Resolved Gravity Waves in High-Resolution WACCM-X: Impact on Thermospheric Mean State and Tides

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Abstract

In this study, the impact of resolved gravity waves (GWs) on diurnal and semidiurnal tides is investigated using a high-resolution configuration of the Whole Atmosphere Community Climate Model with thermosphere-ionosphere eXtension (HR-WACCM-X). The HR simulations explicitly resolve a portion of the mesoscale gravity waves that are either parameterized or not accounted for in corresponding coarse-resolution (CR-WACCM-X) simulations. Comparisons between HR and CR simulations reveal substantial differences in the amplitude and spatial structure of thermospheric tides. To diagnose the physical origin of these differences, resolved GW forcing is quantified in HR-WACCM-X by applying zonal wavelength filtering (200-2000 km) to isolate mesoscale perturbations and computing associated forcing terms. The forcing is further analyzed at diurnal and semidiurnal tidal periods to assess its contribution to tidal variability. The results indicate that resolved gravity waves produce momentum deposition at tidal timescales that can either amplify or damp tidal amplitudes.

Objective: Analyze tides in a GW-resolving model vs. a non-GW-resolving model and investigate GW forcing on thermospheric tides.

Motivation: While GWs are known to influence thermospheric dynamics through momentum and energy deposition, their role in modifying thermospheric tides remains poorly understood.

Data & Method

Data sources

WACCM-X: 1-year of free-running (no meteorological constraints) High-Resolution (HR) WACCM-X and Coarse-Resolution (CR) WACCM-X. Specifications below:

Model configuration	HR-WACCM-X	CR-WACCM-X
Solar & geomagnetic conditions	F10.7 = 120 sfu, Kp = 0.33	F10.7 = 120 sfu, Kp = 0.33
Horizontal resolution	~25 km	~200 km
Vertical resolution	~0.1 scale height	~0.25 scale height
Effective horizontal resolution	~200 km	~1600 km
Gravity wave (GW) parameterization	GWs explicitly resolved; no parameterization	parameterized GWs up to ~110 km; exponentially ramped down above

Data Availability: For tides → cosine and sine coefficients of the diurnal (24 h), semidiurnal (12 h), and terdiurnal (8 h) harmonics for 1-year of WACCM-X.
For GW forcing → January 13 (limited availability of hourly model output)

Extraction of tidal components

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]

Reconstructed T, U, V field → $T,U,V\,(t) = \sum_{n\in\{24,12,8\}} \left[C_n \cos\left(\frac{2\pi t}{n}\right) + S_n \sin\left(\frac{2\pi t}{n}\right)\right]$

C_n and S_n are daily cosine and sine coefficients for each harmonic period n, and t is UT

→ 2D FFT in time and longitude to get migrating and nonmigrating tidal components

Quantification of GW forcing

→ 200-2000 km zonal wavelength filter on T, u, v, ω

Zonal forcing $= -\frac{\partial(u'\omega')}{\partial p}$ Meridional forcing $= -\frac{\partial(v'\omega')}{\partial p}$

"Thermal" forcing $= -\frac{\partial(T'\omega')}{\partial p} - \nabla_h \cdot (u'T', v'T')$

→ 2D FFT in time and longitude to get projection of GW forcing onto tidal components

Damping rate (zonal/meridional/thermal) $= -\frac{\textit{Amplitude of GW forcing}}{\textit{Amplitude of tide}} \cos(\textit{phase difference})$

High-Resolution vs. Coarse-Resolution WACCM-X

Mean State

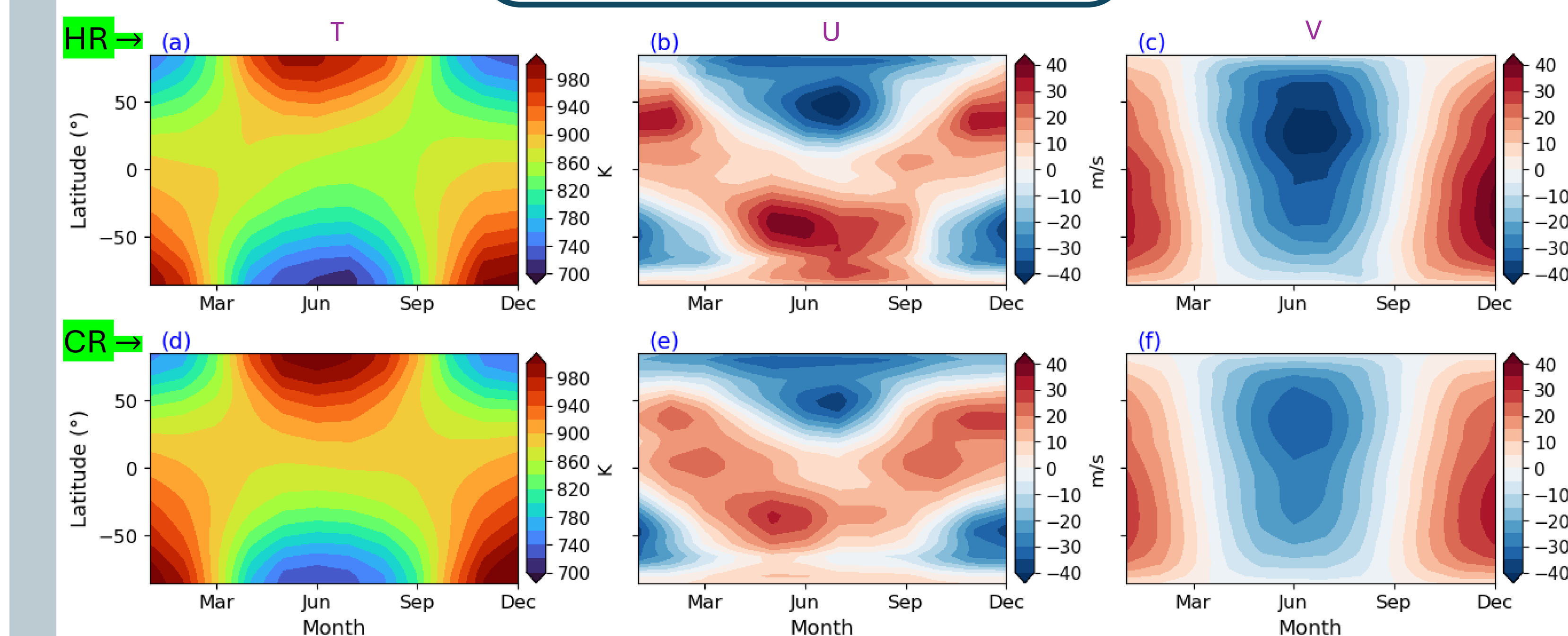


Figure 1. Monthly-mean zonal-mean background temperature and winds at 250 km derived from HR (top row) and CR (bottom row) WACCM-X simulations. (a,d): T, (b, e): U, (c,f): V

- The HR simulation generally exhibits stronger zonal and meridional winds, with larger magnitudes and more pronounced seasonal variability, and distinct asymmetries between the two hemispheres.
- The CR simulation exhibits a systematically warmer thermosphere throughout most of the year.

Tides

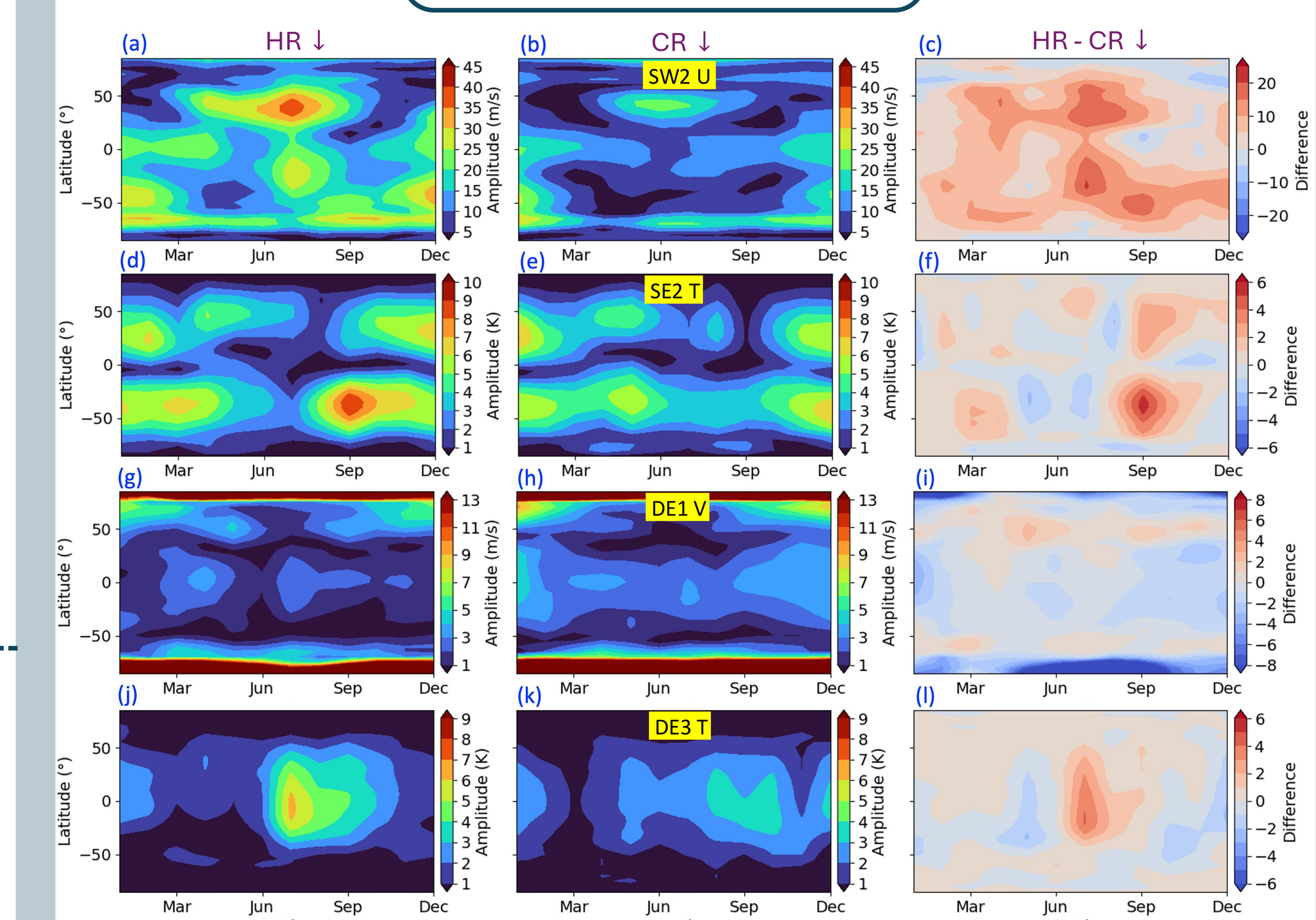


Figure 2. Tidal amplitudes at 250 km from HR (left) and CR (middle) WACCM-X simulations and their differences (right). (a–c): SW2 U; (d–f): SE2 T; (g–i): DE1 V; (j–l): DE3 T

- Representative tidal components are selected to highlight how different tidal modes respond to model resolution and exhibit distinct seasonal and latitudinal structures.
- Thermospheric tidal amplitudes are generally larger in HR-WACCM-X than in CR-WACCM-X for several dominant components, particularly SW2. However, in some nonmigrating components, CR exhibits larger amplitudes.
- The stronger HR tides are consistent with the cooler thermosphere and stronger background winds shown in Figure 1, indicating that tidal propagation and dissipation are sensitive to the underlying mean state.

Gravity Wave Forcing on Tides

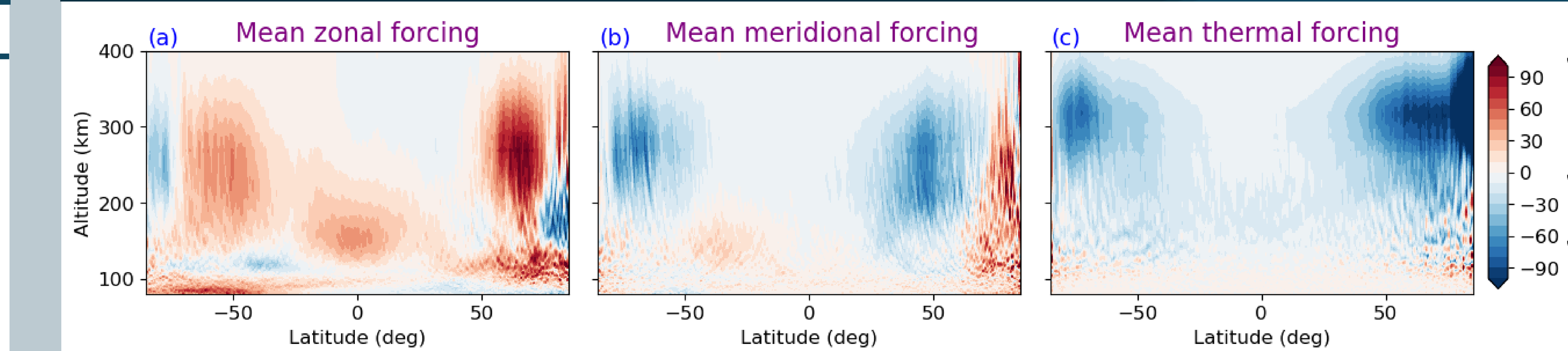
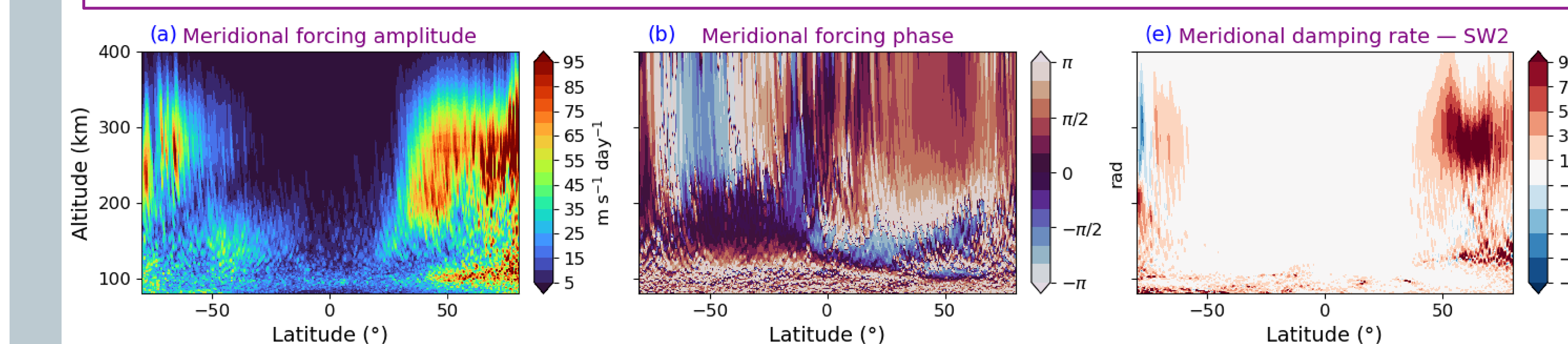


Figure 3. Zonal-mean temporal-mean mesoscale gravity wave forcing from HR-WACCM-X for January 13. (a) zonal forcing, (b) meridional forcing, and (c) thermal forcing



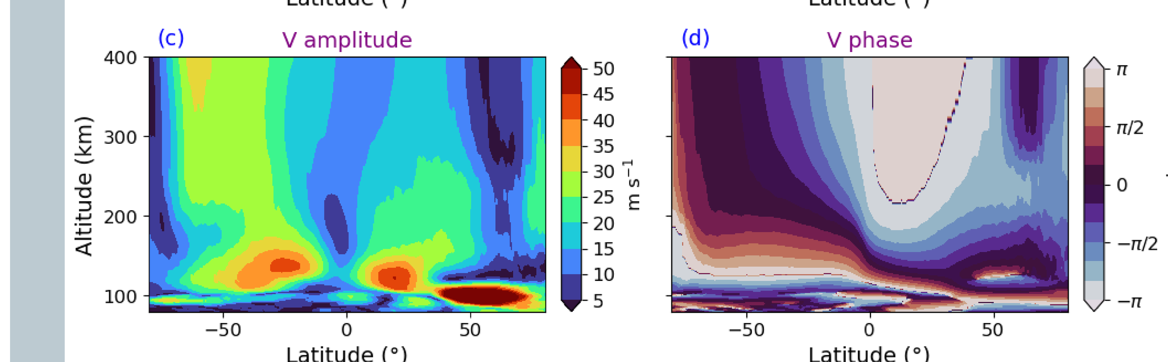


Figure 4. Meridional GW forcing projected onto SW2 V. (a-b): amp and phase of the meridional forcing; (c-d): V amp and phase; (e) meridional damping rate

Figures 4-5 show representative tidal components illustrating direct GW forcing on tides

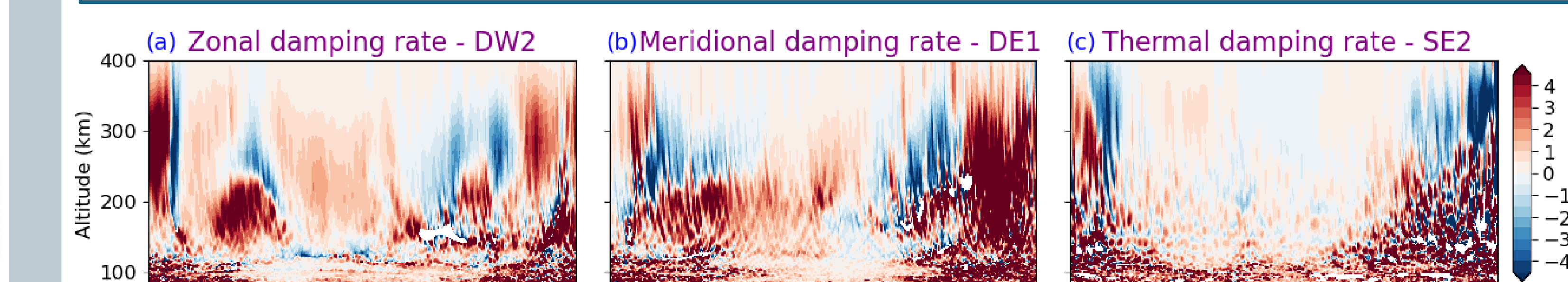


Figure 5. Damping rates due to GW forcing on tides. (a) zonal damping rate for DW2, (b) meridional damping rate for DE1, (c) thermal damping rate for SE2

- Resolved mesoscale gravity waves produce substantial zonal, meridional, and "thermal" forcing in the thermosphere, modifying both the background circulation and tidal environment.
- Gravity-wave forcing projects onto tidal periods, providing a direct source of tidal amplification or damping. The sign of the response depends on the phase relationship between the GW forcing and the tidal oscillation: in-phase forcing amplifies tides, while out-of-phase forcing damps them.

Conclusions

- HR-WACCM-X generally exhibits a cooler thermosphere and stronger mean winds than CR-WACCM-X, consistent with larger tidal amplitudes in dominant components.
- Resolved gravity waves alter thermospheric tides through direct forcing at tidal periods and background state changes.
- Gravity wave forcing can amplify or damp tides depending on phase alignment with tidal components.

Reference

Neogi, M., H.-L. Liu, & J. Oberheide (2026). Resolved Gravity Waves in High-Resolution WACCM-X: Impact on Thermospheric Mean State and Tides, *JGR: Space Physics, 2026JA035590, submitted.*

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