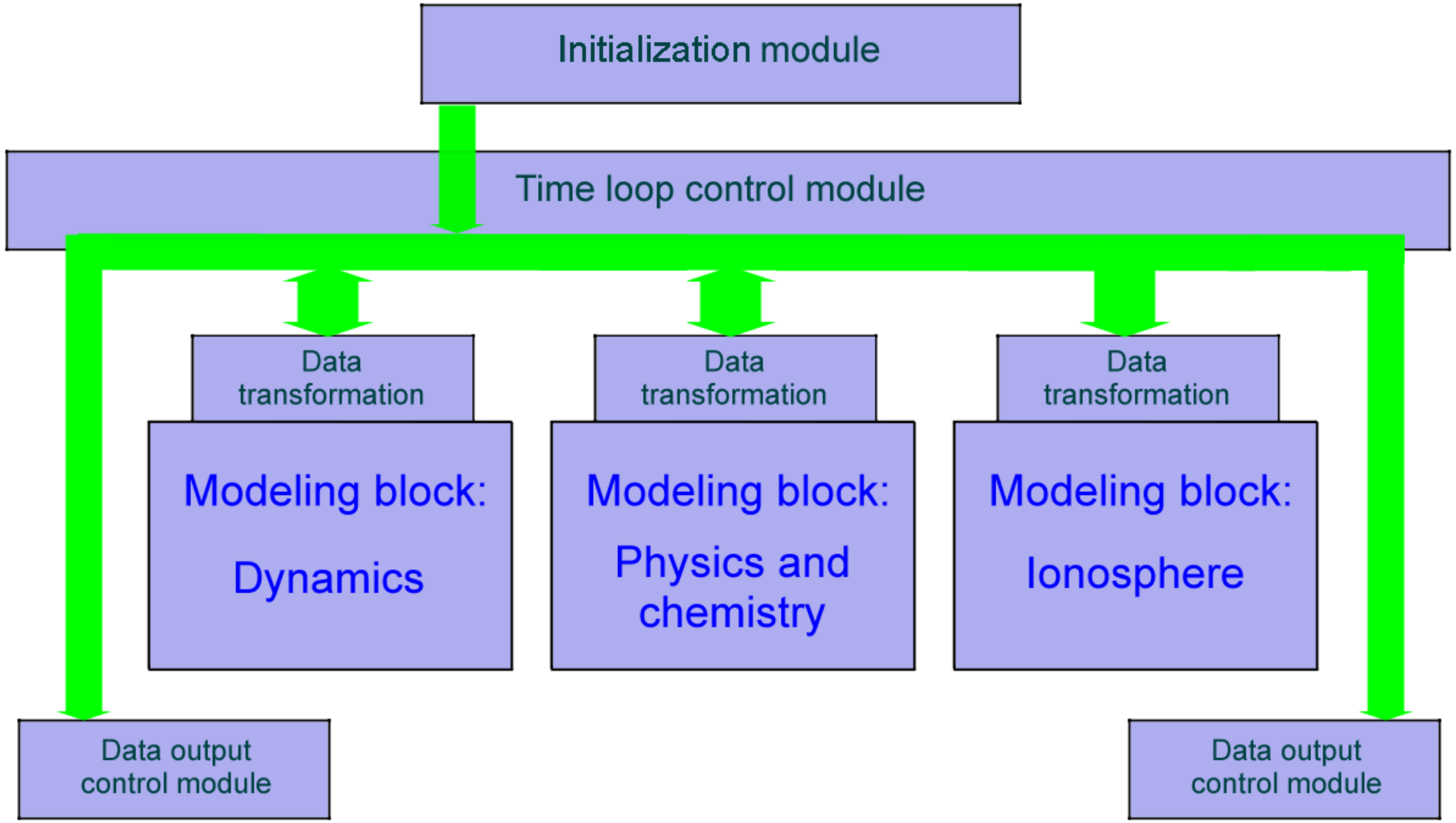
This allows for easy substitution of any such model by another one providing values for the same variables. As an example in theoretical studies we can substitute self-consistent calculation of some fields by empirical model in order to switch off some interactions to separate their impact in order to study their role. Or we can feed the model by the observation results in order to reproduce specific events. This feature is being actively used in the C-IAM.

The UAM structure



A set of alternative models of possible atmospheric domains and processes and a tool to assemble from them any desired model combination

The C-IAM structure



Allows the C-IAM to be used in different modeling combinations

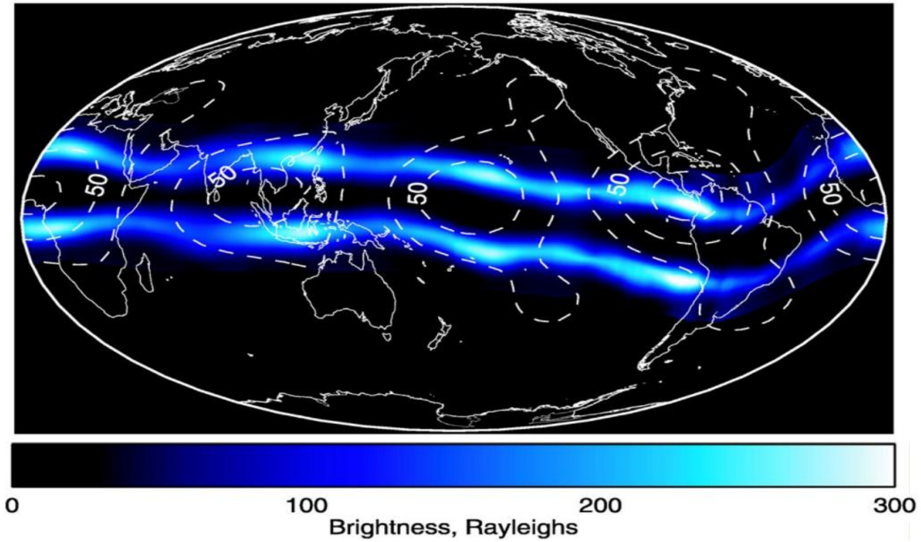
Spatial structure of the 135.6 nm nighttime ionospheric emission (impact of the lower atmosphere on the ionosphere)

Reconstruction of nighttime ionospheric emissions from observations with the IMAGE-FUV imager [*Immel et al*., 2006]

Radiative recombination of the O^+ ion:

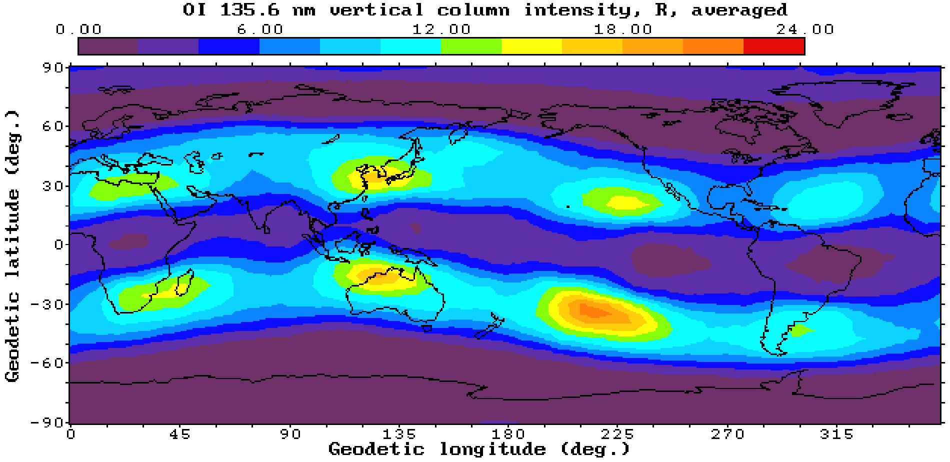
$$O^+ + e^- \rightarrow O^* \rightarrow O + h\nu$$

The 135.6-nm glow is produced by the ^5S-^3P transition.



The C-IAM is able to reproduce the observed wave-4 structure, which is caused by modification of the ionospheric electric field in the E region by waves penetrating from the lower atmosphere (mainly DE3 generated in the troposphere).

Martynenko et al., JASTP, 2014



These images are representative of the local ionospheric properties at 20:00 LT, averaged over March, 20 – April, 20, 2002

Emission intensity obtained using different combinations of neutral atmosphere modeling options

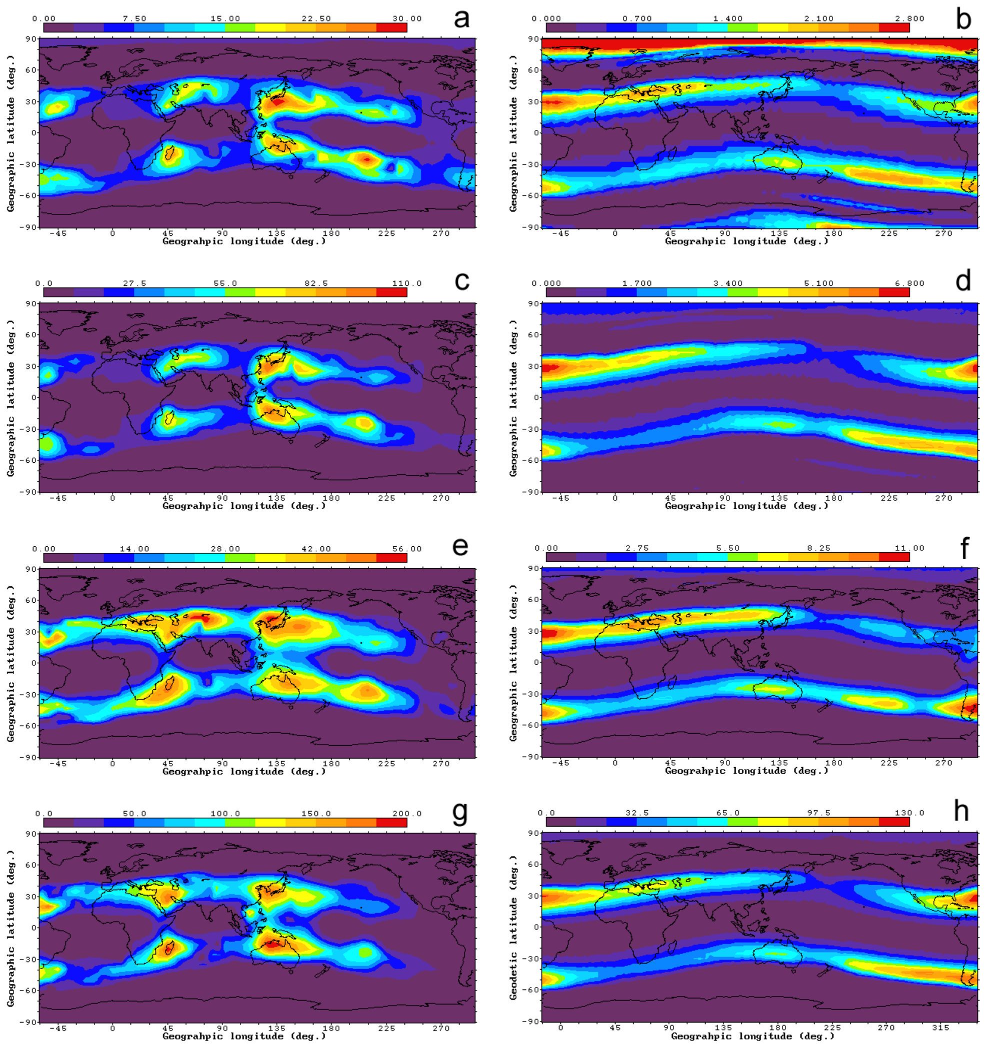
Wind: C-IAM HWM

Temperature: C-IAM
Composition: C-IAM

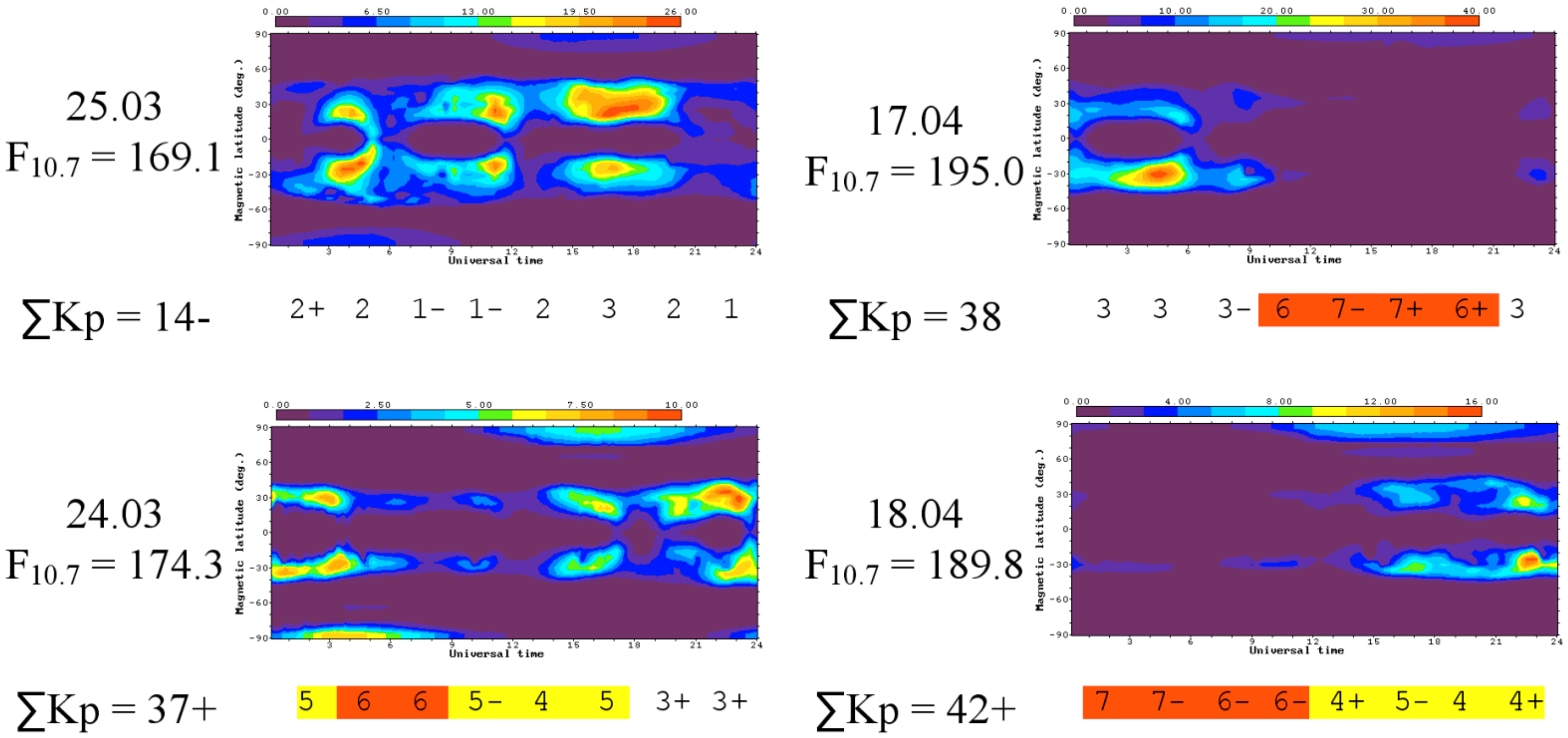
Temperature: C-IAM
Composition: MSISE

Temperature: MSISE
Composition: C-IAM

Temperature: MSISE
Composition: MSISE



Spatial structure of 135.6 nm nighttime ionospheric emission (impact of the magnetosphere on the ionosphere)



3-hr K_p index values are shown below the panels.

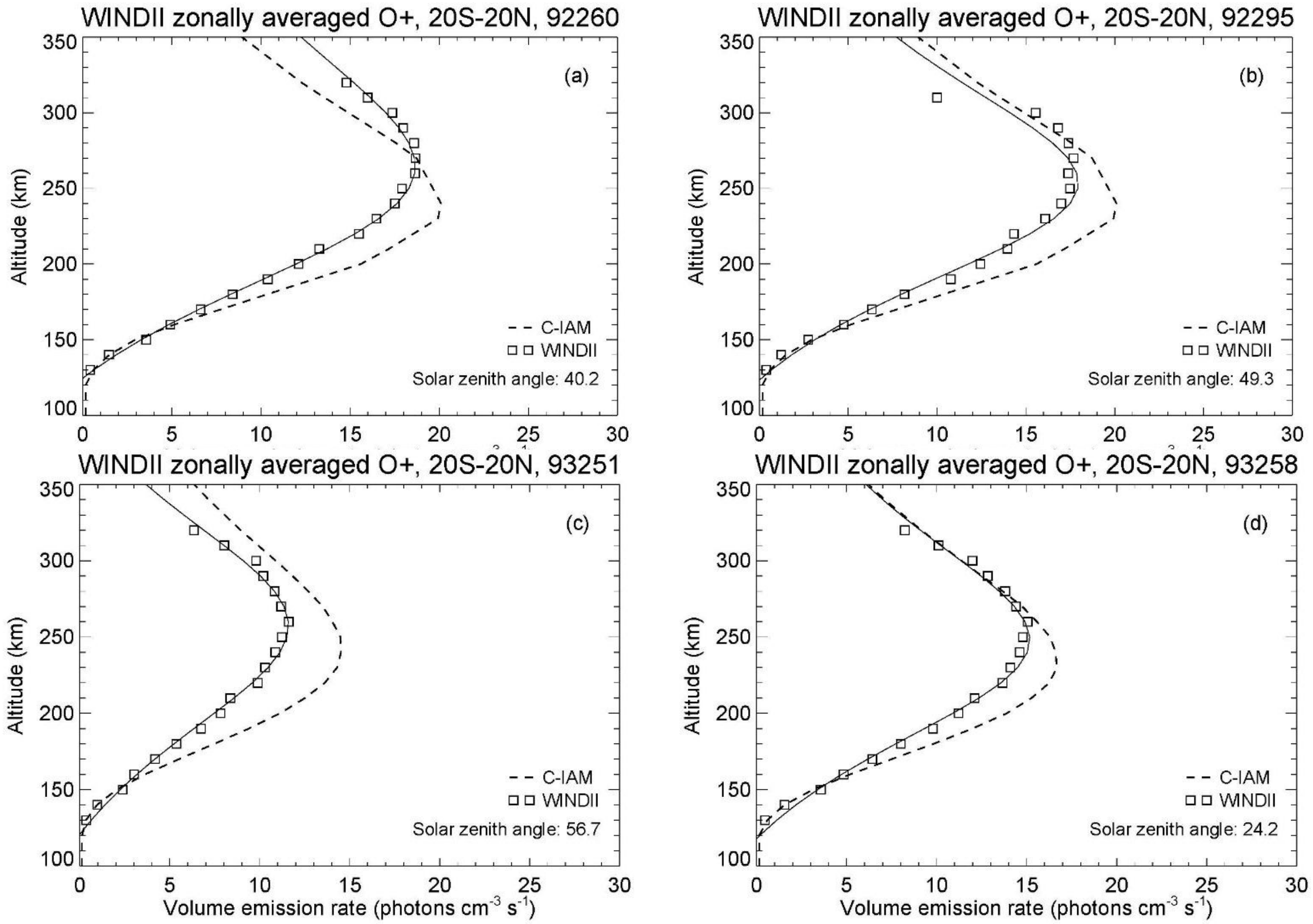
The WN4 structure may be fully suppressed by geomagnetic substorms.

732 nm $O^+(^2P)$ emission modeling

$O + h\nu_{EUV} \rightarrow O^+(^2P) \rightarrow O^+(^2D) + h\nu_{732}$

Due to the short $O^+(^2P)$ lifetime (~4.6 s) this glow characterizes an instant state of the thermosphere. This is different from the nighttime 135.6 nm emission whose intensity depends on plasma accumulated during the daytime.

WINDII data (squares) for four different days, fitted with a solid line;
and C-IAM simulations (dashed).
(Shepherd et al., GRL, 2014).



Good agreement between the model and WINDII $O^+(^2P)$ 732.0 nm volume emission rate

O density retrieving from the WINDII observation

$$O + h\nu_{EUV} \rightarrow O^+(^2P) \rightarrow O^+(^2D) + h\nu_{732}$$

The 732 nm $O^+(^2P)$ emission intensity depends on the O density and EUV flux. It is possible to retrieve the [O] concentration from airglow observations.

The C-IAM has been applied to the extraction of O density from WINDII 732 nm $O^+(^2P)$ emission observations.

For the retrieval of the [O] concentration, the model was iterated using the [O] values to bring the C-IAM O+ emission profiles into agreement with the WINDII 732 nm observations.

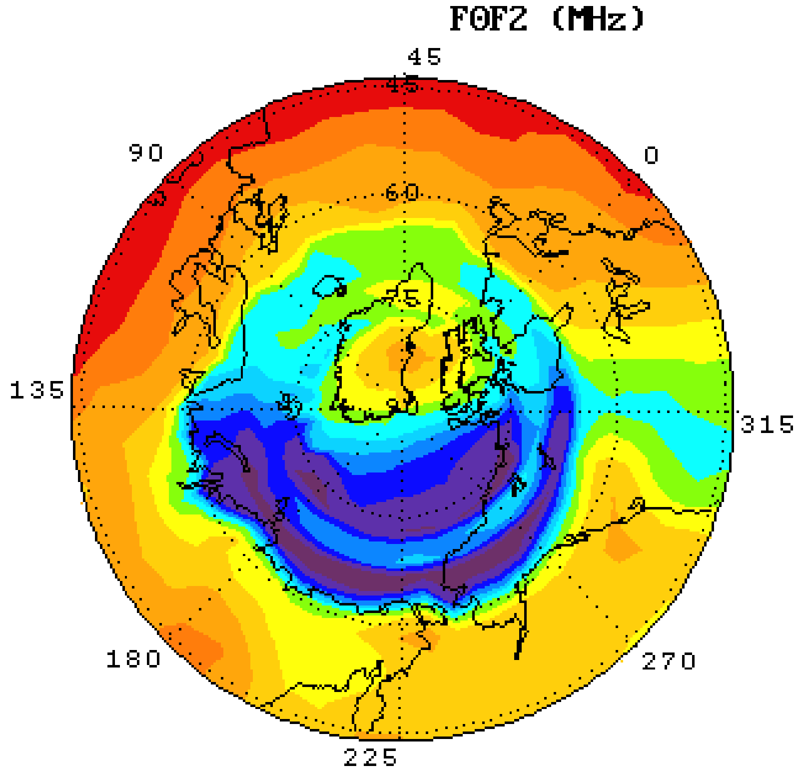
Shepherd et al., 2016, submitted to JASTP

High-latitudinal observations as the C-IAM input

In order to reproduce real events, the high-latitudinal electric field distribution observed by SuperDARN network can be used as the C-IAM external forcing. This allows the neutral atmosphere and ionosphere response to specific space weather events to be reproduced: temporal and spatial variations of neutral and charged atmospheric components density, temperature and motion.
The SuperDARN data are provided by Prof. Kathryn McWilliams (University of Saskatchewan).

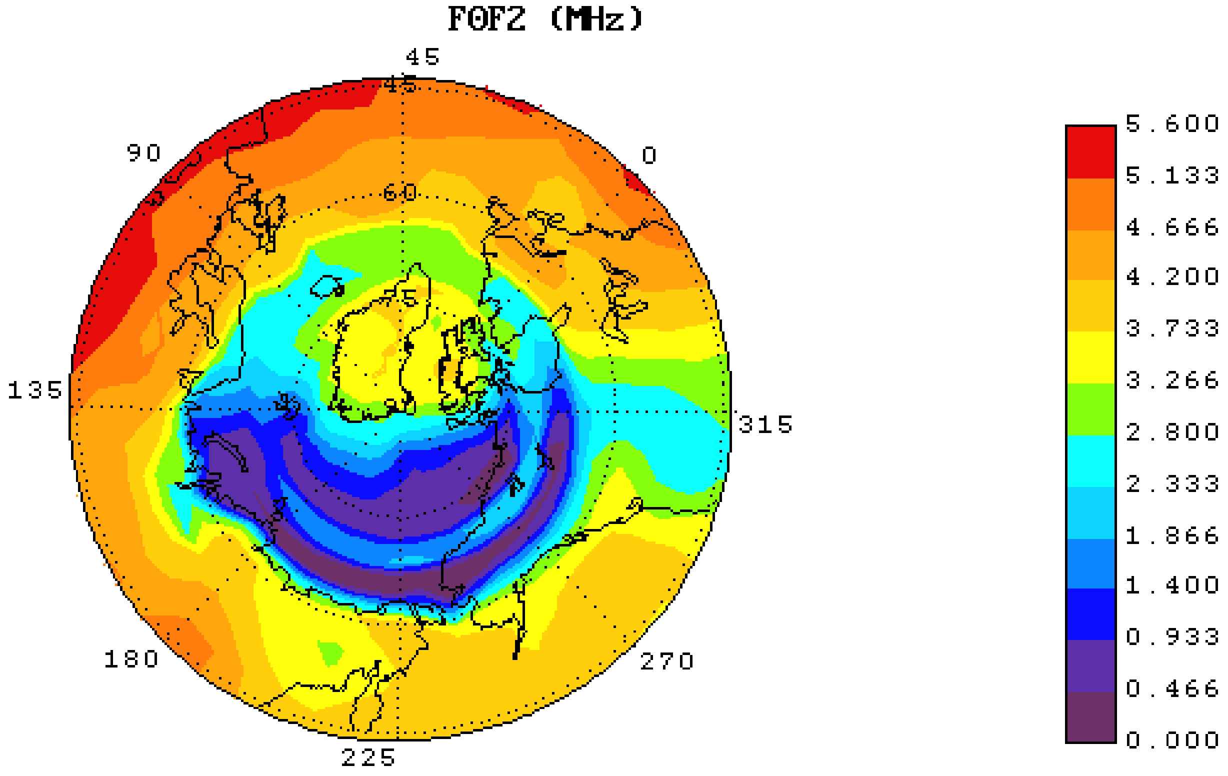
It is also possible to use observed auroral precipitation fluxes (spatial distribution and energetic spectrum) as the C-IAM input, however, this option has not been tested yet.

SuperDARN observations vs K_p proxy as the C-IAM input



Proxy by K_p

10.10.2010 13:40 UT



SuperDARN

10.10.2010 13:40 UT

C-IAM simulations with the use of Kp proxy and SuperDARN data show similar overall ionospheric structures, but there are differences in small-scale details. This can be useful for interpretation of local observations and phenomena.

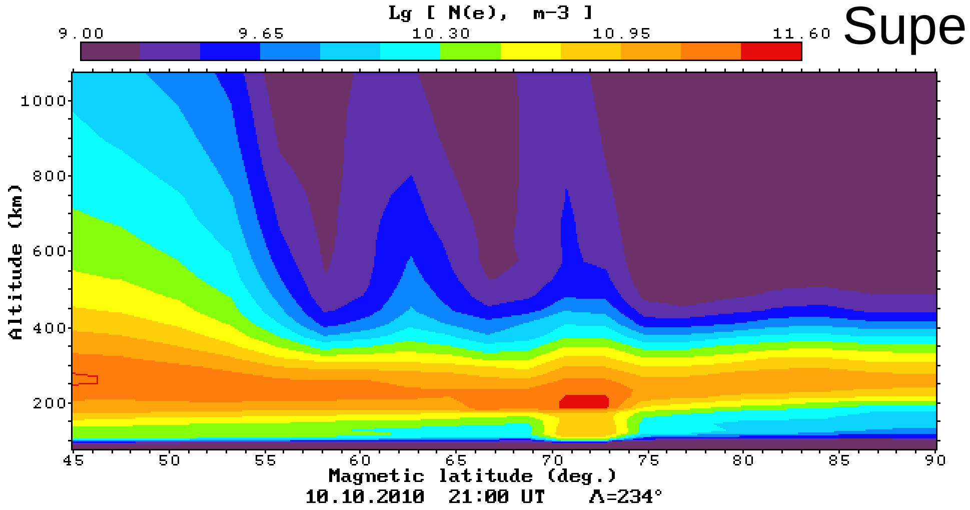
SuperDARN observations vs K_p proxy as the C-IAM input

Both C-IAM configurations reproduce the polar ionosphere structure well and are suitable for general studies.

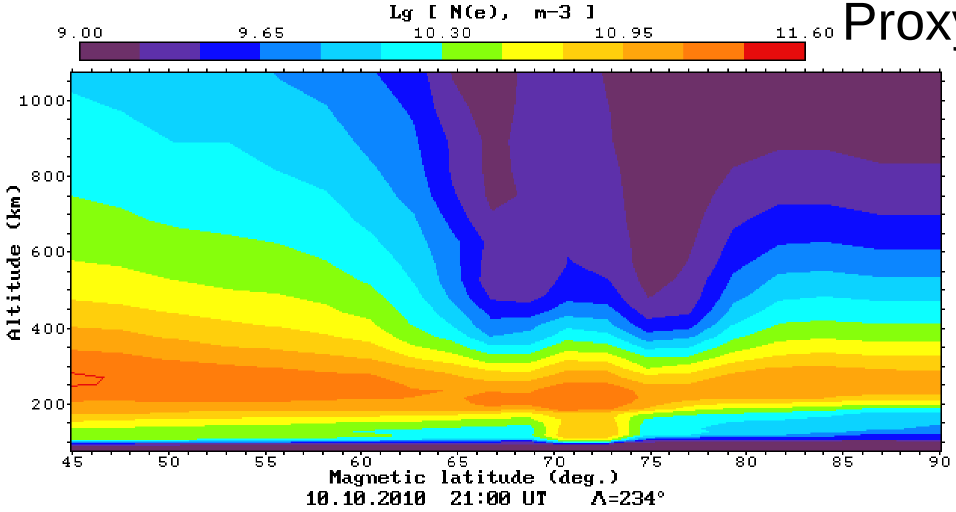
However, using the SuperDARN data allows detailed features in the plasma density distribution to be reproduced, especially in the topside ionosphere at high latitudes. This capability can be important for model use in “real world” tasks, such as model support of satellite and ground-based observations.

Plasma density ~ 9 a.m. LT

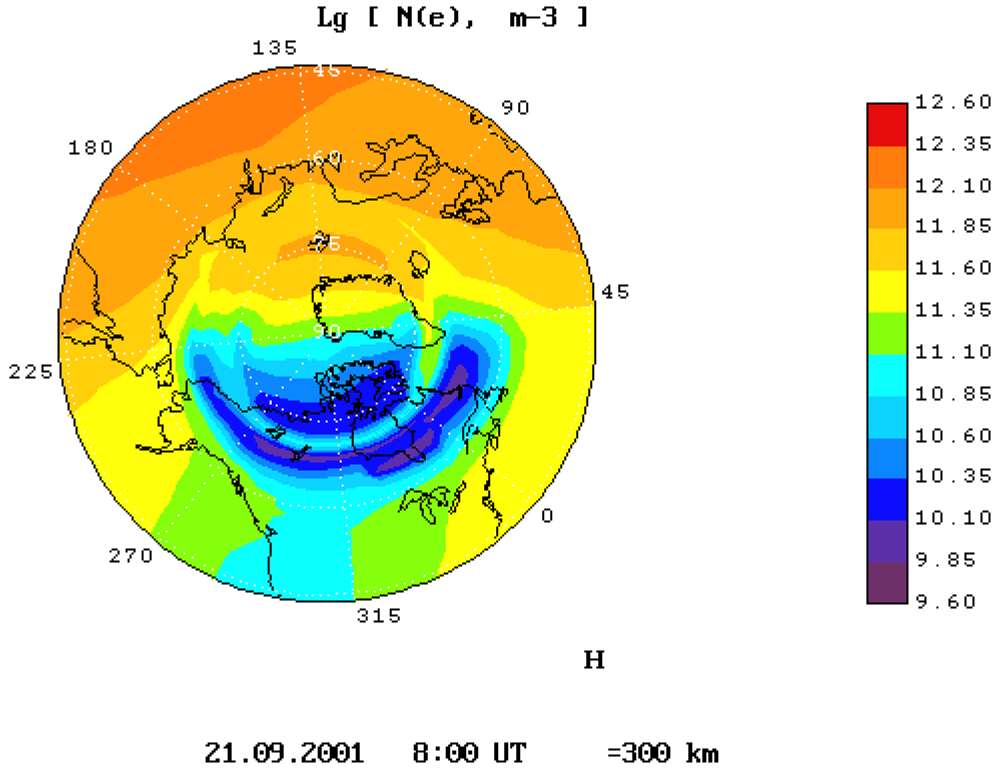
SuperDARN



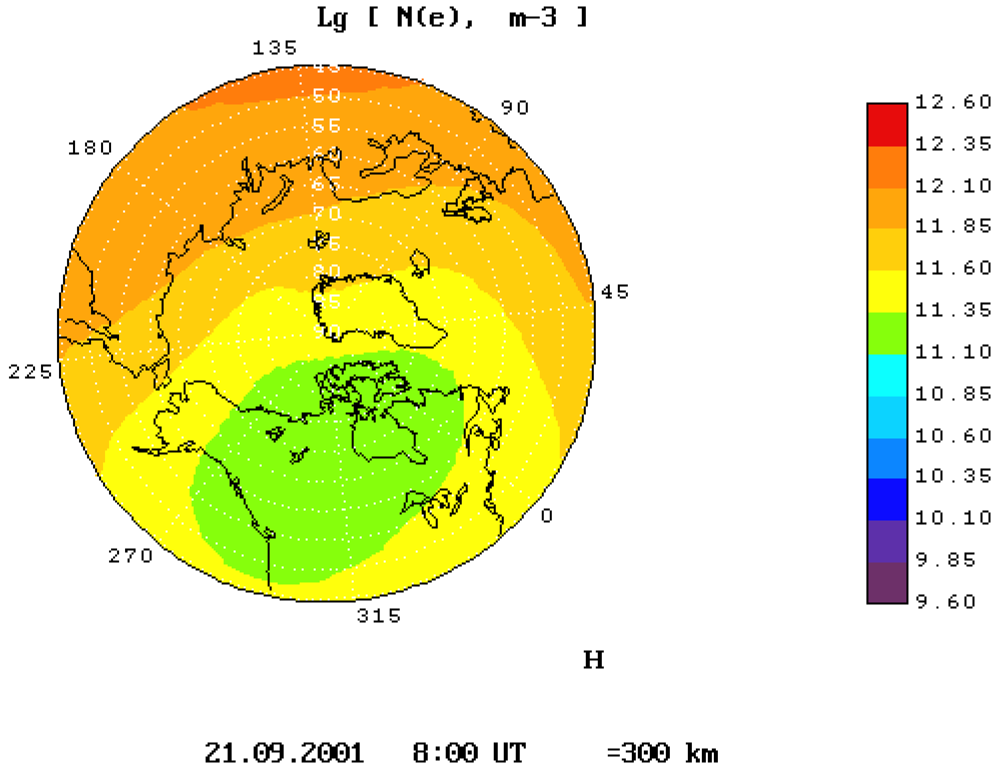
Proxy by K_p



C-IAM vs IRI



C-IAM



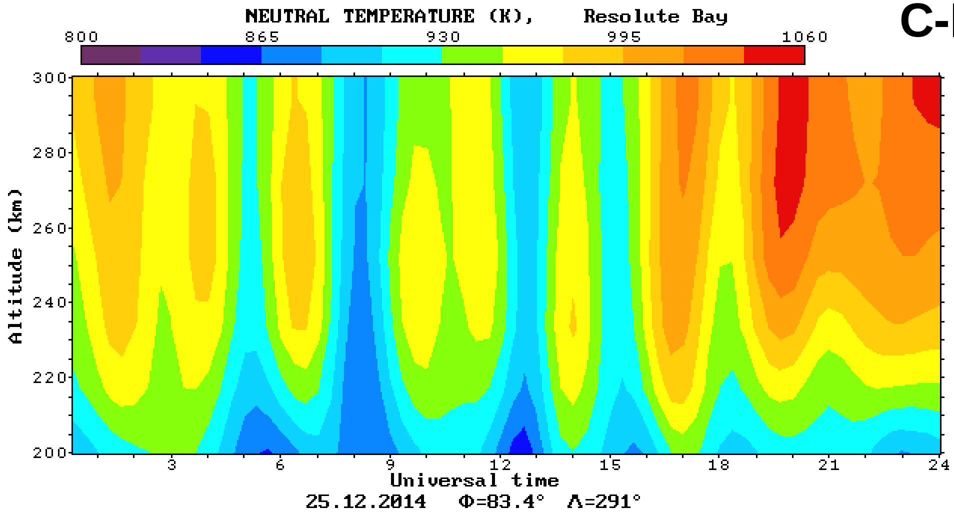
IRI-2012

The C-IAM can reproduce ionosphere structure better than empirical models and is a suitable substitute, thereby increasing the quality of interpretations of the observations.

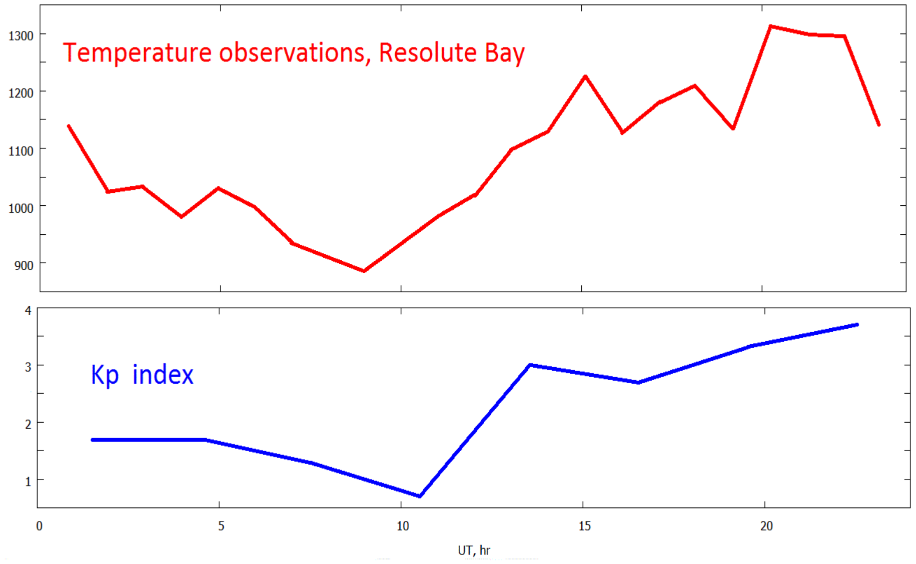
Time-series of temperature: model and observations

Neutral temperature, Resolute Bay, 25.12.2014

C-IAM



Observations



Doppler temperature from O(^{1}D) 630 nm emission observed at Resolute Bay (75ºN, 95ºW) vs C-IAM:

a) T correlated with Kp;

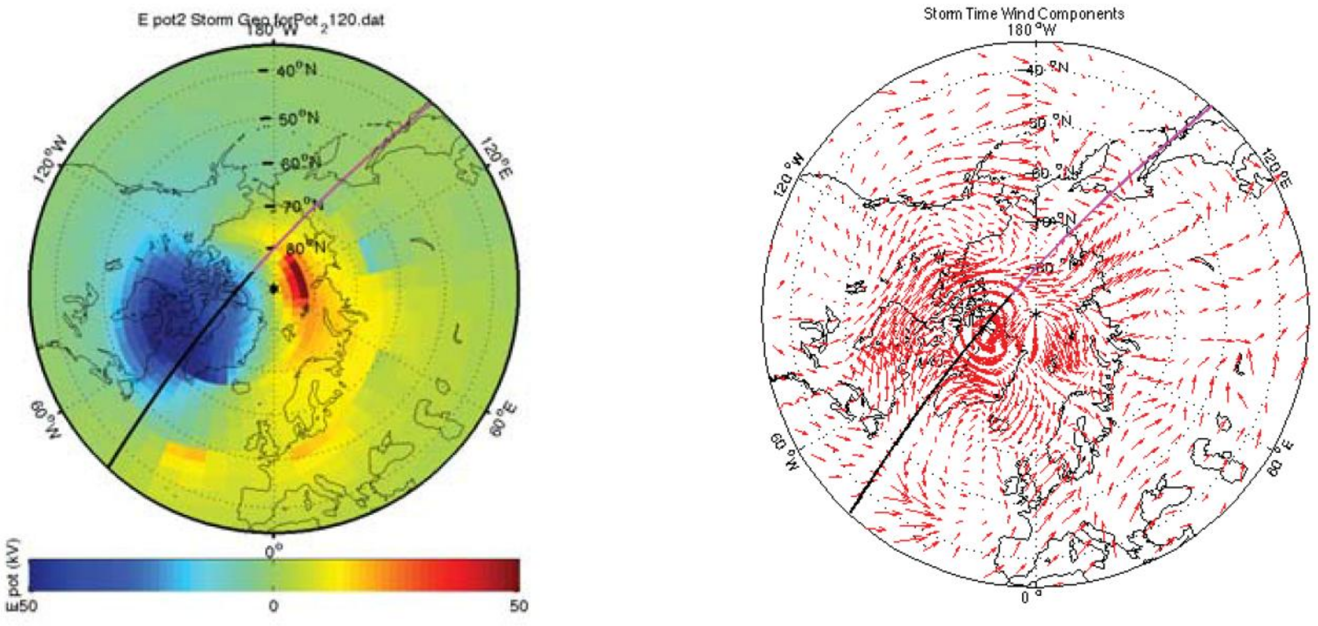
b) good agreement between C-IAM and observations.

Note, the observed results represent T obtained from a wide area over a few hundreds km in the horizontal and a few tens of km in the vertical, whereas C-IAM presents data over the observatory.

In collaboration with Prof. William Ward (UNB)

Model support of the GOCE satellite mission

It was discovered that geomagnetic disturbances at high latitudes appear to affect the motion of the GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite, resulting in significant errors in the determination of Earth’s gravity field (Ince and Pagiatakis, 2016, submitted to Journal of Geodesy).



Electric potential and neutral winds during storm time at 21:20:00 UTC

Preliminary C-IAM simulations showed strong neutral wind and electric field variations that spatially correlate with irregularities measured by GOCE gravity gradiometer during geomagnetic active days.

This task is still in progress
(in collaboration with Prof. Spiros Pagitakis, York University)

Conclusion

The C-IAM is now ready and proven to be reliable tool for different types of studies: both theoretical and model support of satellite and ground-based observations.

It has already been successfully applied to a few investigations and will be applied to a few more tasks (given suitable Canadian future funding support).

Collaboration is welcome.

Thank you!

The C-IAM project was funded by the Canadian Space Agency