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# Development of the Canadian Ionosphere and Atmosphere Model

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The C-IAM is a **3D global** whole atmosphere model based on first principles and extending **from the Earth's surface to the inner magnetosphere**.

Such types of models consider large-scale features in a whole atmosphere and ionosphere that are treated as a single system with all internal interactions described in a self-consistent manner.

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

## Motivation for the C-IAM development:

1. To provide a model support for satellite missions and ground-based observations, mainly for the Canadian Atmospheric and Space Physics Communities.
2. To improve the space weather forecasting by taking into account the perturbations originating in the lower atmosphere (note, 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.**)
3. To estimate the impact of the upper atmosphere on the lower atmosphere (mesosphere, stratosphere and, possibly, troposphere), including the **impact through NO<sub>x</sub> and O<sub>x</sub>** created by solar EUV radiation and by Energetic Particle Precipitation and transported down from the thermosphere.
4. To potentially improve weather forecast and, especially, climate studies by removing effects of the artificial upper boundary conditions used in lower-lid models.

## Model description:

### **Interactive** ionosphere and neutral atmosphere (**global, 3D**)

#### Atmospheric part (a vertically extended GCM with interactive chemistry)

- spectral resolution: T31 (**horizontal resolution 6 degrees**)
- vertical domain: **from the surface up to ~300 km** (depending on solar activity level),  $\Delta z = 0.35 H$
- neutral T, wind and composition extended upward to the whole ionospheric domain  
comprehensive troposphere and middle atmosphere
- full expanded chemistry from 400 hPa up to model top (99% of the atmosphere actively simulated, remaining ~1% being noble gases)

#### Ionospheric part:

- altitude range: **80 km up to 15 Earth radii** (includes inner magnetosphere)
- **variable horizontal resolution** (~2 degrees in auroral area, up to 5 degrees at low latitudes)
- quasi-hydrodynamic equations of continuity, motion and heat balance for ions ( $O^+$ ,  $H^+$ ,  $O_2^+$ ,  $NO^+$ ,  $N_2^+$ ) and electrons
- equation for the electric field potential

1-4 min time step for the full module configuration

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

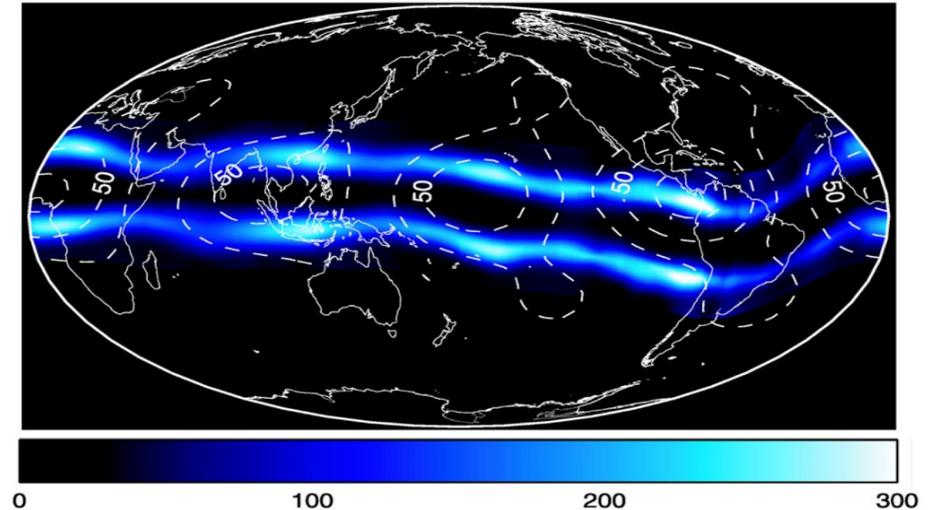
Reconstruction of nighttime ionospheric emissions from observations with the IMAGE-FUV imager [Immel et al., 2006]

A radiative recombination of O<sup>+</sup> ion:



The 135.6-nm glow is produced by the <sup>5</sup>S-<sup>3</sup>P transition.

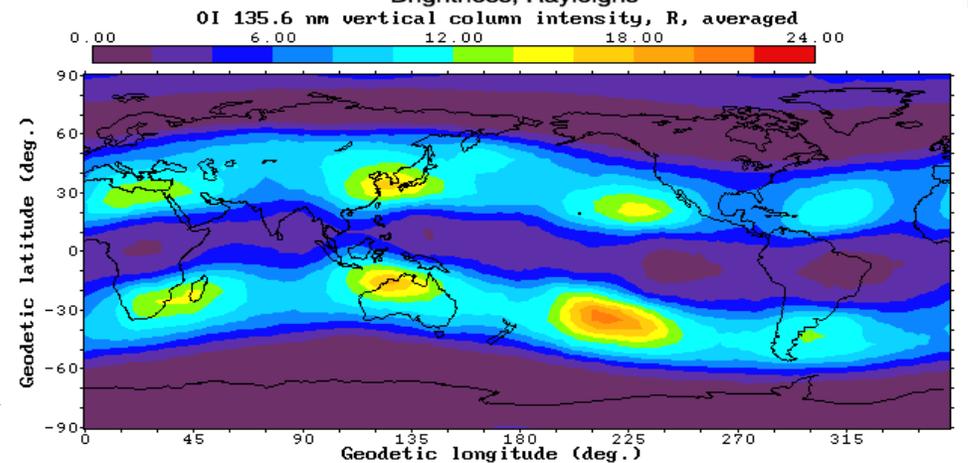
Observations →



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).

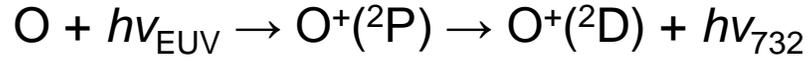
Martynenko et al., JASTP, 2014

Model →



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

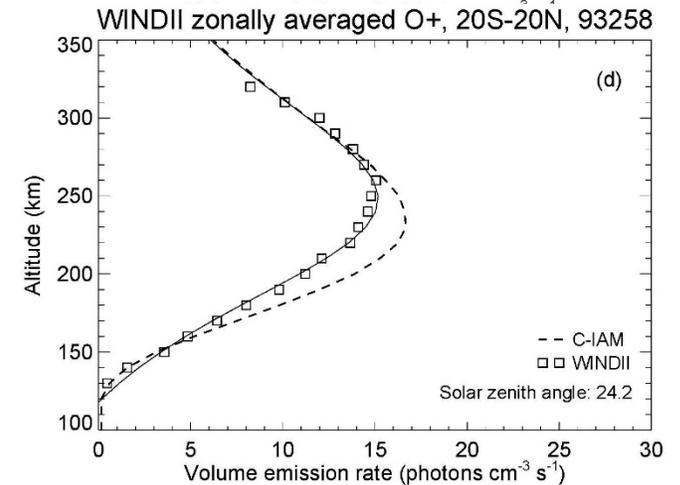
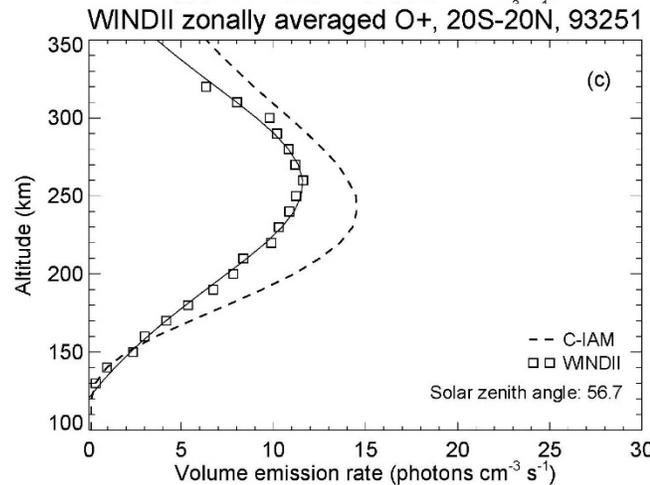
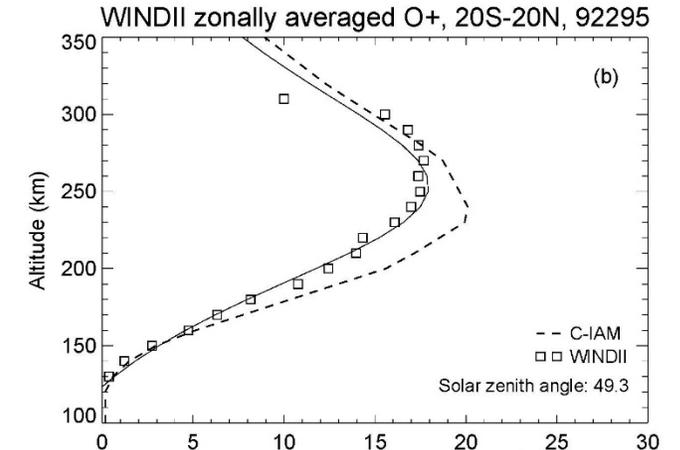
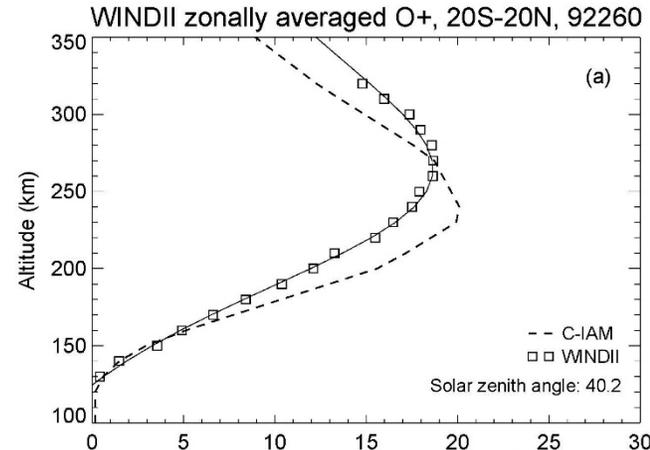
# 732 nm O<sup>+</sup>(<sup>2</sup>P) daytime emission



Due to the short O<sup>+</sup>(<sup>2</sup>P) lifetime (~4.6 s) this glow characterizes an instant state of the ionosphere.

WINDII data for four different days, fitted with a solid line; and C-IAM simulations.

Shepherd et al., GRL, 2014



Squares – WINDII, dashed line – C-IAM

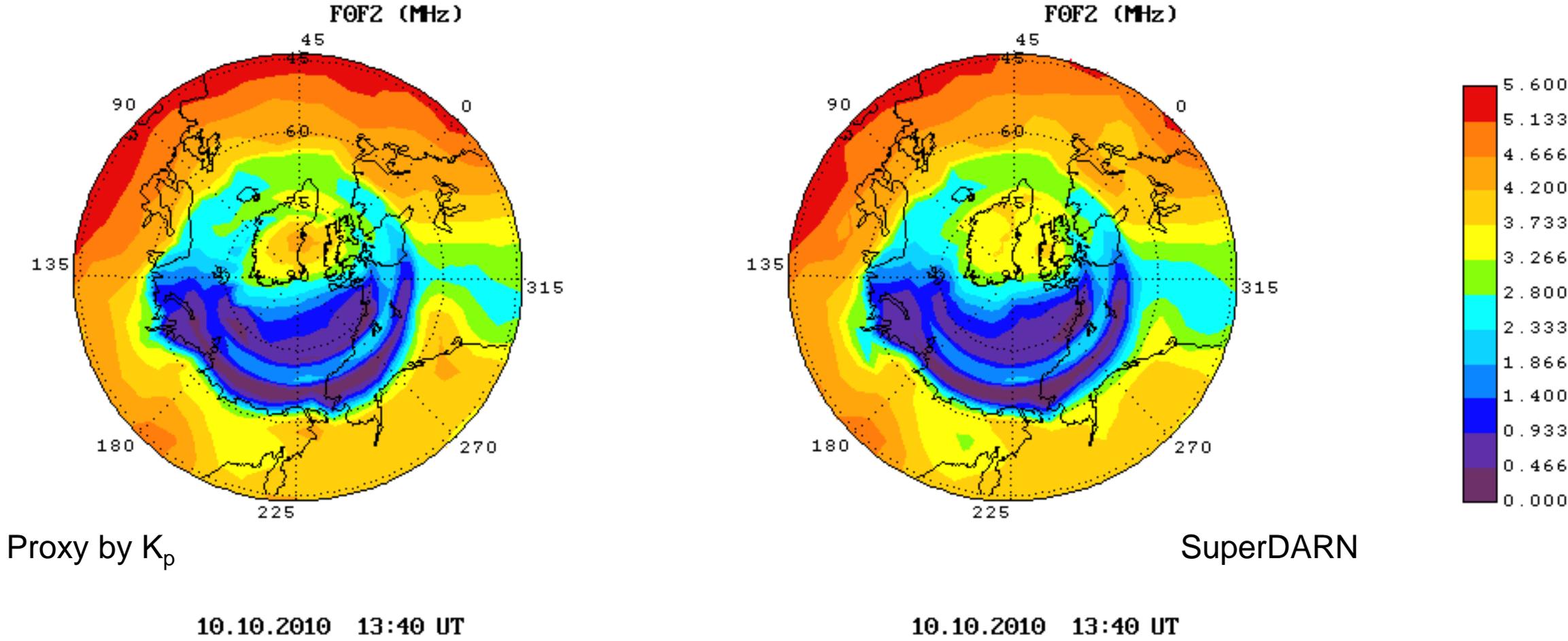
Good agreement of the model and WINDII O<sup>+</sup>(<sup>2</sup>P) 732.0 nm volume emission rate

## High-latitude observations as the C-IAM input

In order to reproduce real events, the high-latitude electric field distribution observed by SuperDARN network can be used as the C-IAM external forcing. This allows for the reproduction of the neutral atmosphere and ionosphere response to specific space weather events: 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 is not tested yet.

# SuperDARN observations vs $K_p$ proxy as the C-IAM input



C-IAM simulations with the use of  $K_p$  proxy and SuperDARN data show similar overall ionospheric structure, but there is difference in small-scale details. This can be useful for interpretations of local observations and phenomena.

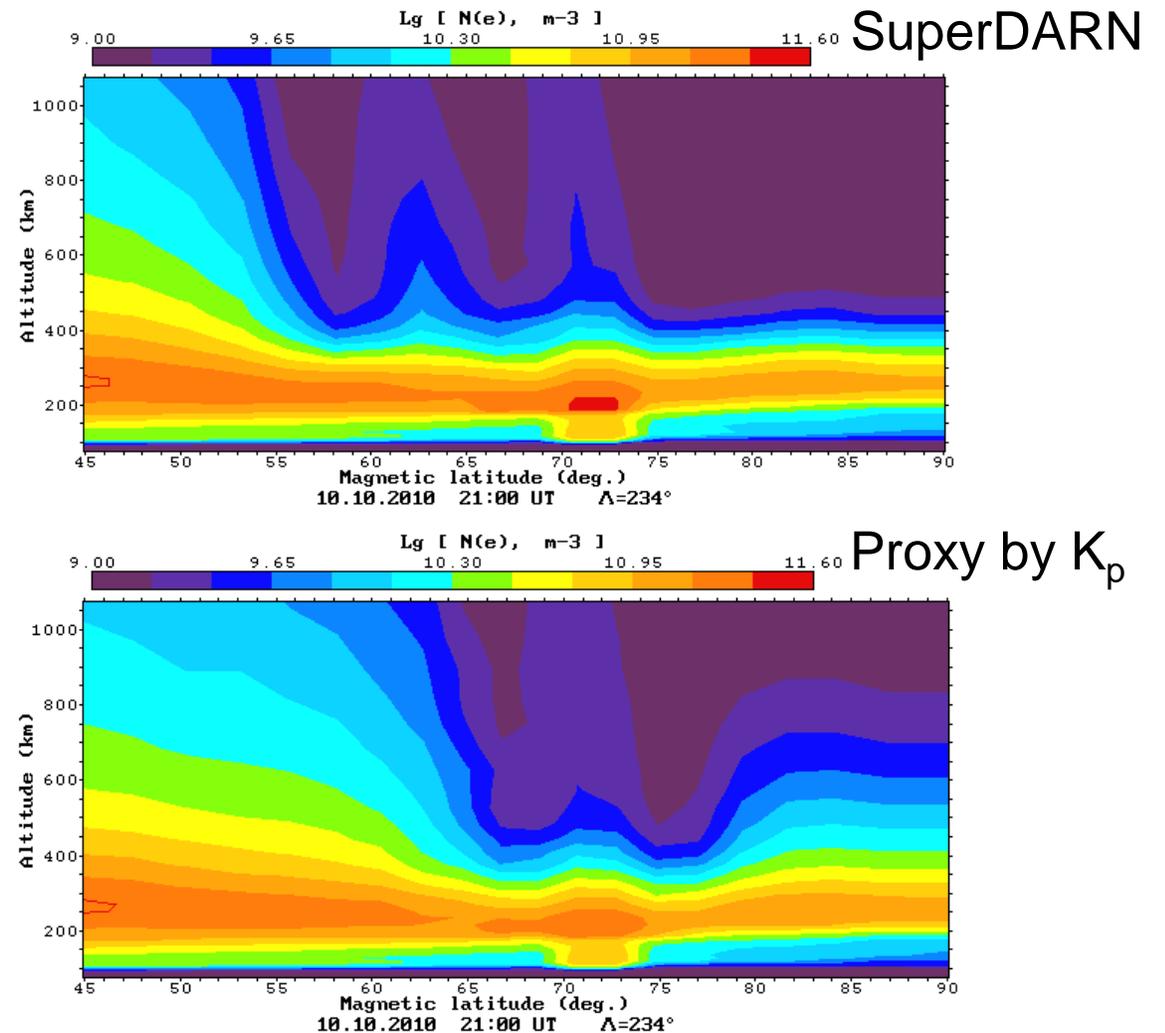
# SuperDARN observations vs $K_p$ proxy as the C-IAM input

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

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

Applicable to ePOP and Swarm missions.

Plasma density ~ 9 a.m. LT



# Time-series of temperature: model and observations

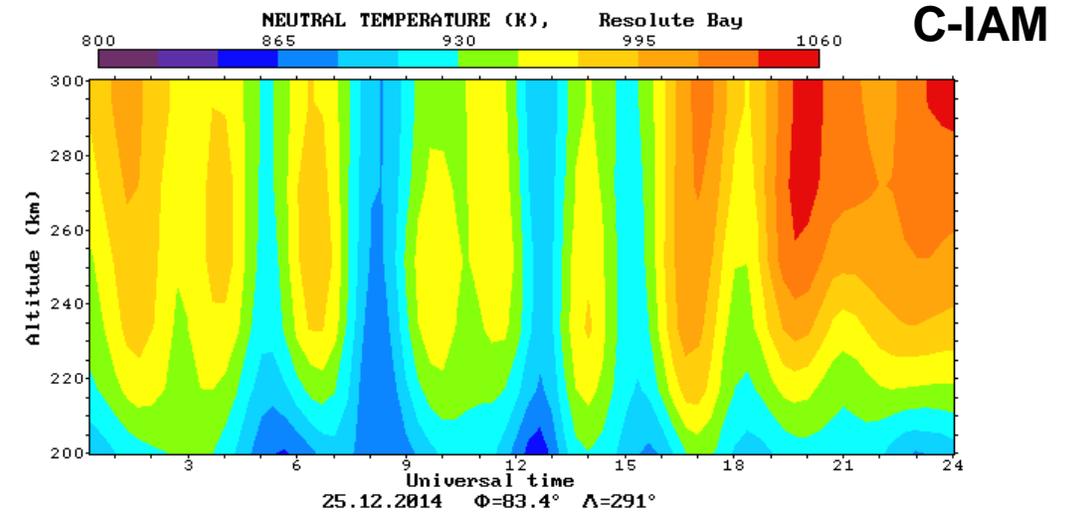
Doppler temperature from O(<sup>1</sup>D) 630 nm emission observed at Resolute Bay (75N, 95W) vs C-IAM:

- a) T correlated with Kp;
- b) good agreement between C-IAM and observations.

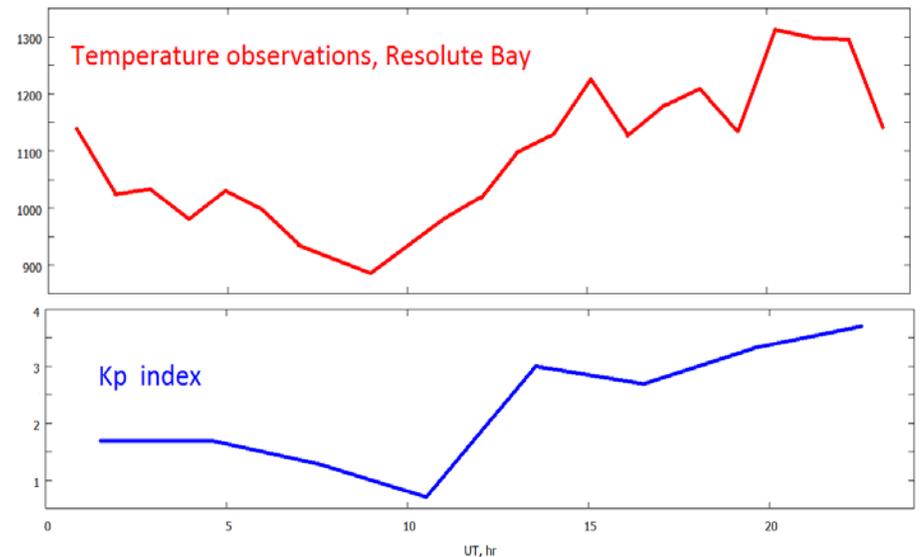
Note, observed results represent T averaged over a few hundreds km in horizontal and a few tens km in vertical, whereas C-IAM presents data over the observatory.

In collaboration with Prof. William Ward (UNB)

Neutral temperature, Resolute Bay, 25.12.2014

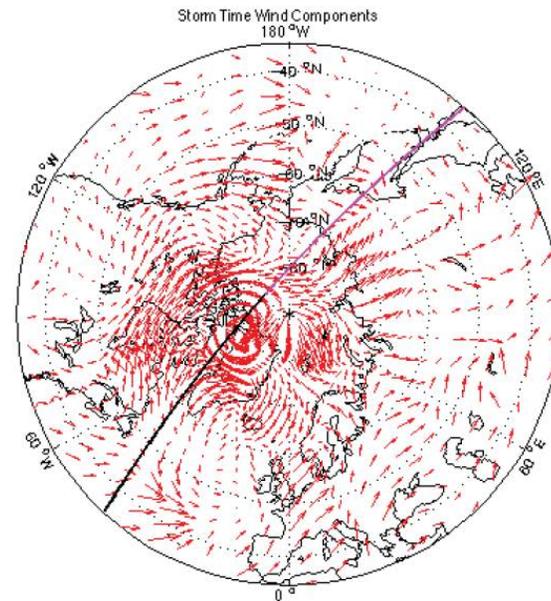
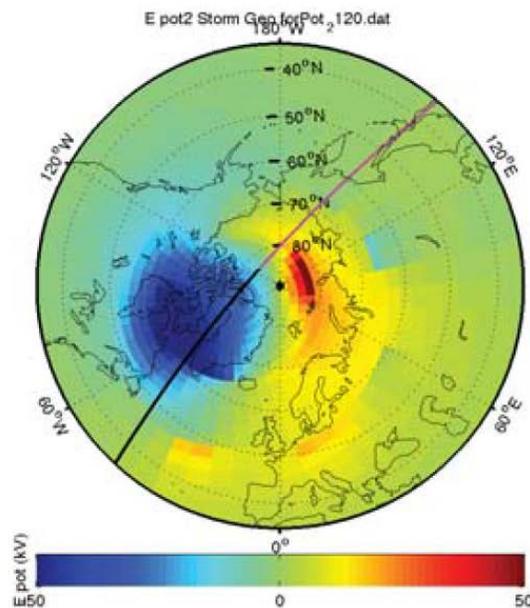


Observations



# 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 (Sinem Ince and Spiros Pagiatakis, 2016, submitted to the 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 Pagiatakis, York University)

## Conclusions

1. The C-IAM has been developed and successfully applied to some specific tasks.
2. It is shown that the model is able to:
  - reproduce the impact of the lower atmosphere on the ionosphere (study of the 4-wave structure in the 135.6 nm emission, slide 5)
  - reproduce the thermospheric atomic oxygen concentration (study of the 732 nm emission, slide 6)
  - accommodate the high-latitude electric field distribution observed by the SuperDARN network in order to reproduce real ionospheric events (slides 8-10)
  - reproduce the neutral thermosphere response to geomagnetic variations in study of Doppler temperature variation, (slide 10),
  - generate perturbations associated with the GOCE satellite orbit, (slide 11)

3. Collaboration is welcome.

**Thank you!**

*The C-IAM project has been supported by the Canadian Space Agency*

**Back up slides**

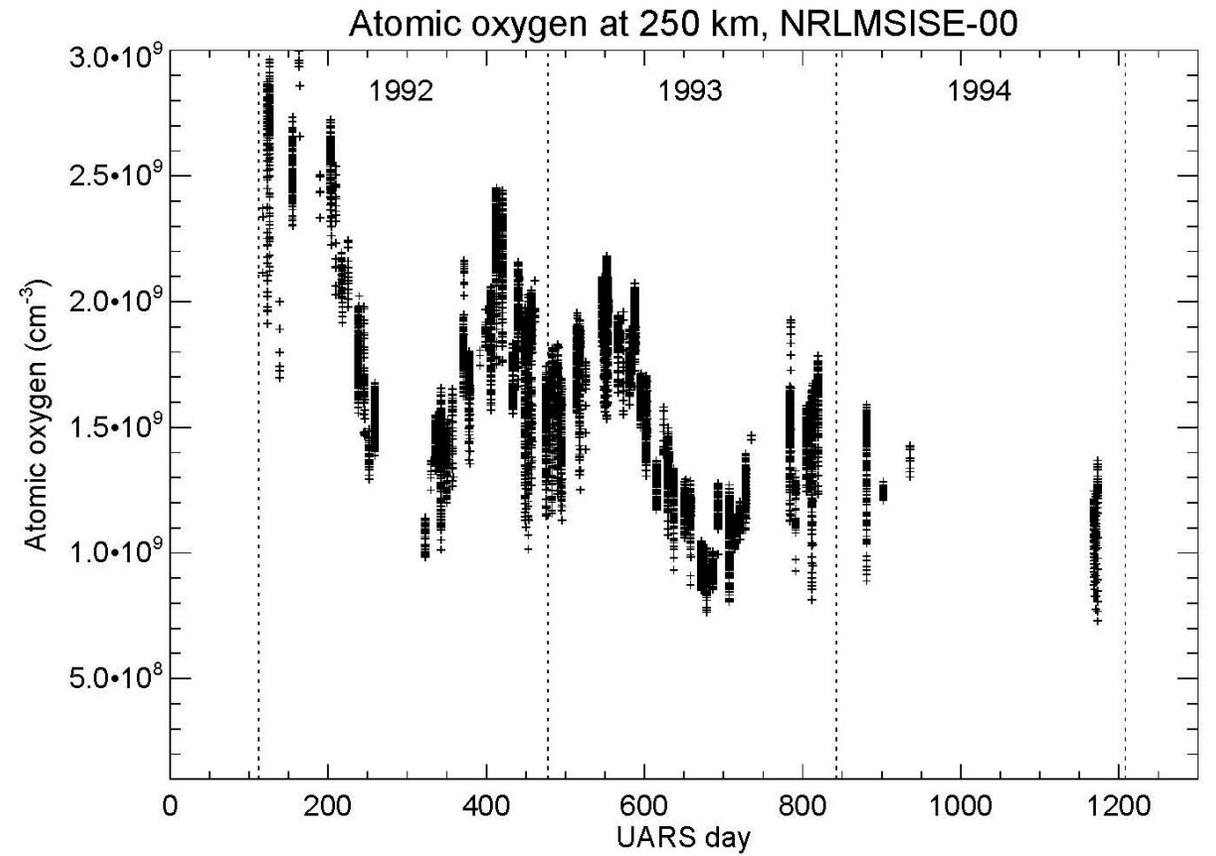
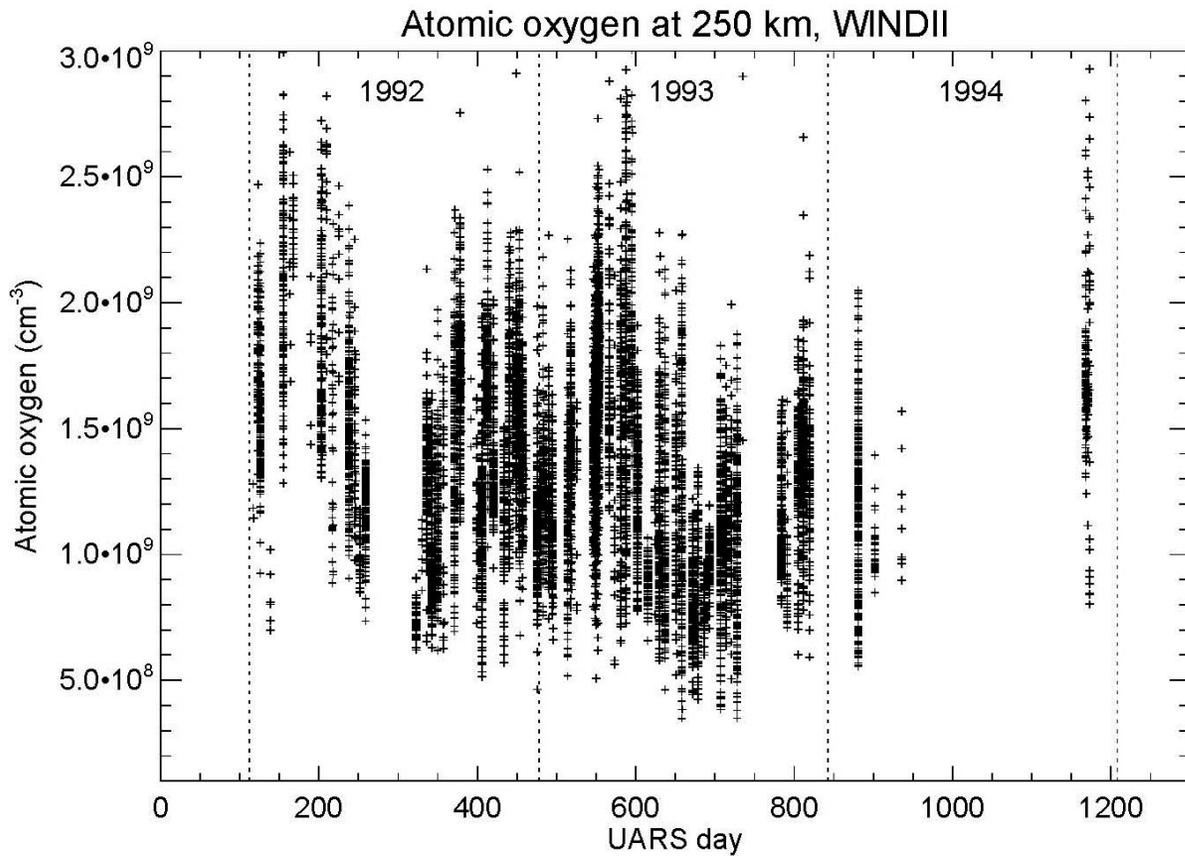
# Future plans

The C-IAM has been applied to some specific tasks. Work planned for the next year:

1. GO Canada network: This study will bridge observations of the ionospheric processes and observations of dynamics of the neutral thermosphere. Observations from SuperDARN and wind observations from Eureka and Resolute Bay will be used.
2. e-POP: Explore the use of the C-IAM model as an improved alternative to IRI and compare both models with e-POP observations in the topside ionosphere at high latitudes.
3. Swarm: Time-dependent spatial distributions of electron density, ion and electron temperatures provided by the C-IAM will be compared with Swarm measurements and incoherent scatter radar observations for specific space weather conditions.
4. GOCE: The C-IAM will be used to identify the physical mechanisms responsible for perturbations in the observations of the Earth's gravity field, which are as yet not very well understood.
5. WINDII: The C-IAM with integrated GLOW model will be used for the analysis of ionospheric airglow emission data.
6. Collaboration with Beijing Aerospace Control Center: This work is aimed at improving the current thermosphere density model in MSIS with the use of a number of space missions, including new Chinese satellites.

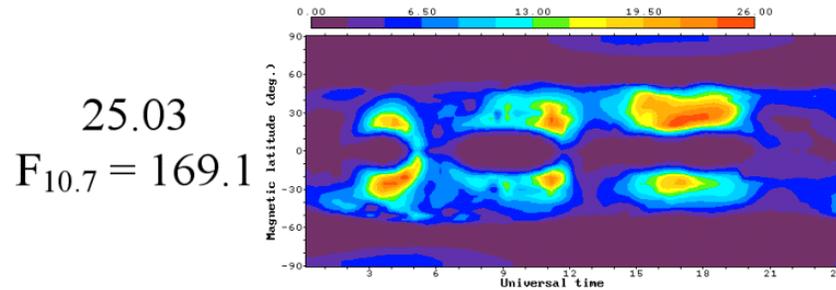
# WINDII/C-IAM [O] compared with NRLMSISE-00

Both follow the solar flux, but WINDII/C-IAM shows much more variation

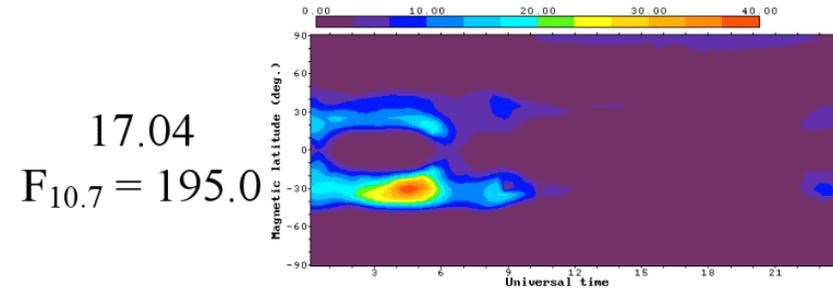


# Spatial structure of 135.6 nm nighttime ionospheric emission (impact of the magnetosphere on the ionosphere)

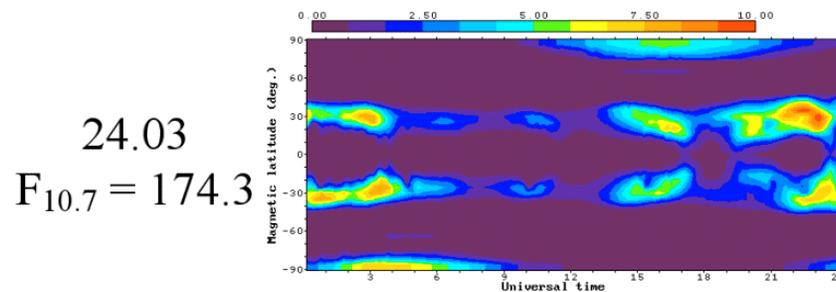
Model simulations for days with different geomagnetic activity



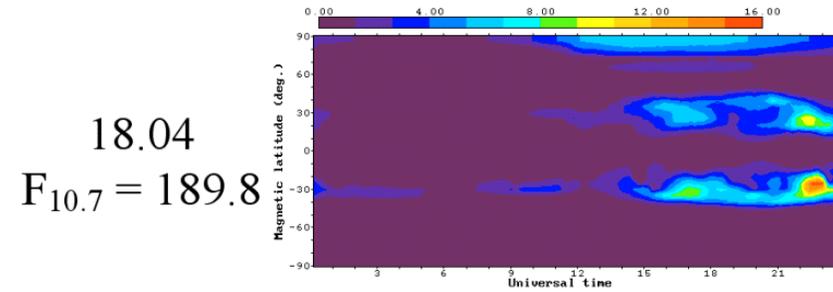
$\Sigma K_p = 14-$     2+ 2 1- 1- 2 3 2 1



$\Sigma K_p = 38$     3 3 3- 6 7- 7+ 6+ 3



$\Sigma K_p = 37+$     5 6 6 5- 4 5 3+ 3+



$\Sigma K_p = 42+$     7 7- 6- 6- 4+ 5- 4 4+

3-hr  $K_p$  index values are shown below the panels.  
WN4 structure may be fully suppressed by geomagnetic substorms.