Validation of Ionospheric Models at Mid- and High-Latitudes: Climatological Performance of WACCM-X (SD) and TIE-GCM in foF2

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Introduction

Accurate modelling of the ionosphere-thermosphere system is critical to understanding the impacts of space weather on modern technology, such as communications and navigation systems. At low and mid latitudes, both physics-based and empirical models are well-developed and capture the variability of the ionosphere to a good degree of accuracy. At high latitudes, however, the complex chemistry and dynamics due to interactions with the solar wind and magnetosphere, added to lack of observations, presents challenges to such models. This study evaluates the climatological performance of TIE-GCM, WACCM-X, and E-CHAIM for the period 1950 – 2022. Model outputs are compared to observational peak critical frequency (foF2 data from the high-latitude Resolute Bay ionosonde and the mid-latitude Chilton ionosonde to assess the limitations of models in reproducing the variability of the high-latitude ionosphere.

Background

- **Winter Anomaly**: phenomenon where ionospheric electron density is greater during winter than summer, which contradicts the expected behaviour of the ionosphere with respect to its dependence on solar zenith angle
- **Equinoctial Asymmetry**: where the magnitude of electron density varies between equinoxes despite similar solar activity levels
- Composition and circulation of the thermosphere (Rishbeth, 1998): high-latitude downwelling in the winter hemisphere enhances O/N_2. This reduces recombination (and therefore NmF2 increases)
- Physics-based models have previously been found to overestimate abundances of O which can introduce errors in representation of thermospheric composition and circulation (Liu et al., 2023)
- Limited observational data and model capacity means the winter anomaly and equinoctial asymmetry phenomena remain poorly characterised at high latitudes

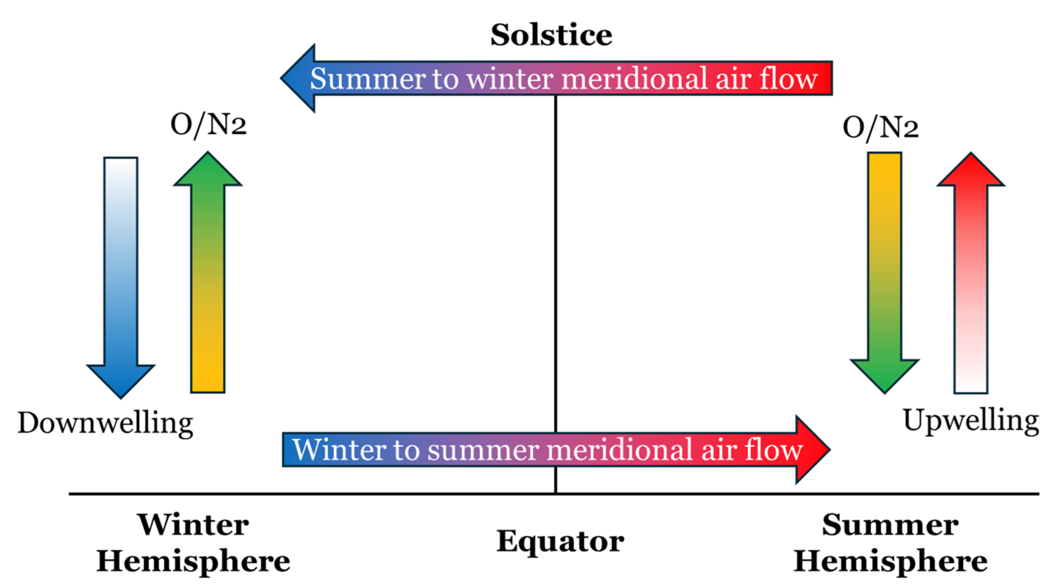

Figure 1: Example of how thermospheric circulation affects the O/N2 ratio

Data

Ionosondes
- Resolute Bay, Canada (74.7°N, 265.1°E)
- Chilton, UK (51.5°N, 359.4°E)

WACCM-X version 2.1.3
- 1950 – 2024
- Hourly resolution
- Heelis electrodynamics driven by F10.7 and Kp

TIE-GCM version 2.0
- 1950 – 2022
- Hourly resolution
- Heelis electrodynamics (F10.7, Kp)

E-CHAIM version 1.1.3
- 1950 – 2022
- Hourly resolution
- High-latitude empirical model

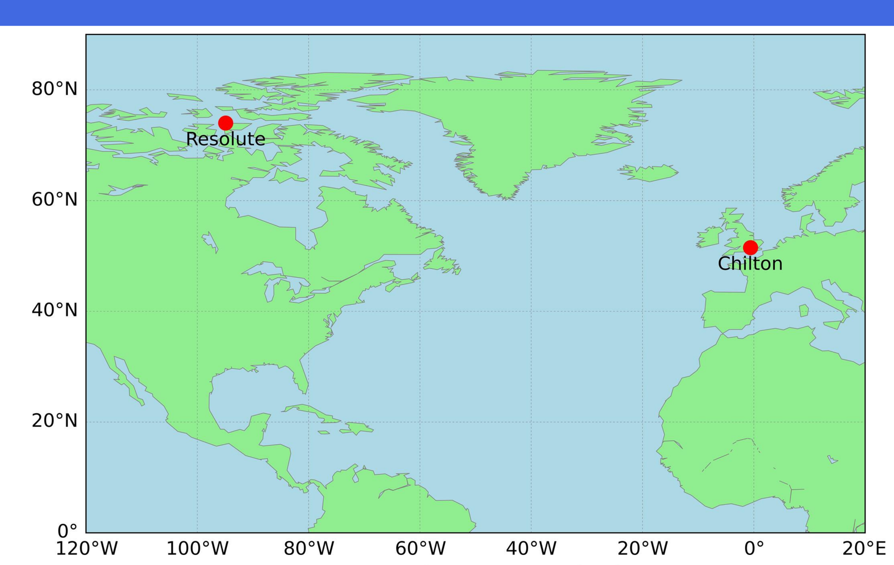

Figure 2: Map of ionosonde locations

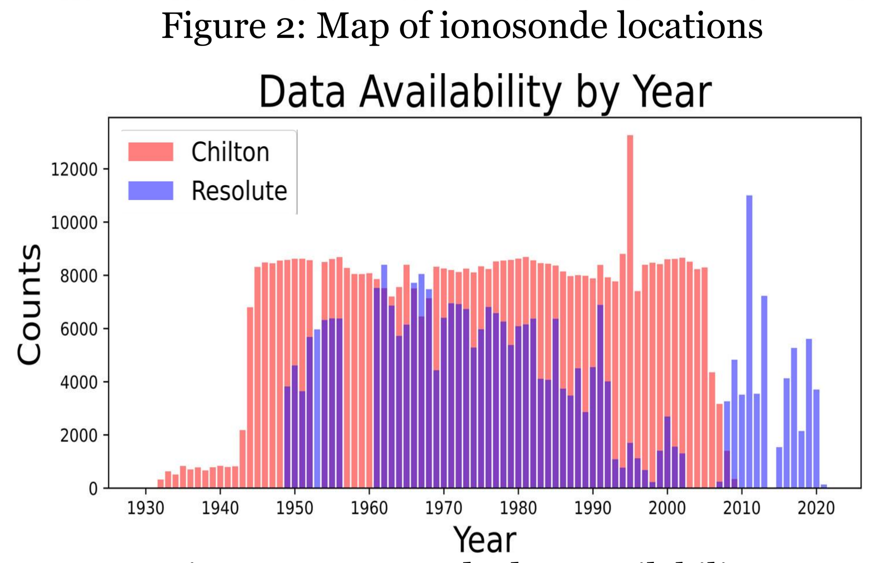

Figure 3: Ionosonde data availability

Ionosonde Results

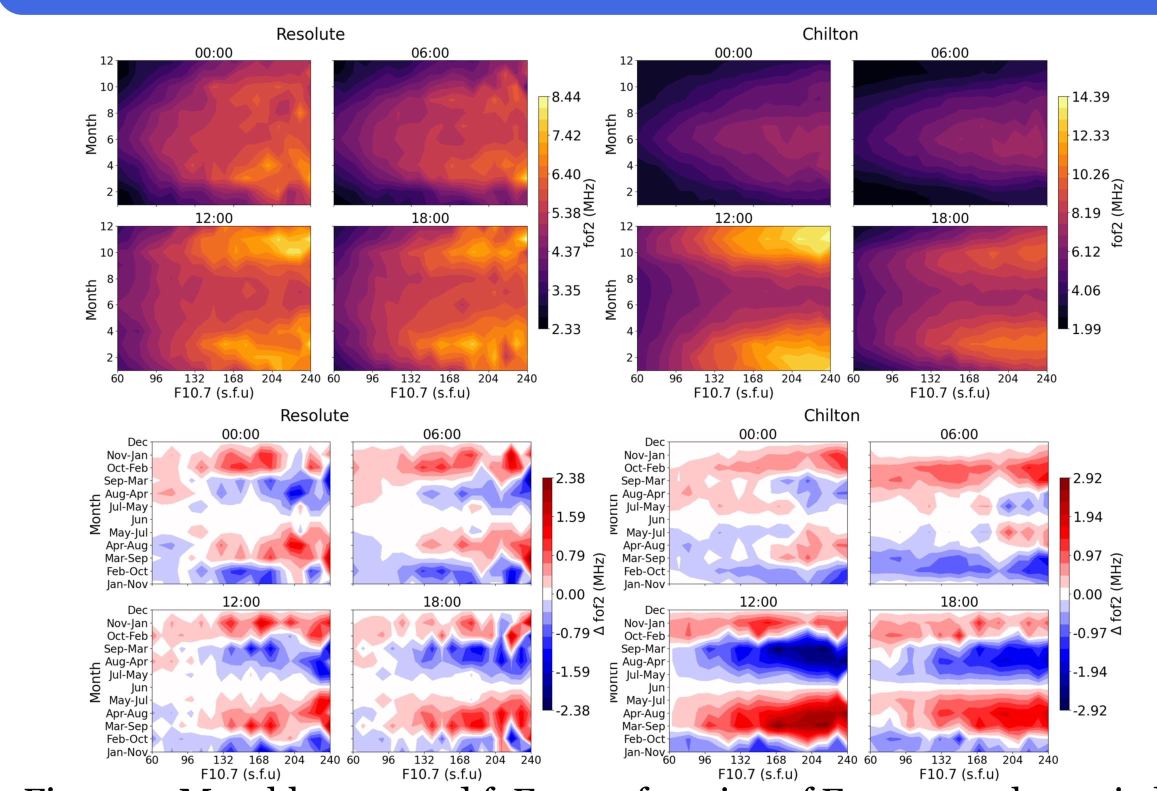

Figure 4: Monthly averaged foF2 as a function of F10.7 over the period 1950 – 2022, and corresponding monthly differences in foF2 centered around solstices, highlighting equinoctial asymmetry.

- Winter anomaly present at all times of day at Resolute (only at high F10.7 at 00 and 06 LT)
- There is also winter anomaly behaviour at 12 and 18 LT at Chilton
- Equinoctial asymmetry at both mid- and high-latitudes at all times of day
- At Resolute this is autumn-favouring at low F10.7 and reverses to become spring-favouring at high F10.7
- At Chilton, the equinoctial asymmetry is typically spring-favouring

Model Results

Resolute
- Physics-based models show winter anomaly behaviour at all times of day, which we don't see in the ionosonde data. WACCM-X overestimates foF2 by up to 197% (8.65 MHz). TIE-GCM overestimates by 122% (6.15 MHz). E-CHAIM only shows 2.50 MHz difference to observations
- Both physics-based models show spring-favouring equinoctial asymmetry across all times of day, while E-CHAIM replicates the autumn-favouring equinoctial asymmetry seen in ionosonde data at low F10.7

Chilton
- At low F10.7, models show expected summertime peak seen in ionosonde data. At high solar activity, winter anomaly behaviour is present for all times of day
- WACCM-X shows 117% overestimation (6.06 MHz). TIE-GCM shows 96% (4.46 MHz) overestimation. E-CHAIM shows under 42% difference (1.49 MHz) to observations

These overestimations can be attributed to increased O in the summer hemisphere (previously identified in WACCM-X) leading to misrepresentation of processes in Figure 1

Resolute

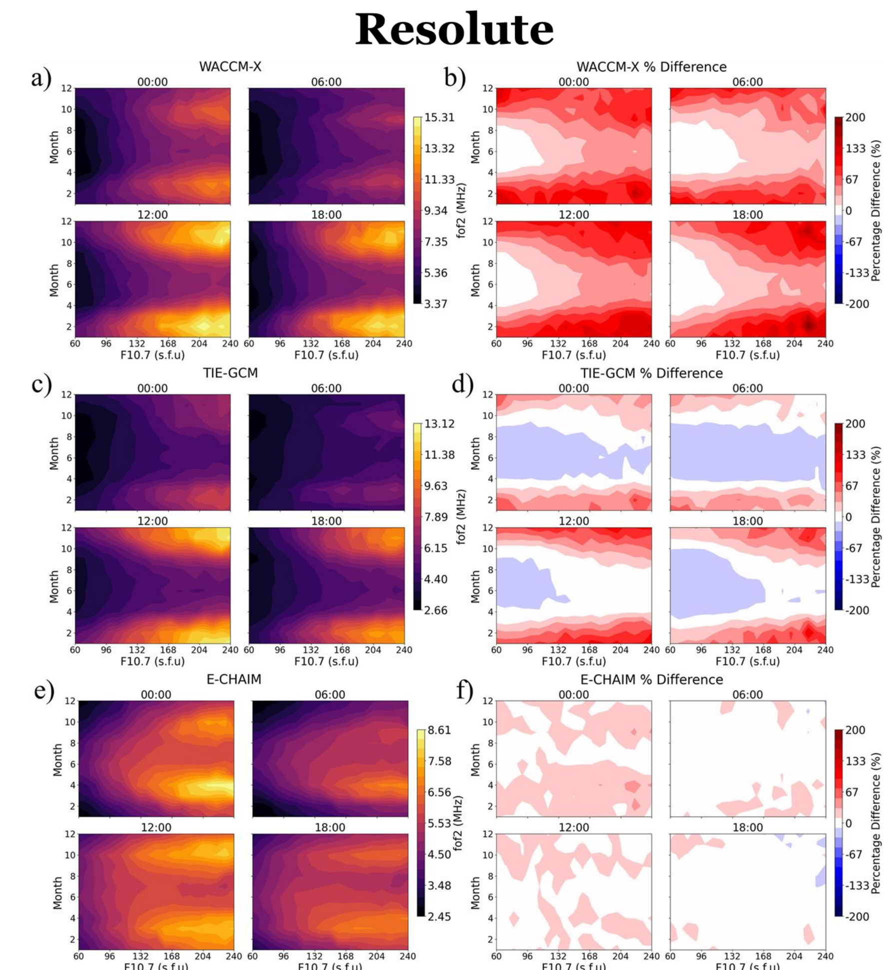

Figure 5: Monthly averaged foF2 (left) and percentage difference (right) from WACCM-X, TIE-GCM, and E-CHAIM at Resolute

Chilton

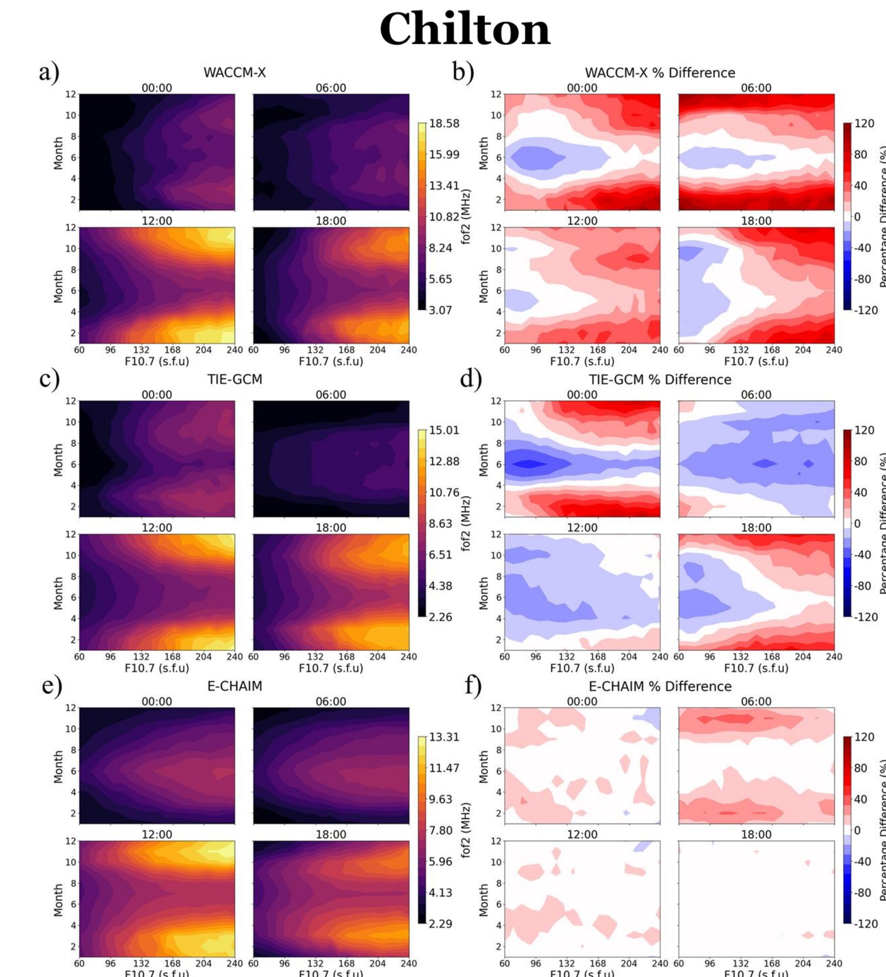

Figure 6: Monthly averaged foF2 (left) and percentage difference (right) from WACCM-X, TIE-GCM, and E-CHAIM at Chilton

Summary

- Physics-based models consistently show winter anomaly behaviour not present in observational data and make overestimates of electron density up to 200%
- This is worse at high solar activity and high latitudes and is likely due to misrepresented transport processes, pointing to a need for improved representation of thermospheric circulation and neutral composition within physics-based models
- Paper also explores impacts of high-latitude electrodynamics models and lower atmospheric forcing as sources of climatological errors, as well as sub-monthly climatology

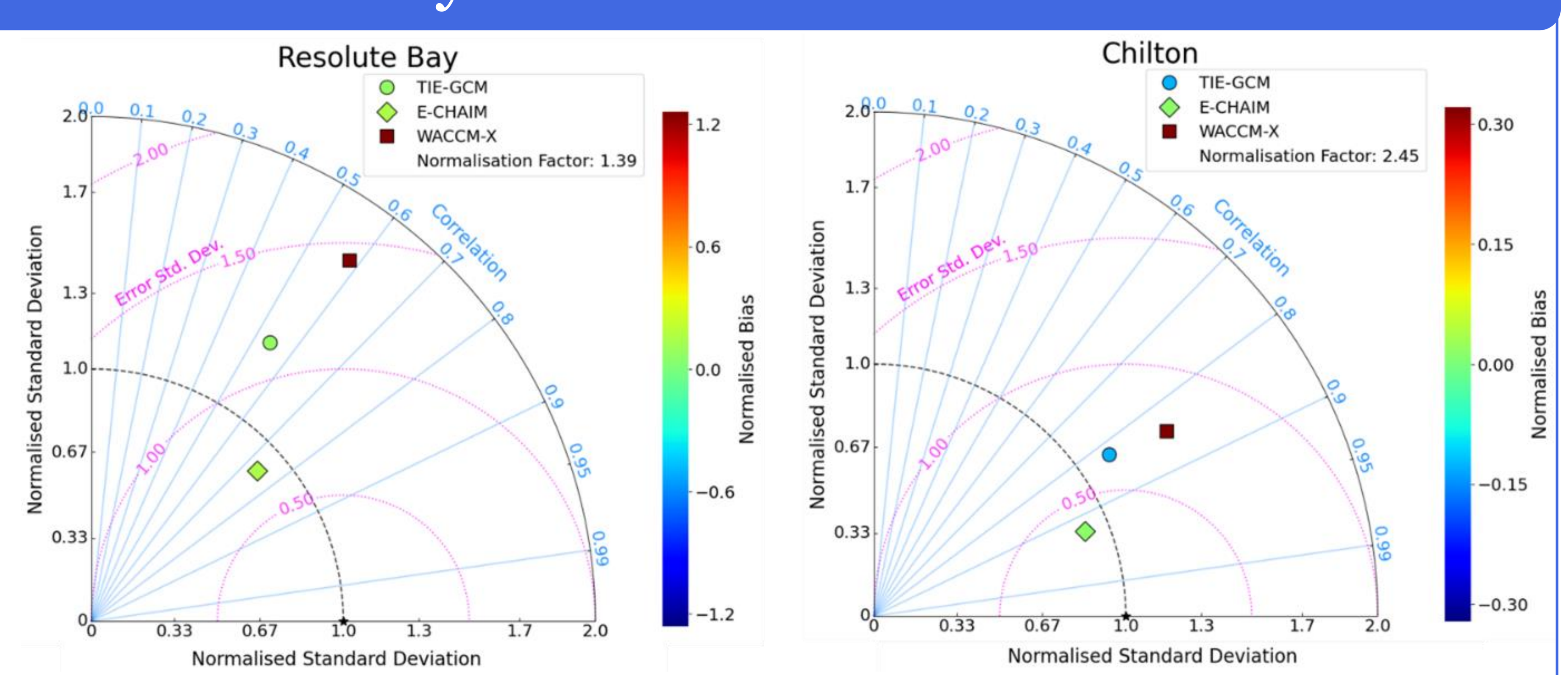

Figure 7: Taylor diagrams to evaluate the overall performance of each model. The colour of each marker indicates its bias (i.e., mean of observational data subtracted from model mean).

References

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Gurney et al. (2026)

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