Quantifying the Relative Importance of Upward Propagating vs. in situ Tides in the Thermosphere

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Abstract

This study quantifies the relative importance of lower atmospheric versus in situ forcing in driving tides in the thermosphere, as well as the impact of solar and geomagnetic activity on these tides using the Specified Dynamics Whole Atmosphere Community Climate Model with thermosphere-ionosphere eXtension (SD-WACCM-X). We employ Hough Mode Extensions (HMEs) to separate upward-propagating tides originating in the lower atmosphere from tides generated in situ within the thermosphere for 2014 (solar maximum year). To understand the influence of solar and geomagnetic activities on the thermospheric tides, we compare standard SD-WACCM-X simulations with control simulations where Kp and F10.7 are fixed at lower values. The model simulations are validated by comparison with independent neutral density tidal observations from the CHAllenging Minisatellite Payload (CHAMP) data at approximately 390 km altitude from 2002–2004 (F10.7=140 sfu). The results highlight the critical role of thermospheric forcings in shaping tidal dynamics, which has implications for future satellite missions.

Objective: Explore tidal sources in the thermosphere vs. upward propagating tides

Motivation: Tidal sources in the thermosphere are not well-understood. HME fits allow us to separate upward propagating and in situ generated thermospheric tides in the whole atmosphere model (i.e., SD-WACCM-X)

Introduction

- **Tidal nomenclature:** 1st letter → period (D for diurnal, S for semidiurnal); 2nd letter → propagation direction (W for westward, E for eastward); number → zonal wavenumber [Migrating → Sun-synchronous; Nonmigrating → Non-Sun-synchronous]
- **Year selected:** 2014, solar maximum (yearly average F10.7 = ~145 sfu, Kp = ~3)
  For validation with CHAMP: 2002–2004 (F10.7 = ~140 sfu; similar value as 2014)
- **Insights from previous work** → Several nonmigrating components (e.g., D0, DE2, DE3, S0, SW4) can reach the upper thermosphere from 110 km *(Forbes et al., 2014)* → in situ generated tides can arise from interactions between various waves and their interactions with the longitudinal structure of ion drag *(Jones et al., 2013)*
- **What's new?** Quantitative insight into the relative importance of forcing from above and below in the thermosphere, and the use of HMEs in separating these forcings.

Data & Method

SD-WACCM-X: First-principles numerical model, hourly data

Control simulations: run 1. Fixed low Kp = 0.3; run 2. Fixed low Kp = 0.3, F10.7 = 70 sfu

CHAMP: Neutral density observations at 390 km

HMEs: Self-consistent latitude vs. height sets of amplitudes & phases of **upward propagating tides** that come from classical tidal theory

– Pole-to-pole, 0-400 km; T, u, v, w, ϕ and Δρ/ρ; do not depend on day of year

HME fitting to T, u, v tides in SD-WACCM-X allows us to extract the upward propagating contribution due to tides & obtain the in situ tidal contribution as the residual [Figure 2]

Validation with CHAMP Observations

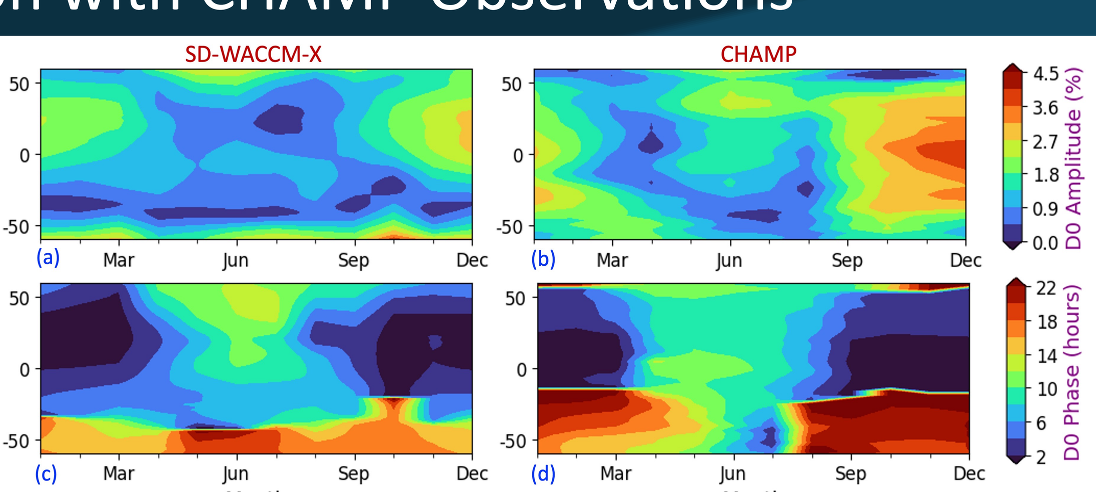

Figure 1. Comparison of D0 relative density tide between SD-WACCM-X (left) and CHAMP observations (right) at 390 km for 2002–2004 (a, b): amplitudes, (c, d): phases.

D0 is shown as a representative example; validation has been performed for all tidal components. Most of the tidal components from the model show good agreement.

SD-WACCM-X can simulate tides in the thermosphere reasonably well

Upward Propagating vs. in situ Generated Tides

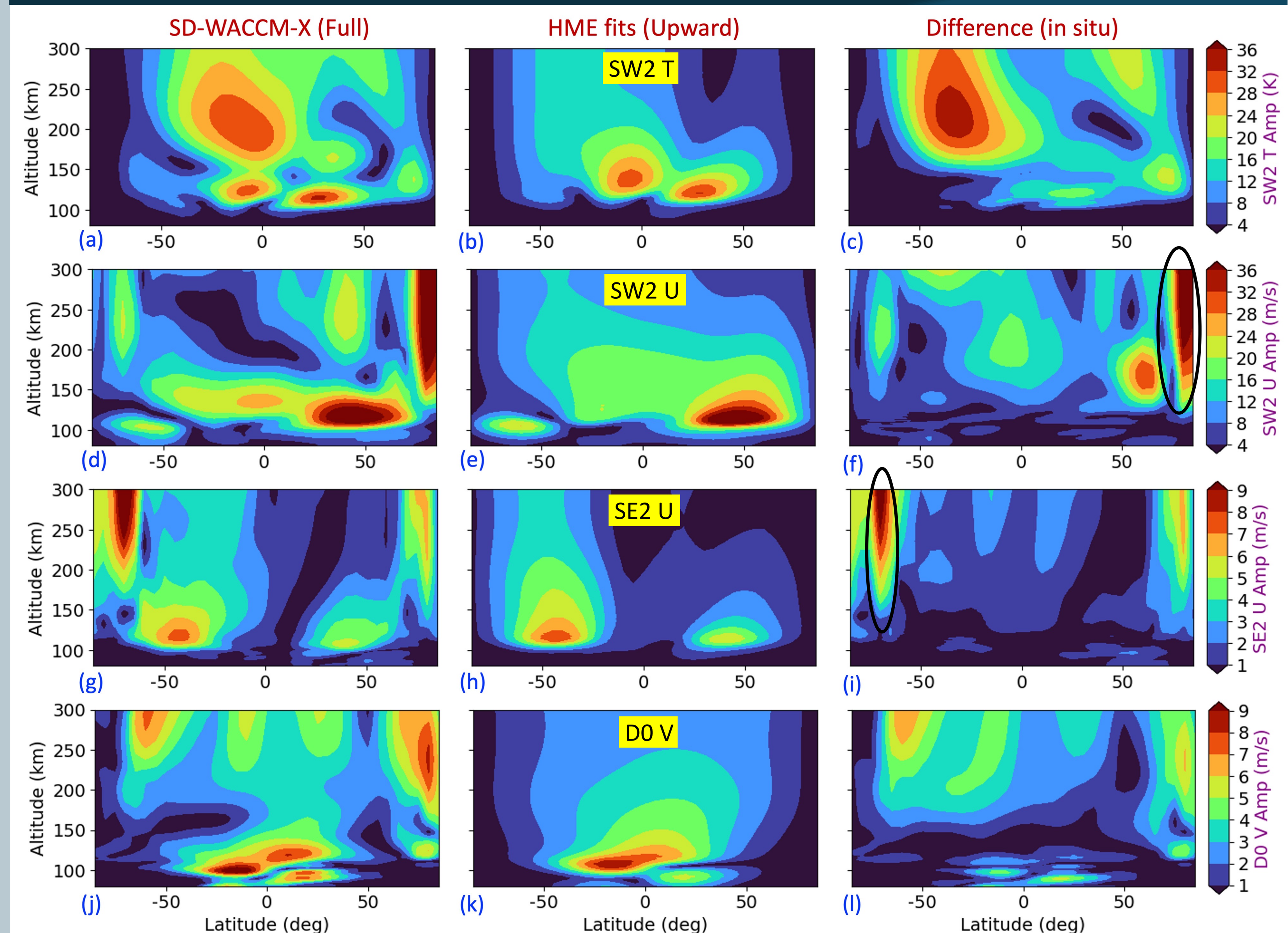

*Figure 2. Latitude–altitude cross sections of tidal amplitudes for June 2014. (a–c): **SW2 T**; (d–f): **SW2 U**; (g–i): **SE2 U**; (j–l): **D0 V***

Left: full tidal fields from SD-WACCM-X (upward propagating + in situ). Middle: HME fits (upward propagating part). Right: difference between full and HME fits (in situ part).

SW2 T, U, SE2 U, & D0 V are selected from *Table 1* as they come from both lower atmosphere and in situ sources — also good for demonstrating HME fitting and separation methodology.

- SW2 T shows significant in situ generation at low-to-mid lats, whereas SW2 U has about equal contribution at those lats; significant peak at NH high-lat, unlike SW2 T
- SE2 U is mostly upward propagating at mid-latitudes; high latitude peaks present
- D0 V has a moderate contribution from both upward and in situ forcings

Relative importance

Mid = 50° S – 50° N, High = 85° S – 50° S & 50° N – 85° N

	T		U		V	
Lat →	Mid	High	Mid	High	Mid	High
D0	0.4	0.3	0.1	~ 0	0.8	0.3
DW1	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0
DW2	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0
DE1	0.7	0.4	0.2	0.1	0.8	~ 0
DE2	1.9	0.4	1.2	0.1	0.6	0.1
DE3	2	0.6	1.6	0.1	0.8	0.1
S0	1.1	0.7	0.1	~ 0	1.3	0.9
SW1	0.6	0.4	0.3	0.1	0.6	0.1
SW2	0.6	0.3	~ 1	0.4	~ 1	0.3
SW3	1.3	0.2	0.7	0.1	0.7	0.1
SW4	1.3	0.1	0.9	0.1	0.6	~ 0
SE1	1.2	0.9	0.3	0.2	1.3	0.2
SE2	2.1	1.8	1.7	0.6	2.1	0.4

***Table 1.** Forcing ratio (**FR**), defined as the ratio of upward propagating to in situ generated tidal amplitudes (annual mean) at **250 km**.*

FR < 1 indicates that in situ forcing contributes more than upward part;
FR = 1 suggests equal contributions;
FR > 1 indicates that upward propagating tides contribute more;
FR = 0 indicates no contribution from upward propagation.
FR < 0.5 marked in blue,
FR > 1.5 marked in red.

The FRs in the table provide comprehensive insight into the relative importance of lower atmospheric and in situ forcings in the thermosphere.

- DW1, DW2 are entirely in situ at 250 km; same for D0 U, S0 U, SW4 V, DE1 V (FR =~0)
- SW2 U and V tides at mid-latitudes have almost equal contributions from above and below (FR = ~1); at high latitudes, the in situ contribution dominates
- Nonmigrating components like DE2, DE3, SE1, & SE2 are mostly upward propagating
- Most components show higher in situ forcings at high-lats, compared to mid-lats

Impact of Solar and Geomagnetic Activity on in situ Tides

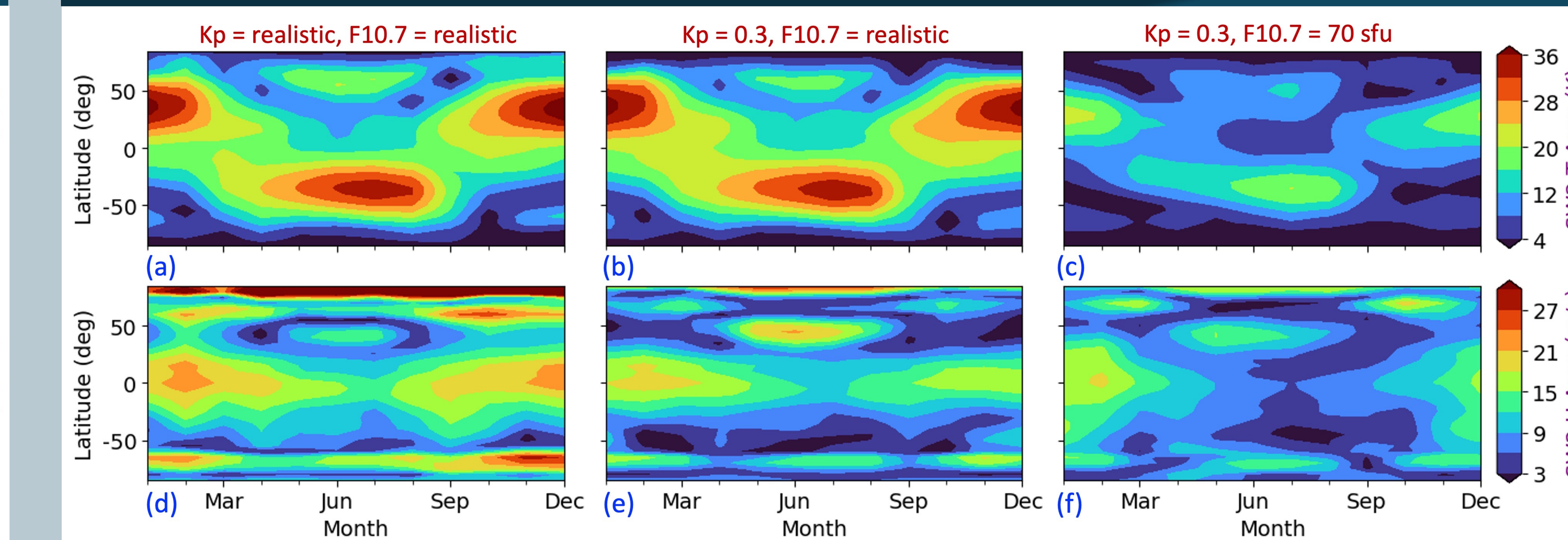

***Figure 3.** Seasonal variation (year 2014) of in situ generated **SW2 T** (top row) and **SW2 U** (bottom row) at **250 km** under different forcing conditions from SD-WACCM-X. (a, d): Kp, F10.7 = realistic; (b, e): Kp = 0.3, F10.7 = realistic; (c, f): Kp = 0.3 and F10.7 = 70 sfu.*

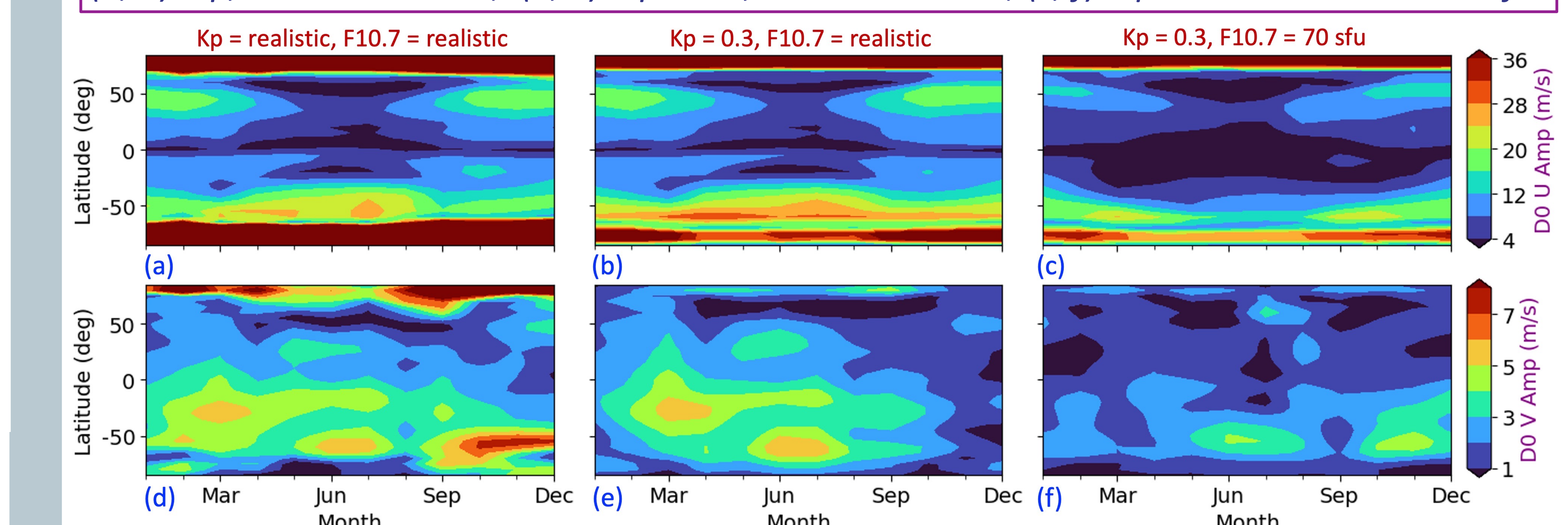

***Figure 4.** Same as Figure 3, except for **D0 U** and **D0 V** tides*

- Higher solar activity strengthens both temperature and wind tidal amplitudes.
- Higher geomagnetic activity strengthens wind tides at high latitudes but does not affect temperature tides much, this is because ion drag acts directly in the horizontal momentum equation via hydromagnetic coupling, generating large in situ wind tides. In contrast, temperature tides are shaped by adiabatic heating & cooling from vertical wind perturbations, which are not directly influenced by ion drag.

Conclusions

- SD-WACCM-X thermospheric tides have been validated with CHAMP observations.
- Most thermospheric tides are in situ forcing dominated, except for a few nonmigrating components – supported by a quantitative analysis [Table 1].
- Higher solar activity strengthens both temperature and wind tidal amplitudes, whereas higher geomagnetic activity strengthens wind tides at high latitudes, but does not affect temperature tides much.
- Understanding tidal origins is the key to interpret in situ measurements, identify lower atmospheric forcings and separate them from thermospheric processes, which will enable improved space weather forecasts, and numerical modeling capabilities.
- **Future work:** Utilize high-resolution SD-WACCM-X to fully quantify gravity wave breaking–related in situ tidal generation in the thermosphere.

References

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