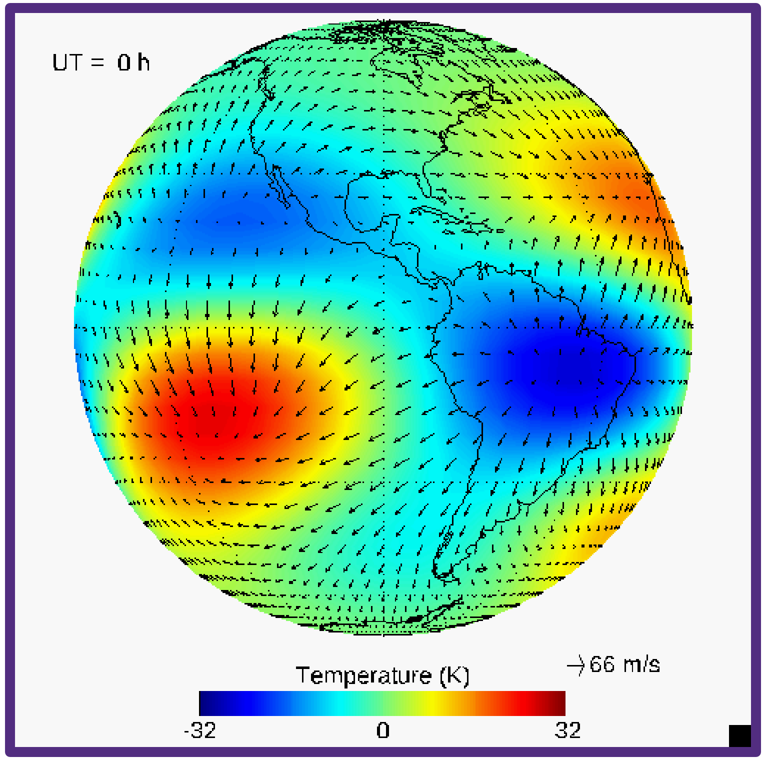
Global-scale wave impacts on the coupled IT system from daily to sub-seasonal timescales



Tidal temperatures and winds in the E-region from TIMED

Jens Oberheide

Department of Physics & Astronomy Clemson University

CEDAR Prize Lectures on Tides & Planetary Waves

- **2004: Maura Hagan**
  Tidal coupling in the Earth's atmosphere
  Solar and latent heat forcing; PW-tide and tide-tide interactions
- **2014: Jeff Forbes**
  Atmosphere-ionosphere coupling by tides and planetary waves
  IT complexity introduced by tides; outstanding issues and challenges
- **2023: Ruth Lieberman**
  The role of tides and planetary waves in atmospheric vertical coupling
  Recent mission progress in meeting the challenges; future observational needs
- **This presentation:**
  Observing the tidal & PW "weather" from space. **How so?**
  Ionospheric response and space weather predictability. **What for?**

Waves Couple the Lower with the Upper Atmosphere and Ionosphere

Sun Magnetosphere

LTI

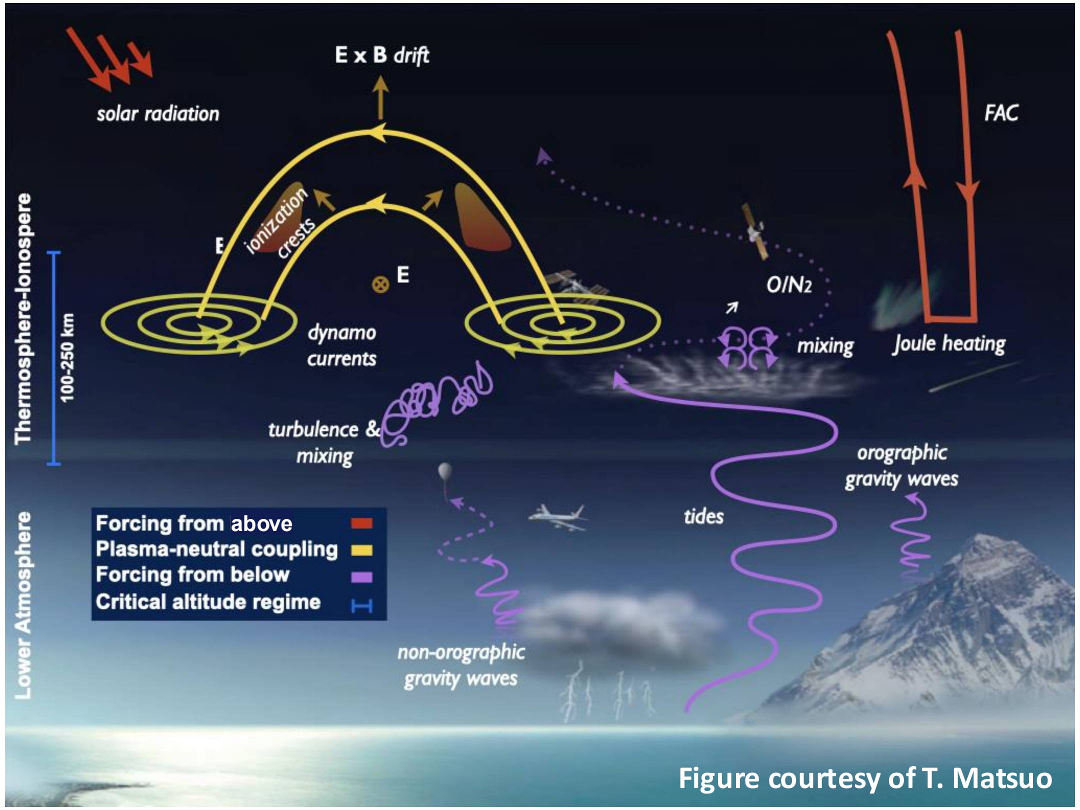


Figure courtesy of T. Matsuo

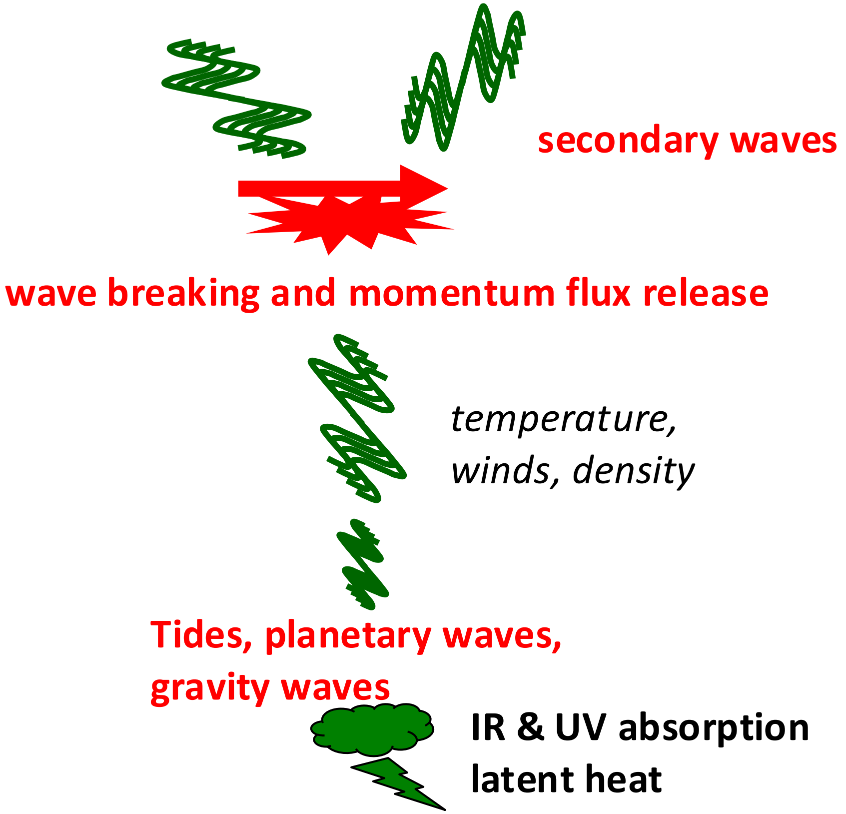
Wave Spectrum

Gravity Waves
min-hours
10's to 1000 km

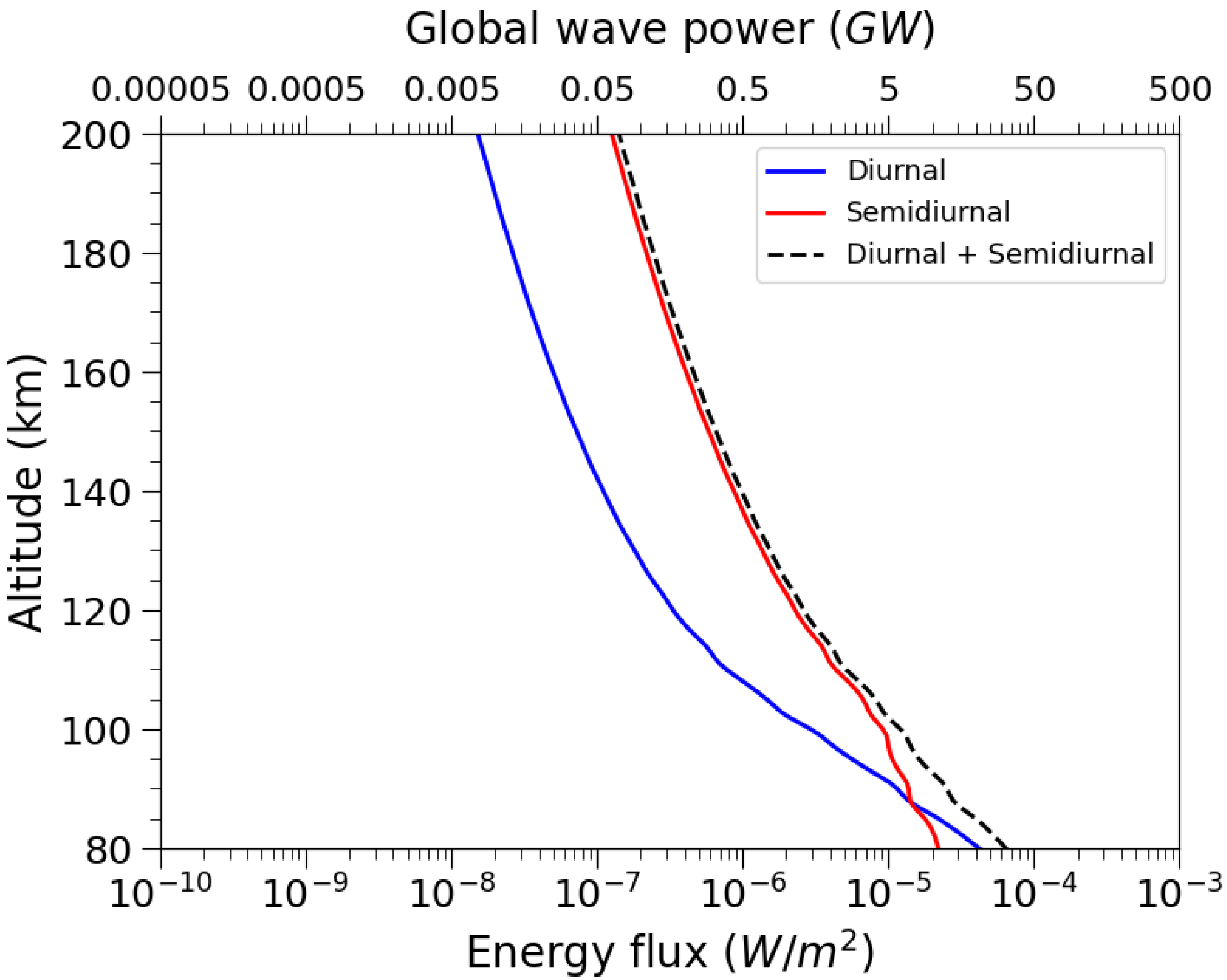
Tides
24, 12, 8 hours
1000's to 10,000 km

Planetary Waves
2-20 days
1000's to 10,000 km

forcing from below



Global-Scale Waves Transport Energy into the Upper Atmosphere

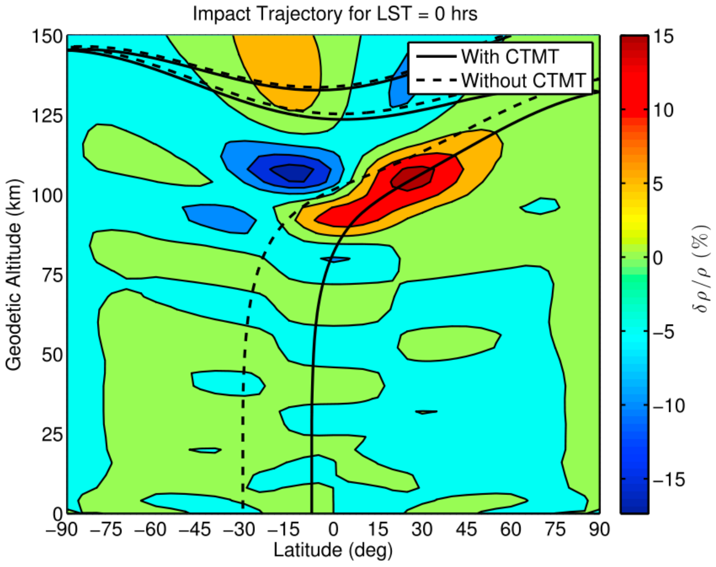


- Global annual mean vertical energy flux and global wave power due to **upward propagating tides** based on TIMED observations for the year 2009

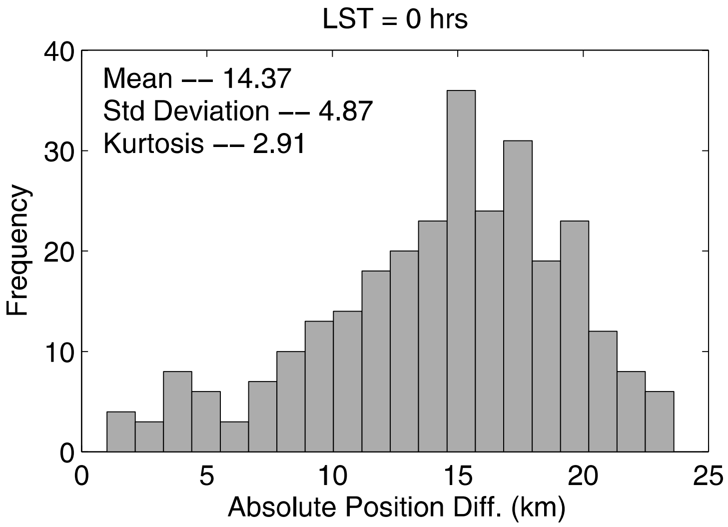
- The global tidal wave power is around **5 GW at 100 km**.

Neogi & Oberheide (2025), 2024GL113257

Global-Scale Waves and Precise Orbit Prediction in VLEO



(b) Reentry trajectory comparison



Color contours: neutral density perturbation (%) due to global-scale waves (tides) from empirical CTMT model

Solid line: orbit trajectory WITH tides

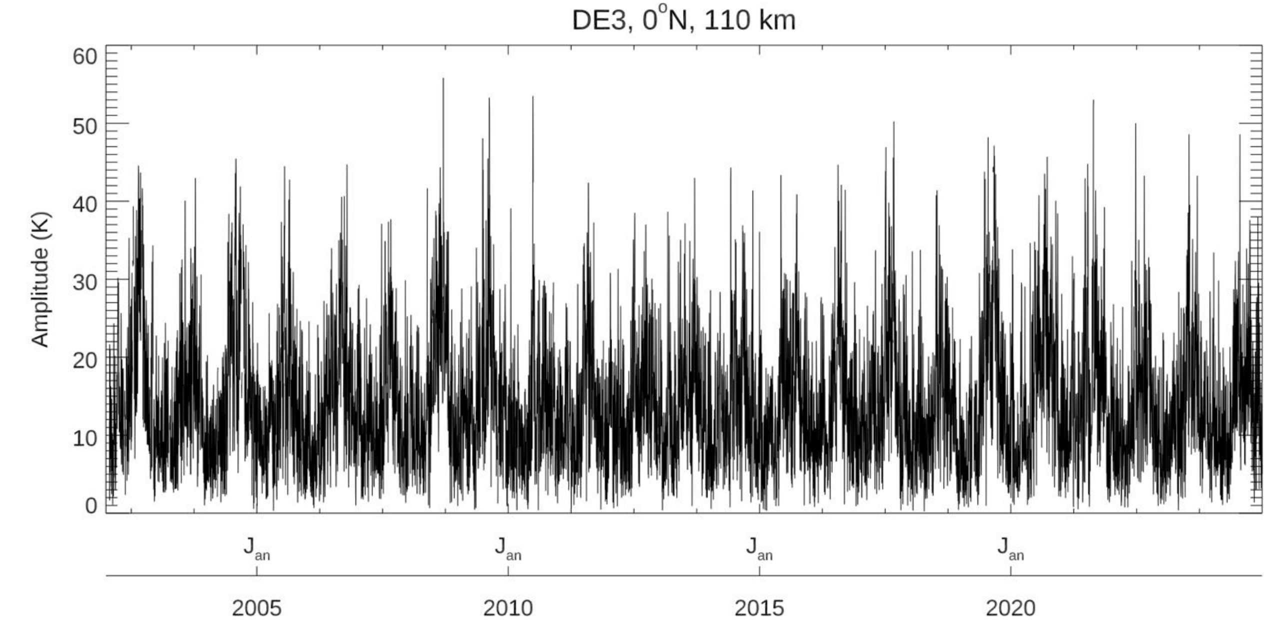
Dotted line: orbit trajectory WITHOUT tides

Orbit prediction difference histogram for
24-hr orbit integration at 200 km.
Absolute position difference: 14 km; standard deviation: 5 km

Leonard et al. (2012), Space Weather
doi:10.1029/2012SW000842

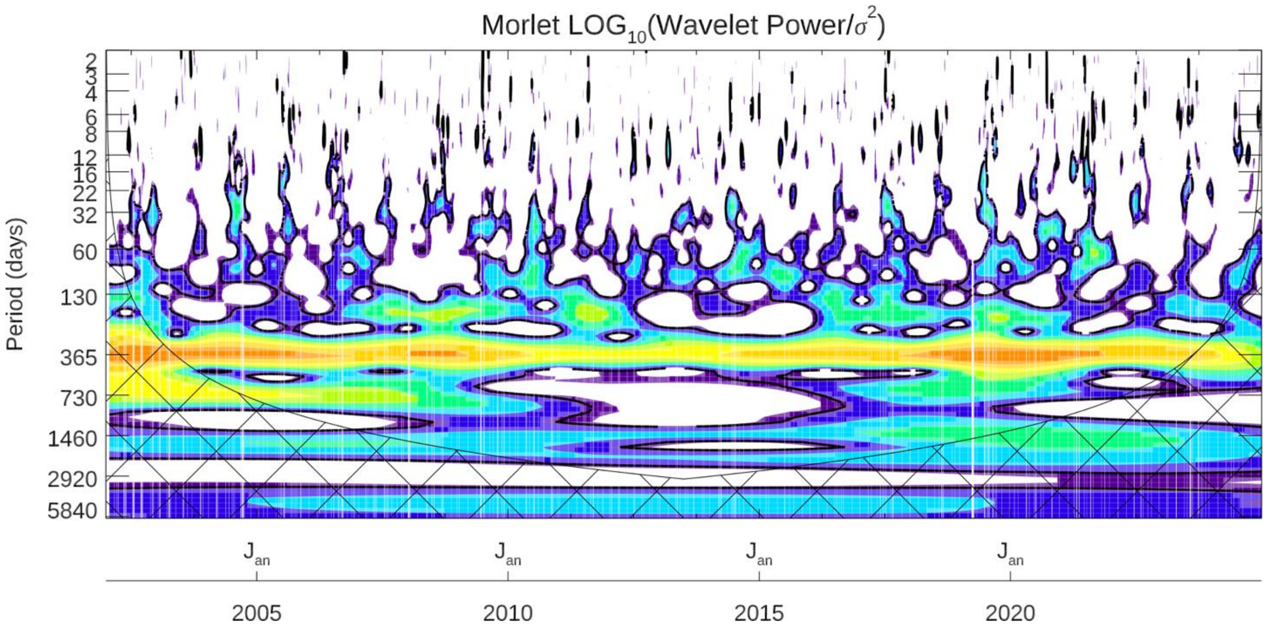
Precise orbit prediction of objects in VLEO requires precise knowledge of global-scale waves

Global-Scale Waves Vary from Days to Decades



Tidal “weather” in the E-region,
SABER/TIMED temperature tides

Extended from
Kumari & Oberheide (2020), 2019JD031910



Days, weather, interaction with planetary waves, polar vortex strength, …

1-3 months, recurring tropical convection
Madden-Julian Oscillation (MJO)

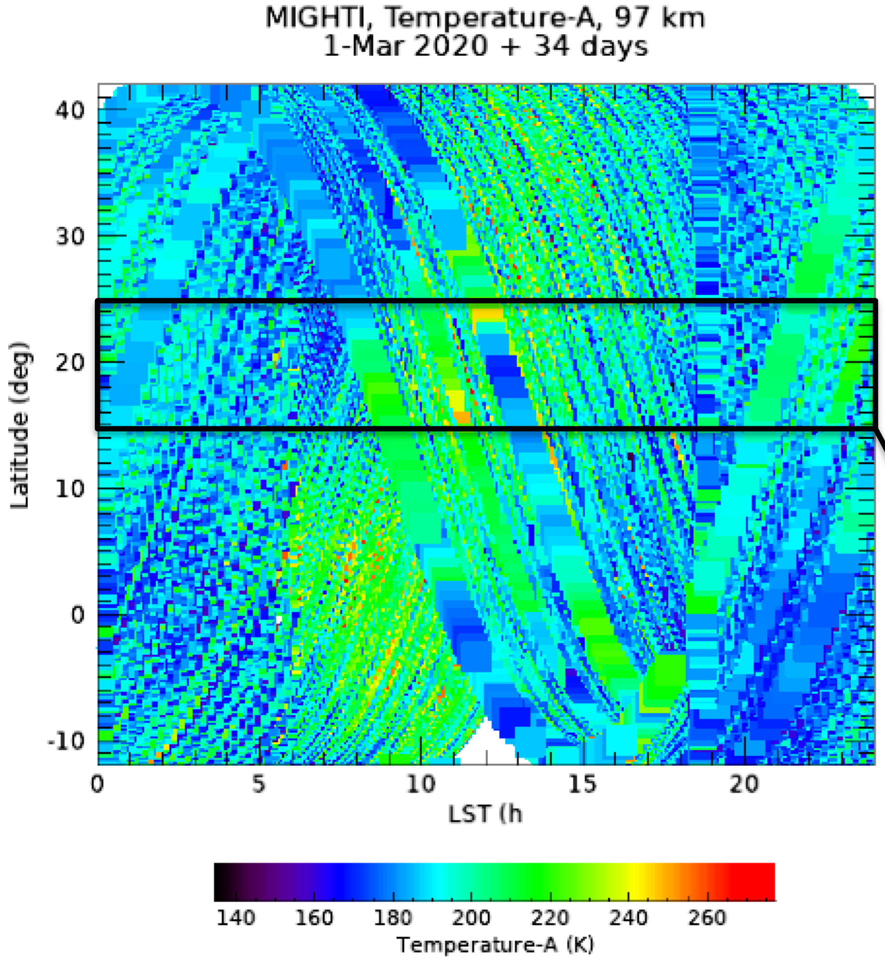
3-12 months, circulation, forcing

2 years, stratospheric QBO
4-5 years, El Niño
interaction

11 years, solar cycle

How to observe tides from space?

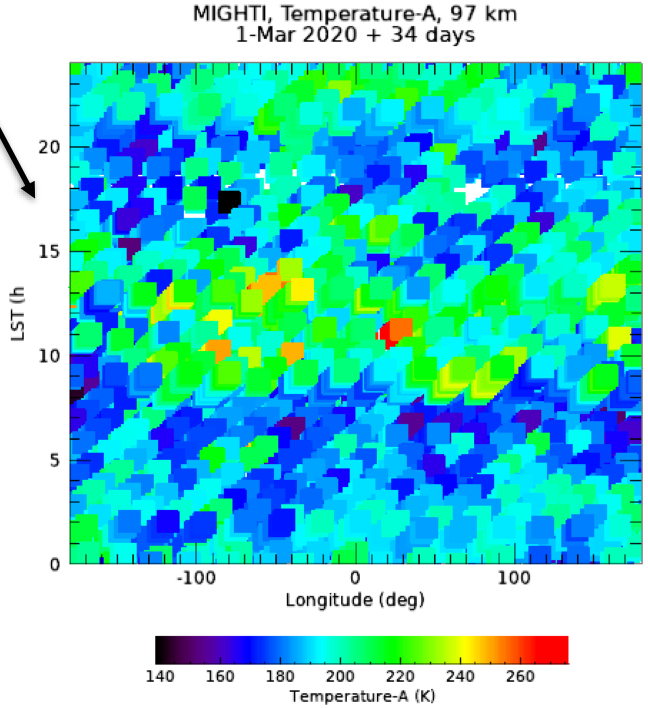
ICON/MIGHTI Local Solar Times and Tides

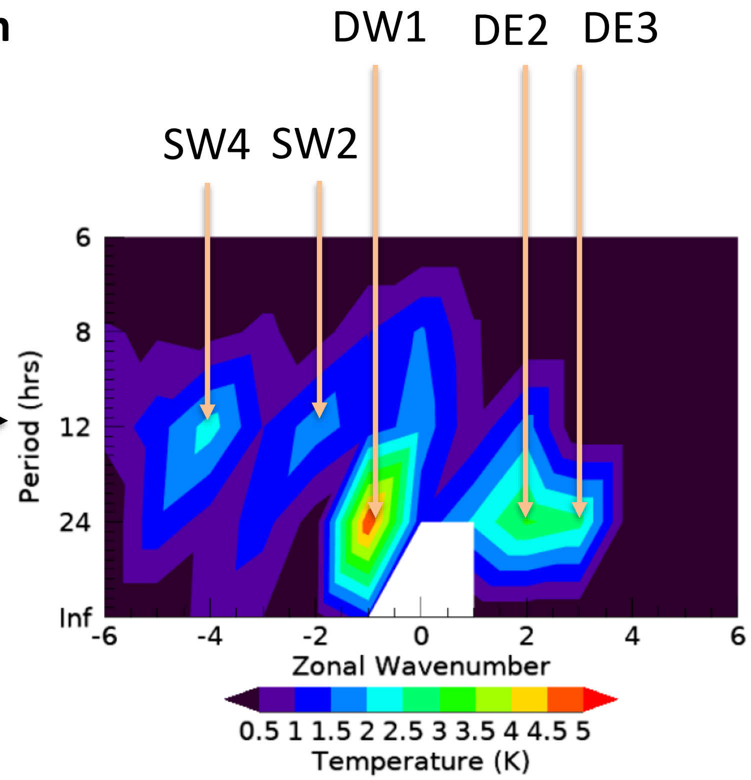


Full (24 hr) local solar time coverage at <u>all</u> latitudes within 35-day window

For each latitude & altitude
do 2D-FFT (lon, lst) -> (wavenumber, period)

-> **diurnal and semidiurnal tidal spectrum as 35-day running mean average**





COSMIC-2 Global Ionospheric Specification (GIS) Data

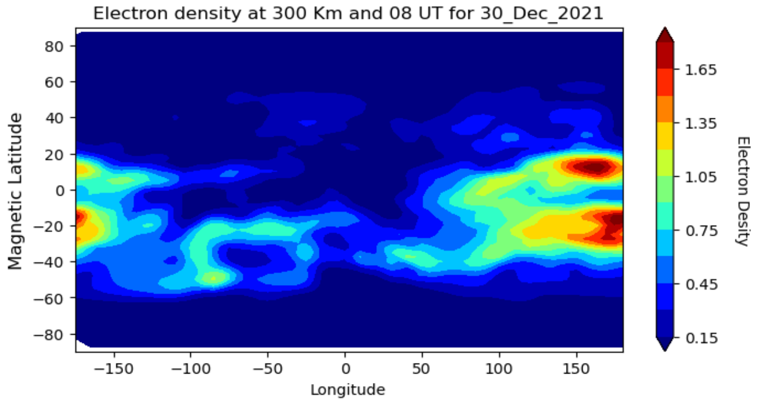
Six satellites, 24^{o} inclination, 530 km, launched on 25 June 2019

- Since Feb 2021, sats are in final configuration with a ~60^{o} lon separation
- IVM instrument & RO soundings

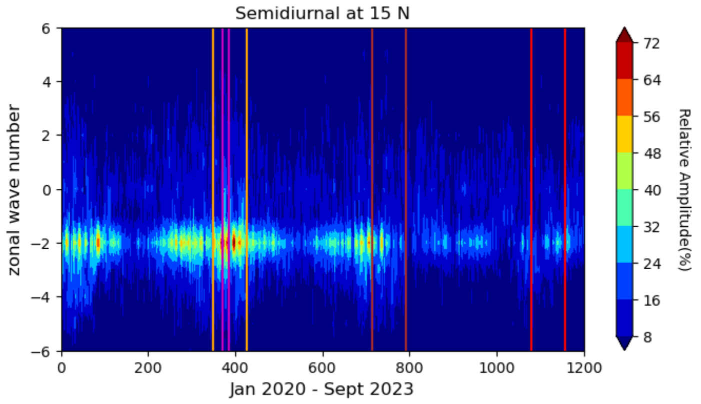
formosat7.earth.ncku.edu.tw
Lin et al., 2020; Chou et al., 2021

GIS electron density profiles

- Assimilates ground-based GNSS and COSMIC-2 RO slant total electron content
- Hourly, pole-to-pole, gridded, 2.5^{o} x 5^{o} (lat x lon), 20 km vertical resolution



Tidal spectra
every day



How to Measure Tidal Variability on Shorter Timescales?

Fly satellite constellations

- COSMIC-2 (6 sats) in F-region ionosphere; day-to-day variability
  Rajesh et al., 2021; Oberheide 2022
- Don't have this for the neutral atmosphere
- In special cases, MLS & SABER can be combined
  Nguyen & Palo, 2013; Wang et al., 2021

Make some assumptions/special cases

- Resolve variability within a few days by neglecting some tides
  Oberheide et al., 2015; Gasperini et al., 2015; Dhadly et al., 2018; …

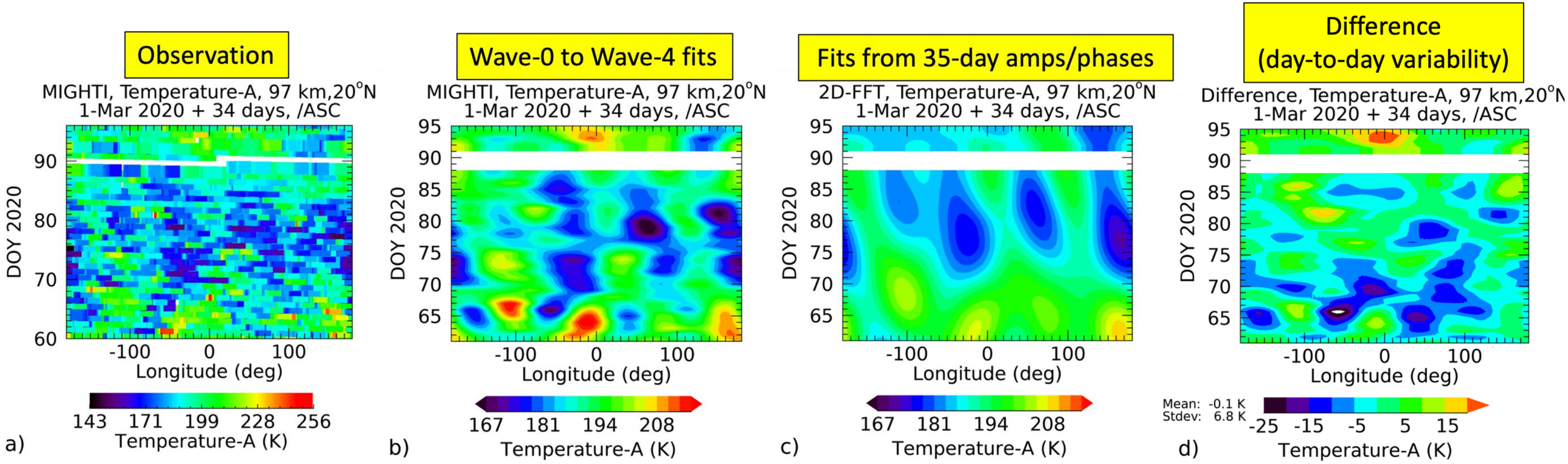
Statistical approaches

- <35-day in MIGHTI (standard deviations): *Oberheide et al., 2024*
- <30-day in SABER (autoregression methods): *Vitharana et al., 2019*

The Statistics of Short-Term Tidal Variability in the Mesosphere/Lower Thermosphere from MIGHTI/ICON

Oberheide et al. (2024), JGR 2024JA032619

Extracting Short-term Variability as Standard Deviation



Local time
AND
Wave Variability

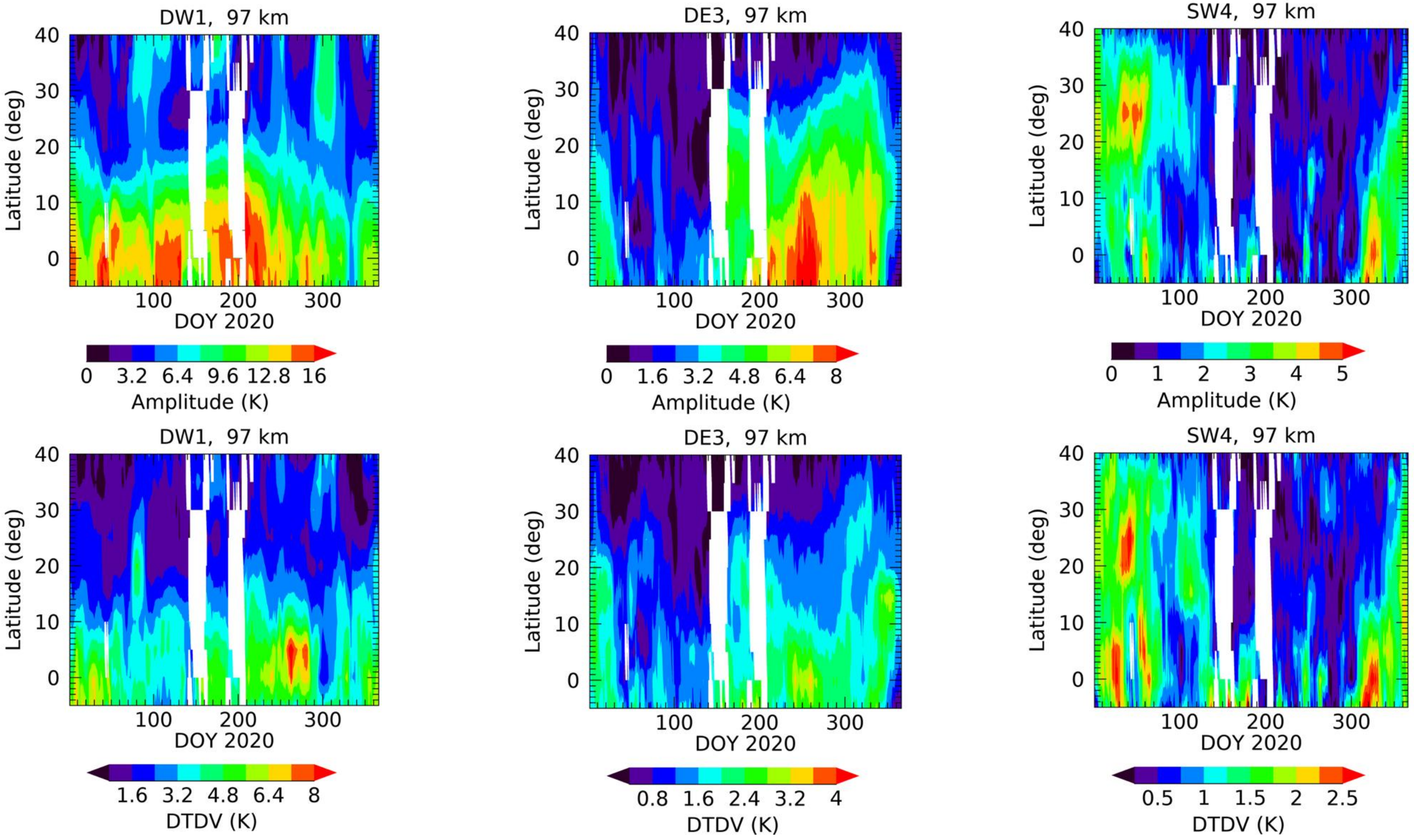
Local time
ONLY

Wave Variability
ONLY

Short-term Variability at 97 km, a few Examples

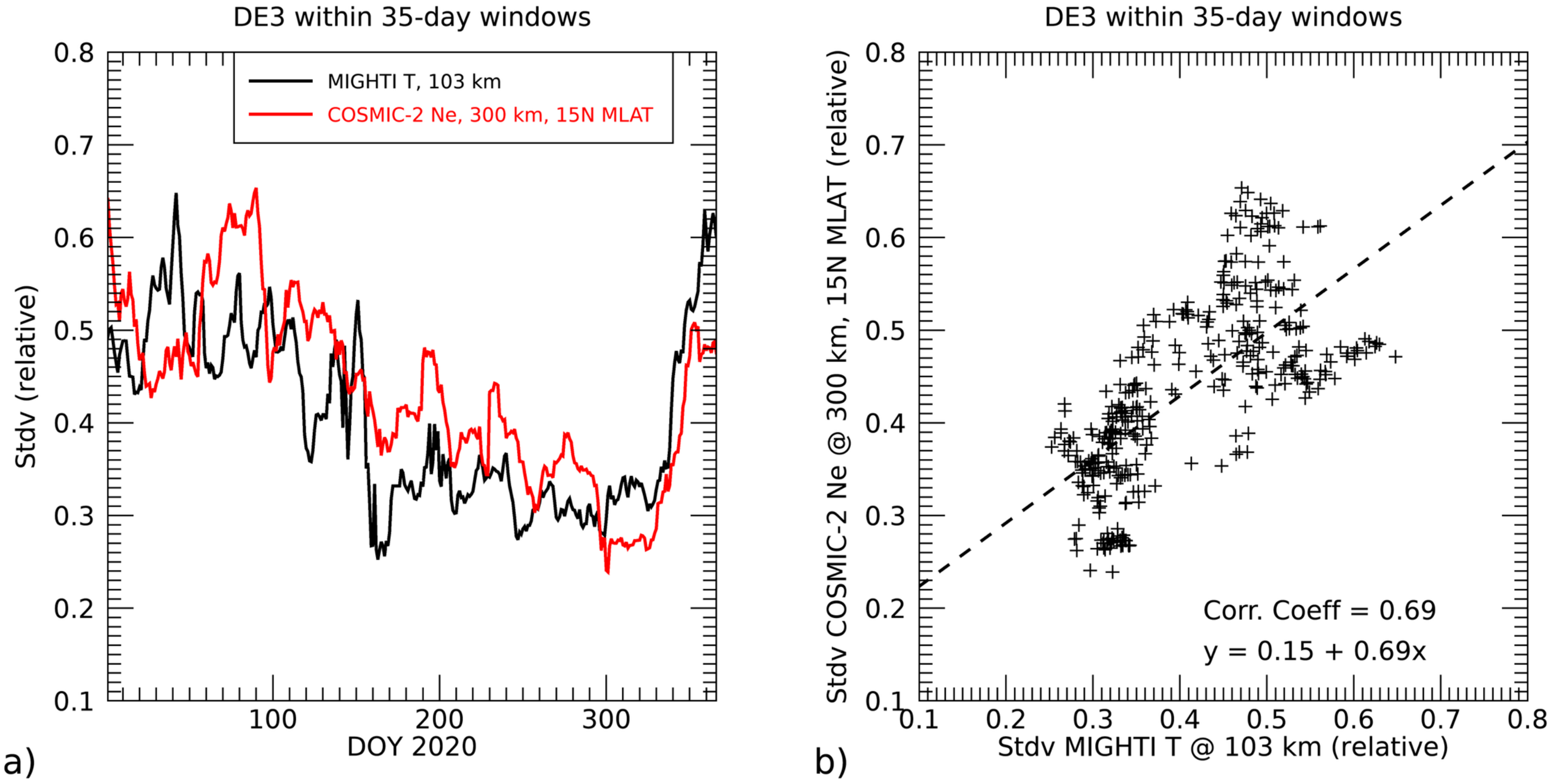
35-day running mean amplitude from 2D-FFT

Standard dev. within 35-day running mean window



Short-term tidal variability is on order 40-50% of the 35-day running mean amplitudes.
Similar results for other diurnal and semidiurnal tidal components.

Validation with COSMIC-2



T Standard Deviation

We know the "true" tides for every day from COSMIC-2. Can thus compute "true" 35-day standard deviation.

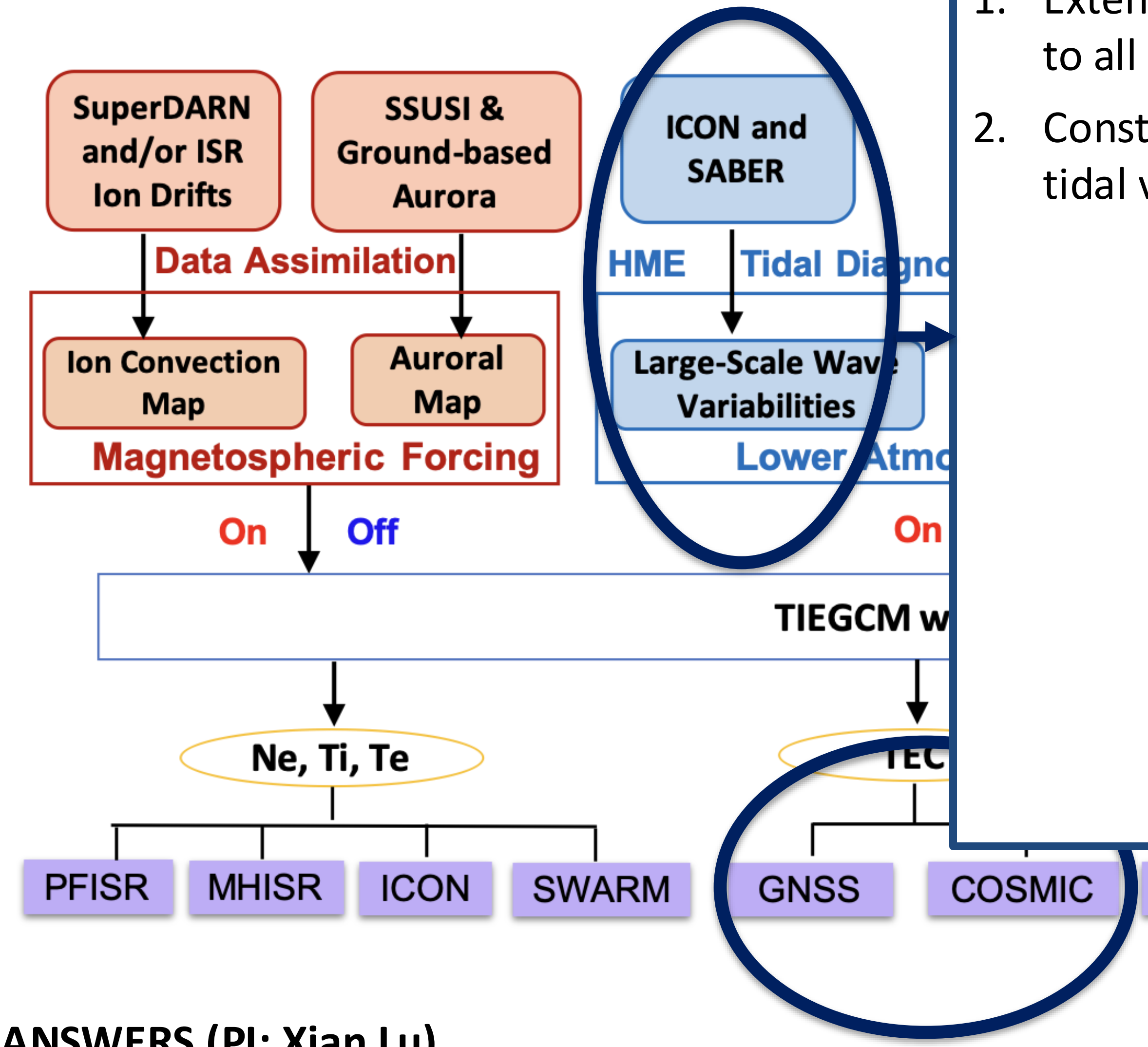
Compares very well (for DE3) with MIGHTI E-region standard deviation in T, as it should be

(DE3 does not have thermospheric sources and coupling is E-region dynamo)

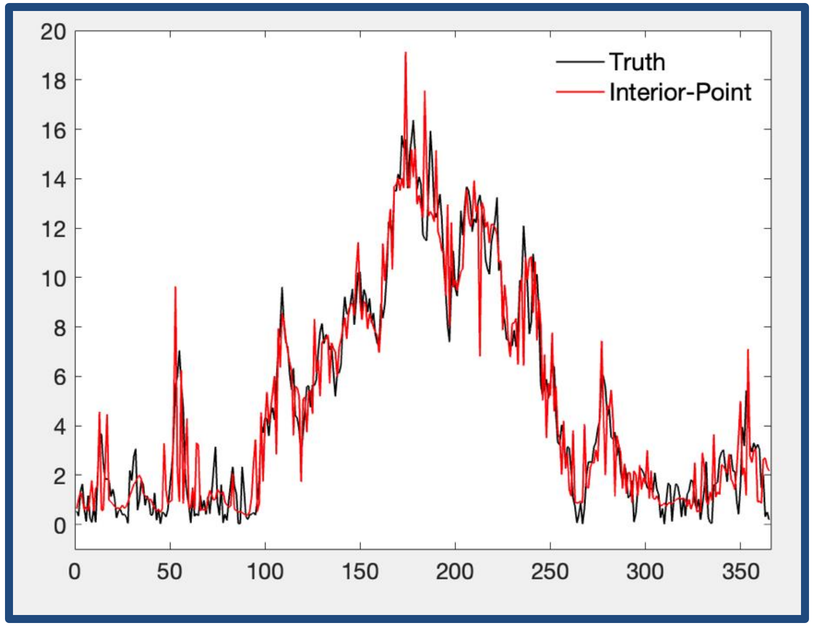
TIE-GCM with MIGHTI-based statistical tidal variability

Towards understanding pre-conditioning of the IT

Drive TIE-GCM with Observed Tidal Standard Deviations



1. Extend MIGHTI tidal fields and their standard deviations to all latitudes (Hough Mode Extensions)
2. Construct lower boundary time series with day-to-day tidal variability using interior-point optimization approach



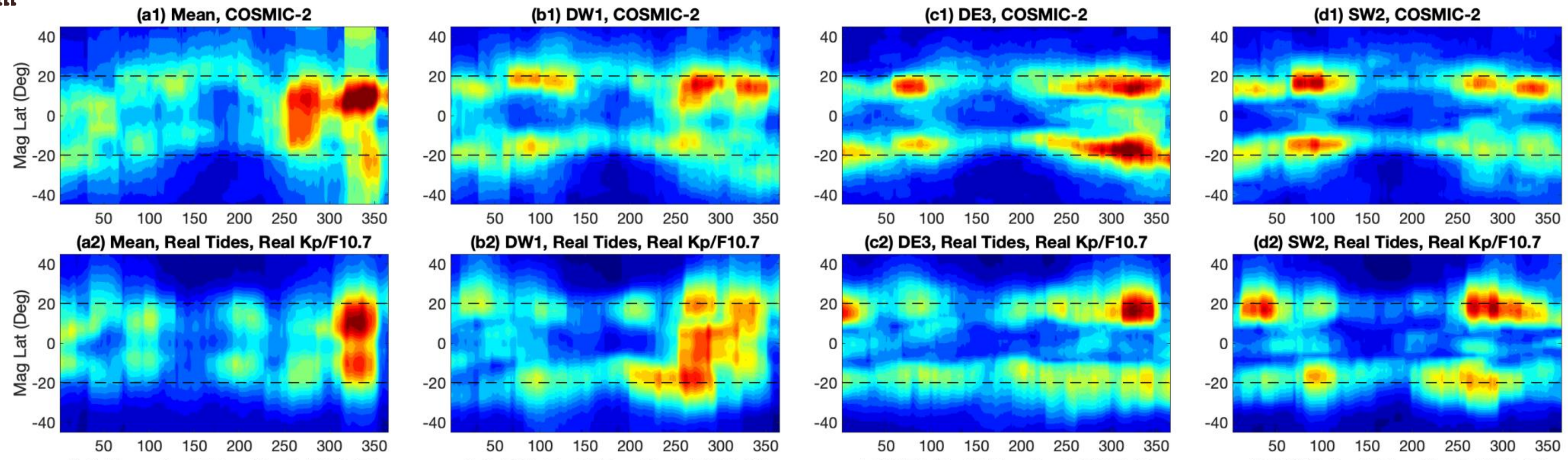
NSF-ANSWERS (PI: Xian Lu)

Observationally-Driven TIE-GCM Reproduces Ionospheric Variability, N_e @ 300 km

Unit: $\#/cm^3$

COSMIC-2

Run 1: Realistic Tides, Kp, F10.7



Courtesy of Xian Lu

Successfully incorporated observed lower boundary tidal variability into TIE-GCM.

Resulting F-region electron density variability (2-35 days) compares well with COSMIC-2.

Work in progress looks into importance of tidally induced variability for ionospheric response to solar/geomagnetic forcing.

Tidal & Planetary Wave Variability in the F-region Ionosphere in Response to the Weather of the Stratosphere and Troposphere

Predictability potential

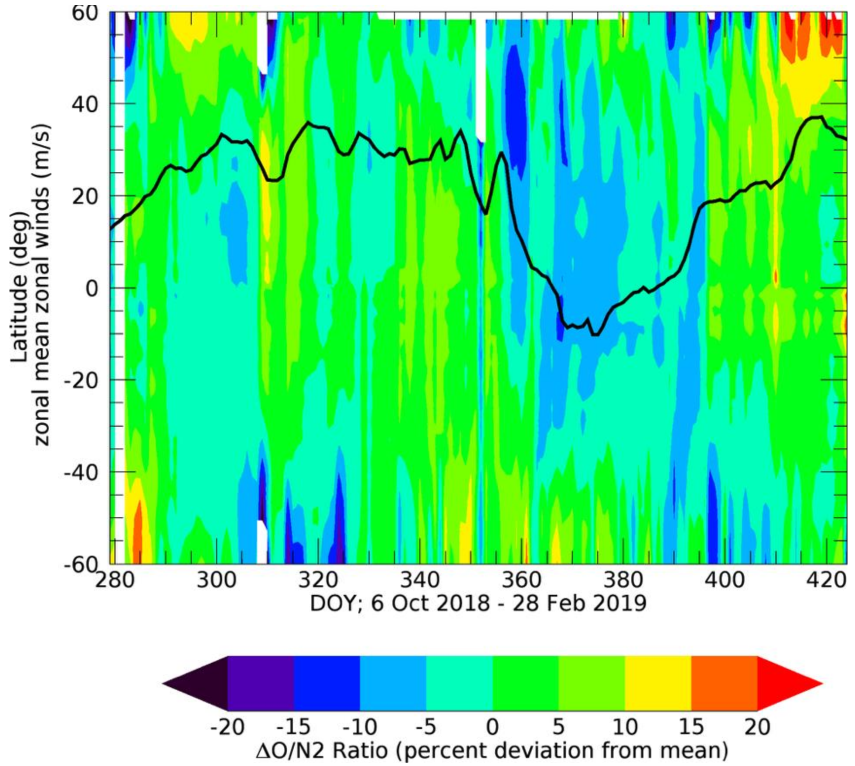
Sudden Stratospheric Warmings (SSW)

split of polar vortex, large mean circulation and temperature changes in polar stratosphere; predictable ***1-2 weeks in advance***

SSW and Composition of the Thermosphere

1. SSW enhances global-scale wave driving, particularly SW2
2. This changes residual mean circulation
3. 2-cell circulation pattern in lower thermosphere reduces [O]
4. Propagates through molecular diffusion into upper thermosphere
5. Results in observed 10-15 % O/N_2 depletion

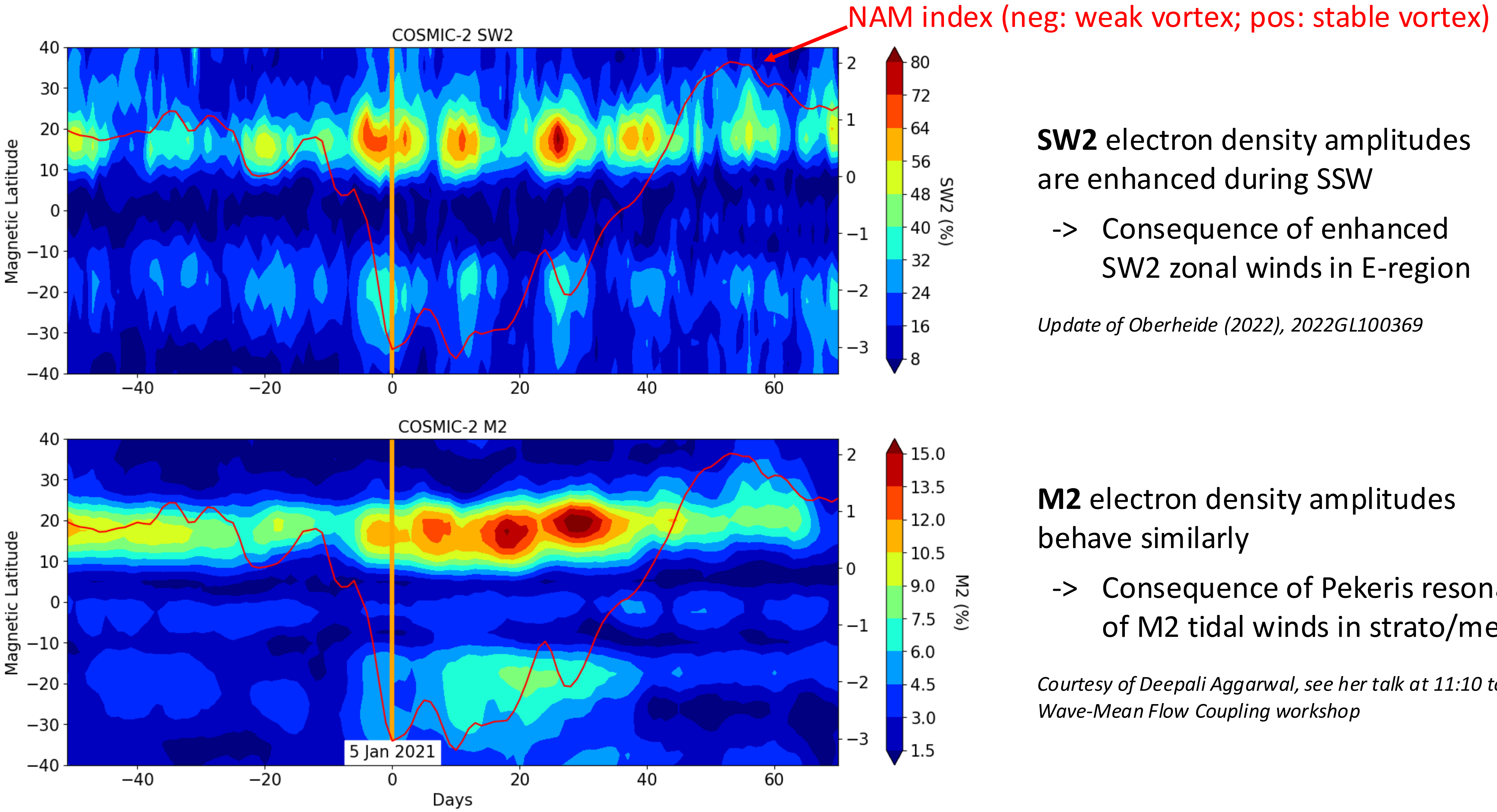
GOLD, 2019 SSW



Oberheide et al. (2020), 2019GL086313

GOLD observation are the first observational proof of this mechanism that was proposed by Yamazaki and Richmond (2013) and Pedatella et al. (2016)

The Solar SW2 & Lunar M2 Tides in the Ionosphere @ 300 km



SW2 electron density amplitudes are enhanced during SSW

-> Consequence of enhanced SW2 zonal winds in E-region

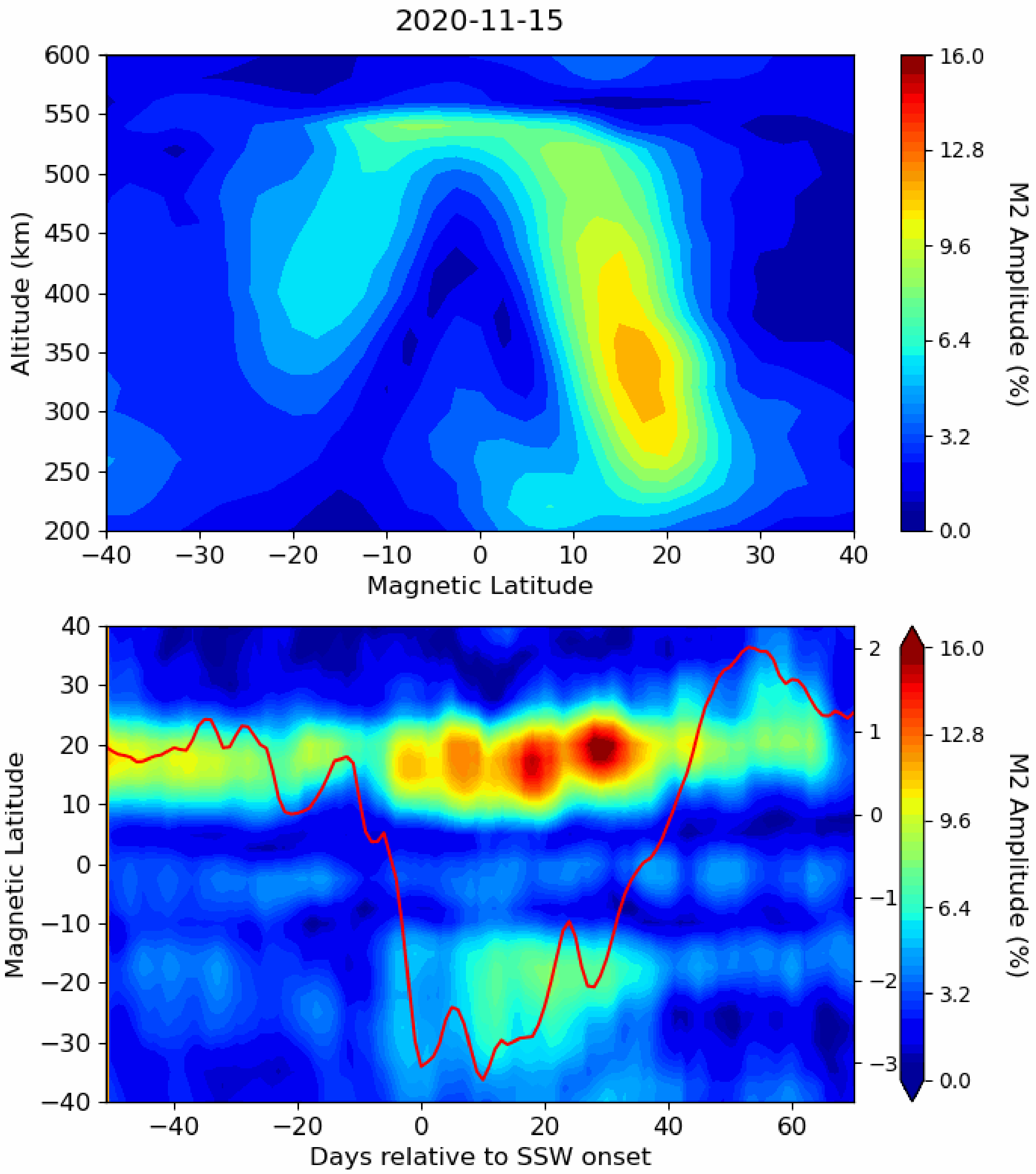
Update of Oberheide (2022), 2022GL100369

M2 electron density amplitudes behave similarly

-> Consequence of Pekeris resonance of M2 tidal winds in strato/mesosphere

Courtesy of Deepali Aggarwal, see her talk at 11:10 today in the Wave-Mean Flow Coupling workshop

The Lunar M2 Tide in the Ionosphere @ 300 km



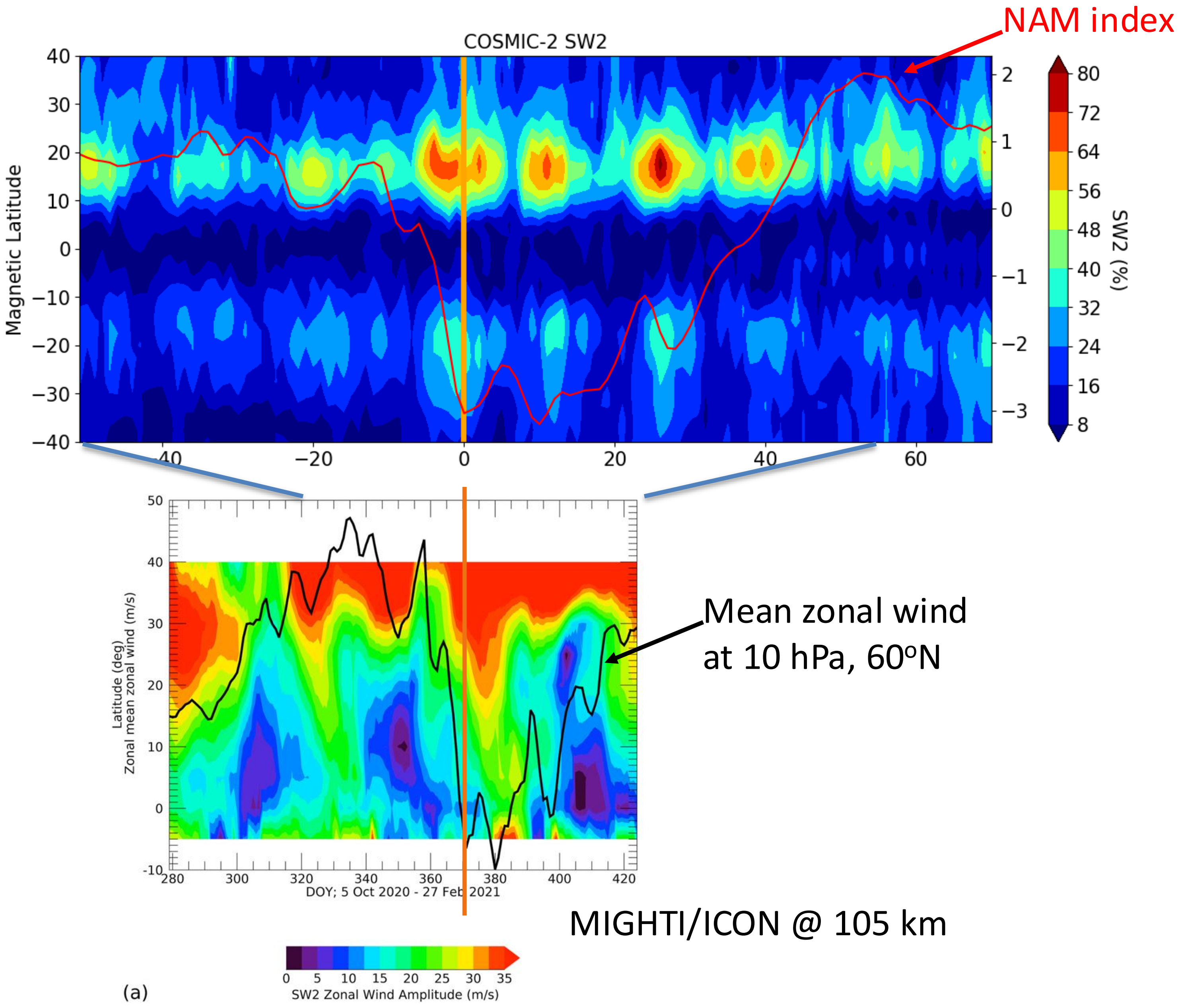
M2 response to SSW throughout the ionosphere in BOTH hemispheres

M2 electron density amplitudes behave similarly

-> Consequence of Pekeris resonance of M2 tidal winds in strato/mesosphere

Courtesy of Deepali Aggarwal, see her talk at 11:10 today in the Wave-Mean Flow Coupling workshop

The Solar SW2 Tide in the Ionosphere @ 300 km



SW2 electron density amplitudes are enhanced during SSW

-> Consequence of enhanced SW2 zonal winds in E-region

Update of Oberheide (2022), 2022GL100369

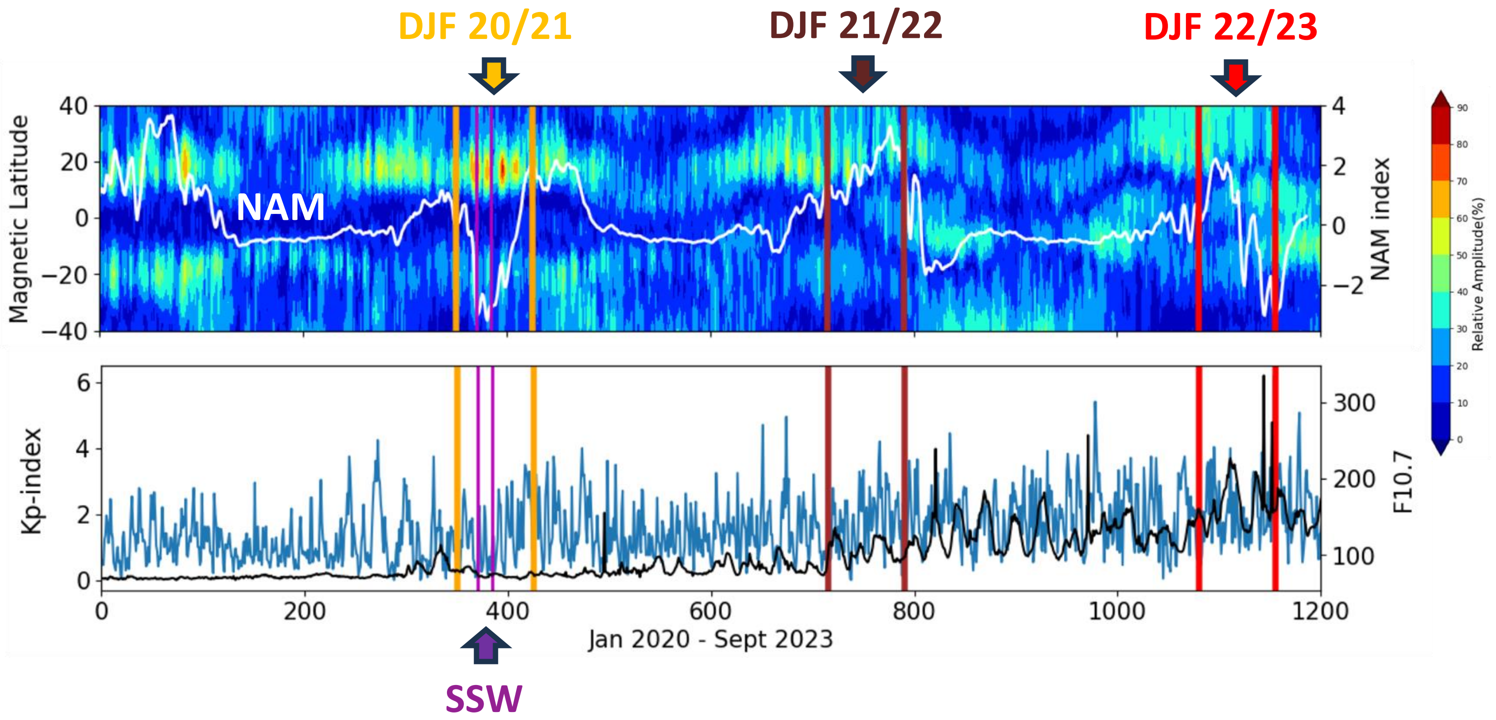
SW2 zonal wind amplitudes in E-region are enhanced during SSW

-> Consequence of mainly circulation changes during SSW

Ionospheric Response to Polar Vortex Strength outside SSW

SSW occur only ~once per year but the vortex can be "wobbly" all the time
Northern Annular Mode (NAM)
predictable ***1-2 weeks in advance***

The Solar SW2 Tide in the Ionosphere @ 300 km

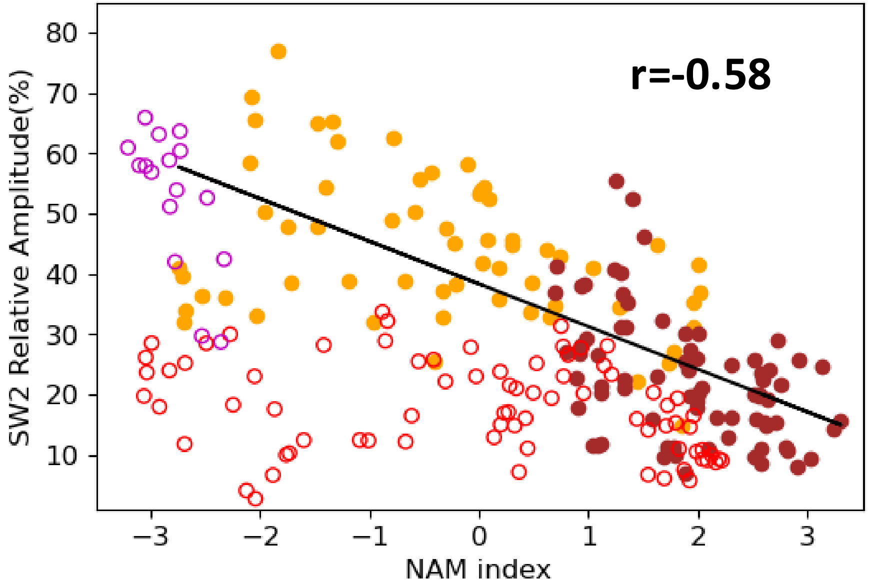


SW2 very sensitive to strength of polar vortex (NAM index) **OUTSIDE SSW**

Weak vortex = strong tides

Aggarwal et al. (2025), 2024GL111313

MLAT=20N



Clear anti-correlation during low solar activity

Less correlation during high solar activity

DJF 20/21 ● **DJF 21/22** ● **DJF 22/23** ○ **Jan 21 SSW** ○

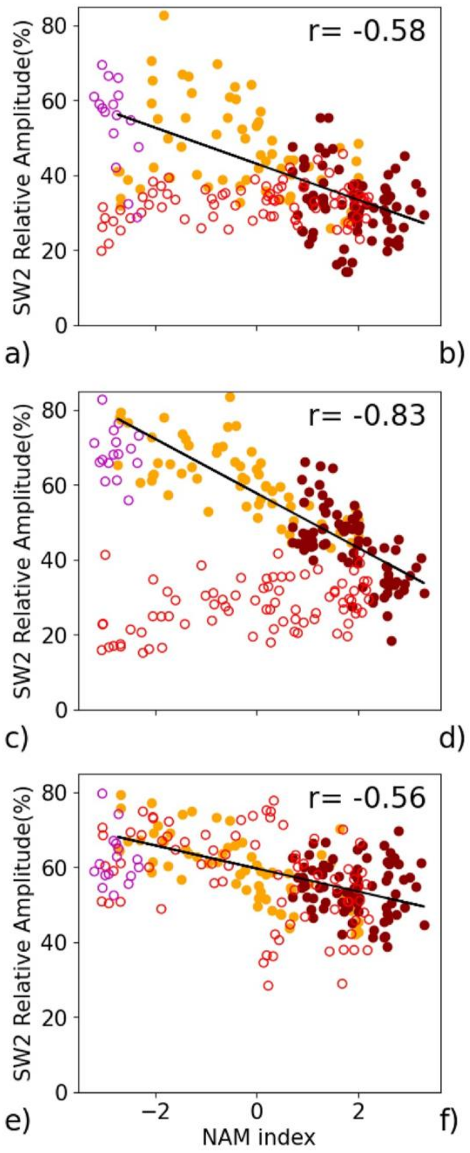
The Solar SW2 Tide in the Ionosphere @ 300 km

DJF 20/21 ● DJF 21/22 ● DJF 22/23 ○ Jan 21 SSW ○

COSMIC-2

SD-WACCM-X

SD-WACCM-X
control simulation
(low solar activity)



Model reproduces the observed
NAM/SW2 relationship

Low solar activity simulation aligns
DJF 22/23 with the previous years

High solar activity causes a hotter thermosphere, causing
more tidal dissipation, causing smaller tidal winds in the E-region,
causing smaller vertical drifts, causing smaller ionospheric tides

Aggarwal et al. (2025), 2024GL111313

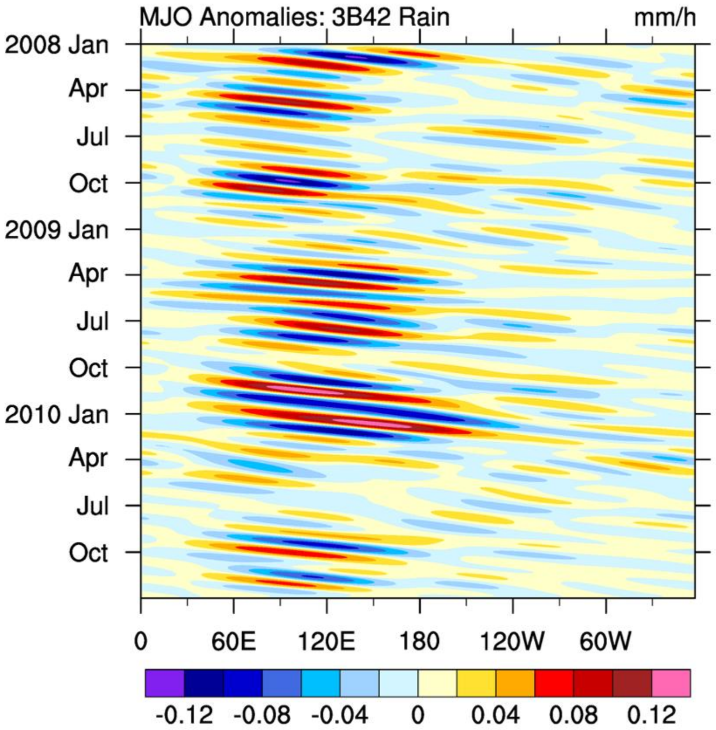
Ionospheric Response to the Madden-Julian Oscillation (MJO)

MJO is recurring weather phenomenon in the tropical troposphere,
subject of intense study due to its relevance for climate
and medium-range weather forecast;
*predictable **several weeks in advance***

Connecting Recurring Weather Events with Ionospheric Variability: the MJO

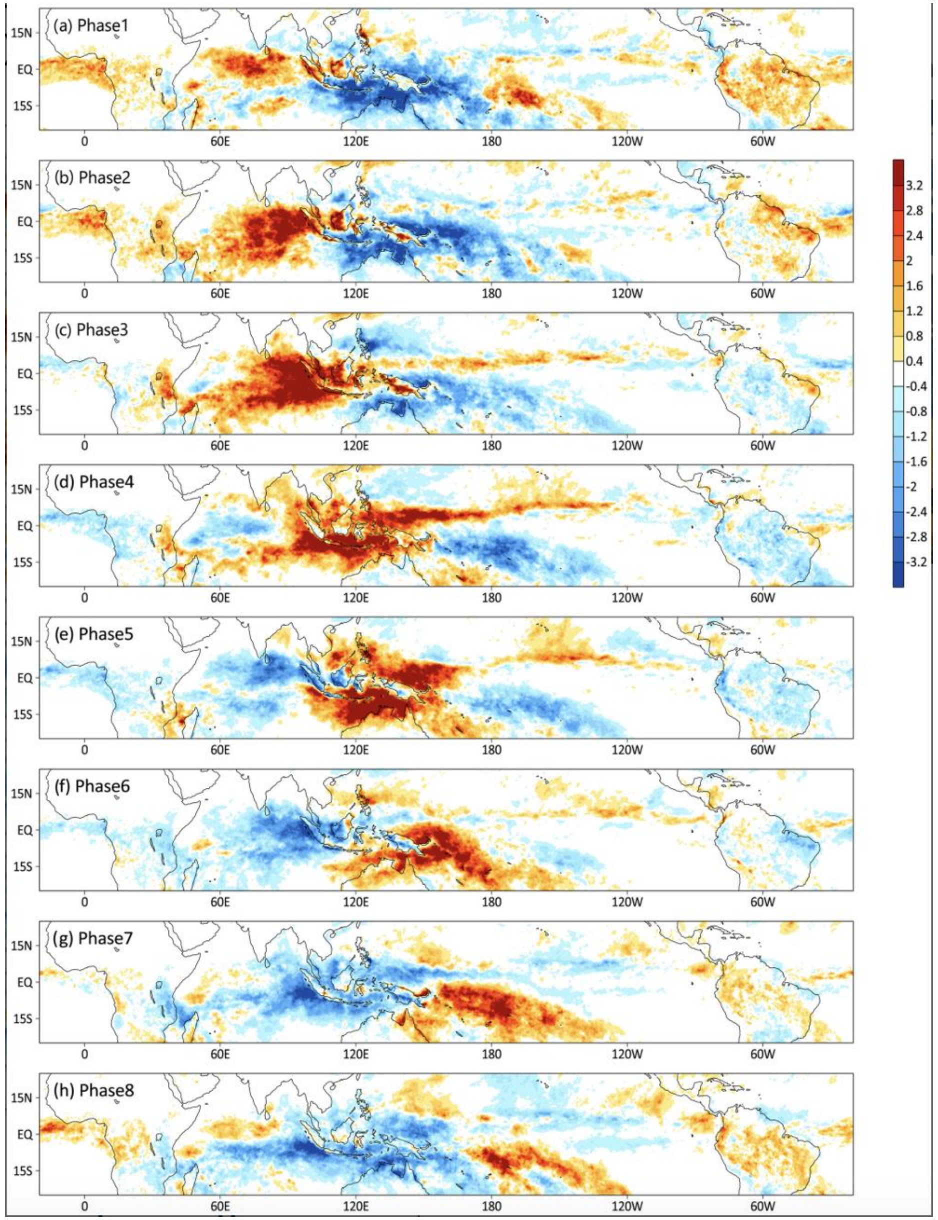
Madden-Julian Oscillation (MJO)

- Eastward, 30-96 days
- Changes convection and circulation
  wave sources and wave filtering



MJO-filtered convective rainfall anomalies from TRMM satellite observations

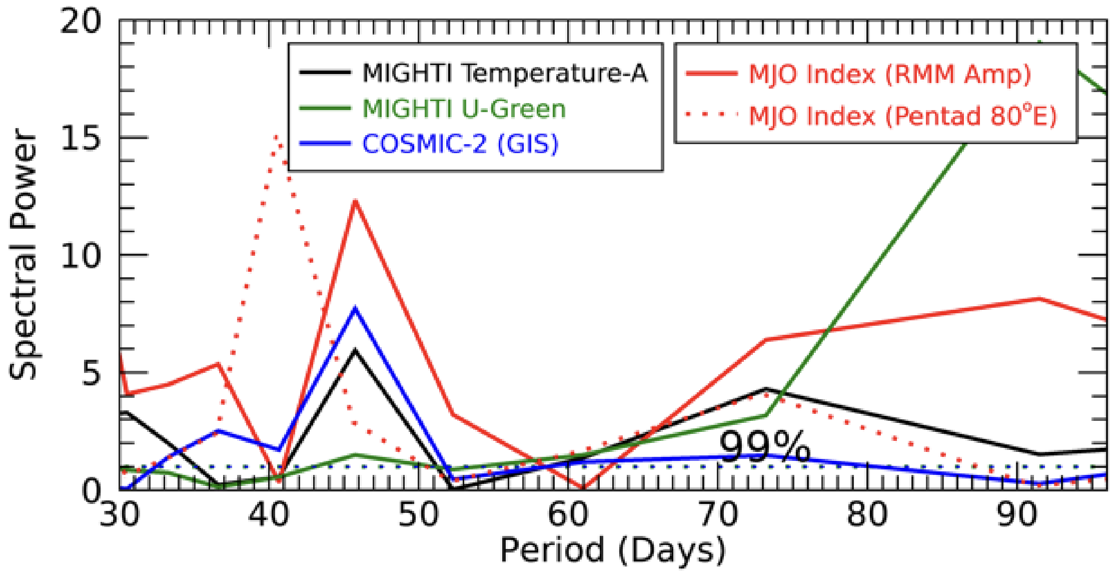
MJO impact on tides is largely due to forcing modulation
Kumari et al. (2021), 2021JD034595



Jiang et al. (2020)

Connecting Recurring Weather Events with Ionospheric Variability: the MJO

2020, Fourier spectrum of DW1 (diurnal migrating tide)



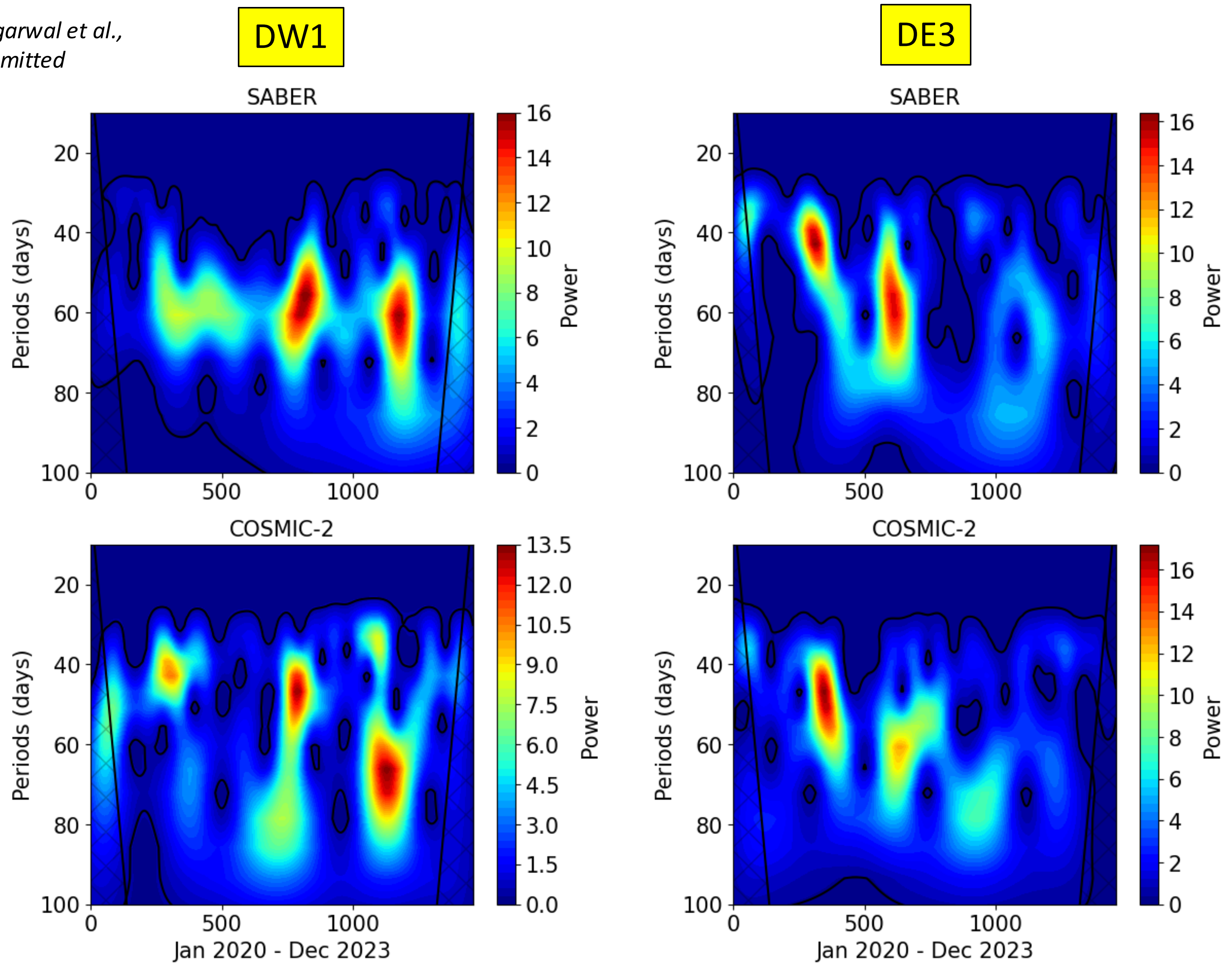
Consistent spectral signals from the troposphere to the E-region to the F-region

Know: MJO modulates tidal temperatures in the E-region on order 10% (DW1) and 25% (DE3)

Kumari et al. (2020), 2020GL089172

Connecting Recurring Weather Events with Ionospheric Variability: the MJO

Aggarwal et al., submitted



Wavelet of MJO-filtered temperature tides in the E-region

Wavelet of MJO-filtered Electron density tides in the F-region

Largely due to E-region dynamo although field-aligned winds have some contribution (work in progress)

Planetary Waves in the F-region Ionosphere

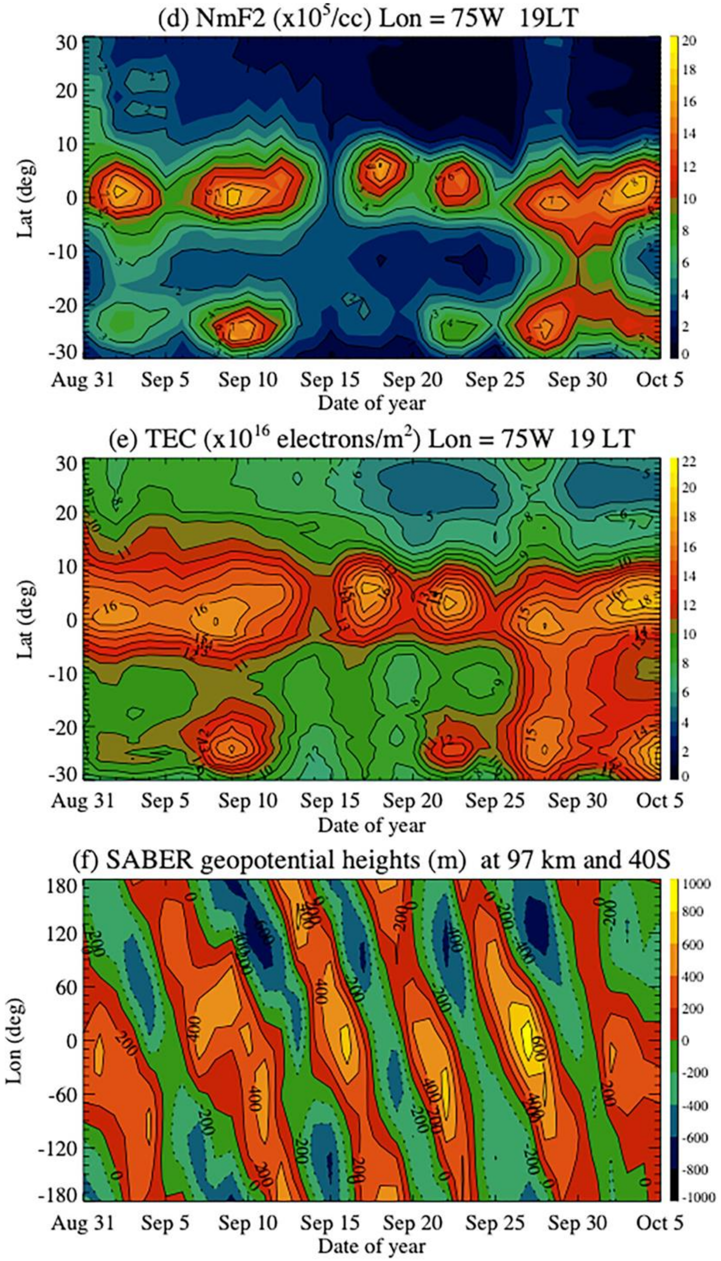
Ionospheric oscillations at planetary wave periods 2-20 days
are consequence of 2nd order PW-tide interactions
because PWs cannot easily propagate into the E-region
moderate predictability of a ***few days***

Short-term Variability in the Ionosphere due to Planetary Waves

GOLD

GNSS

SABER



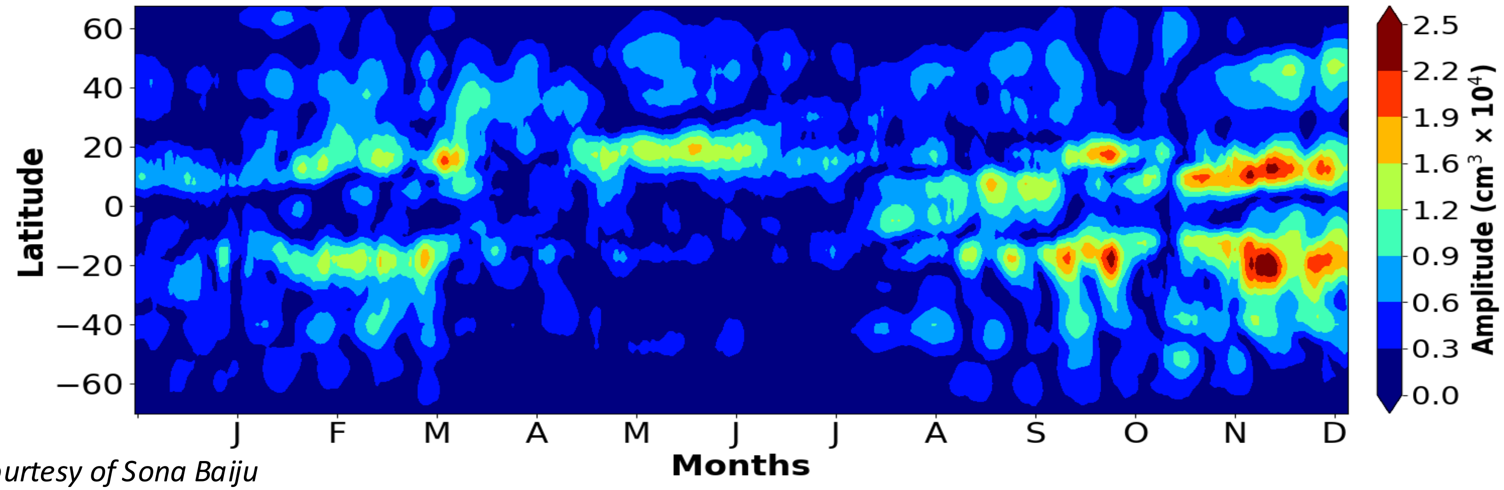
6-day westward propagating
zonal wavenumber 1 (Q6DW1)
evident in MLT and F-region ionosphere;
2019 Antarctic SSW

Possible coupling

- E-region dynamo
- Tidal wind modulation of pre-reversal enhancement of vertical ion drifts

Gan et al. (2023), 2023GL103386

Short-term Variability in the Ionosphere due to Planetary Waves

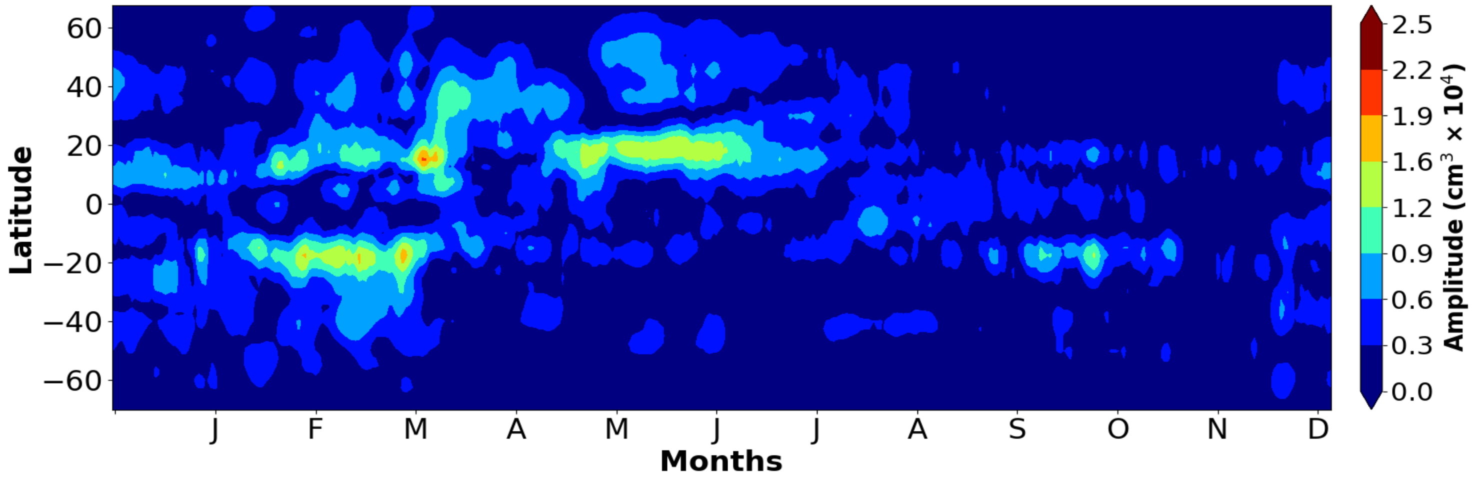


Courtesy of Sona Baiju (poster on Tue)

2020

16-day westward propagating zonal wavenumber 1 (Q16DW1) at 300 km from COSMIC-2

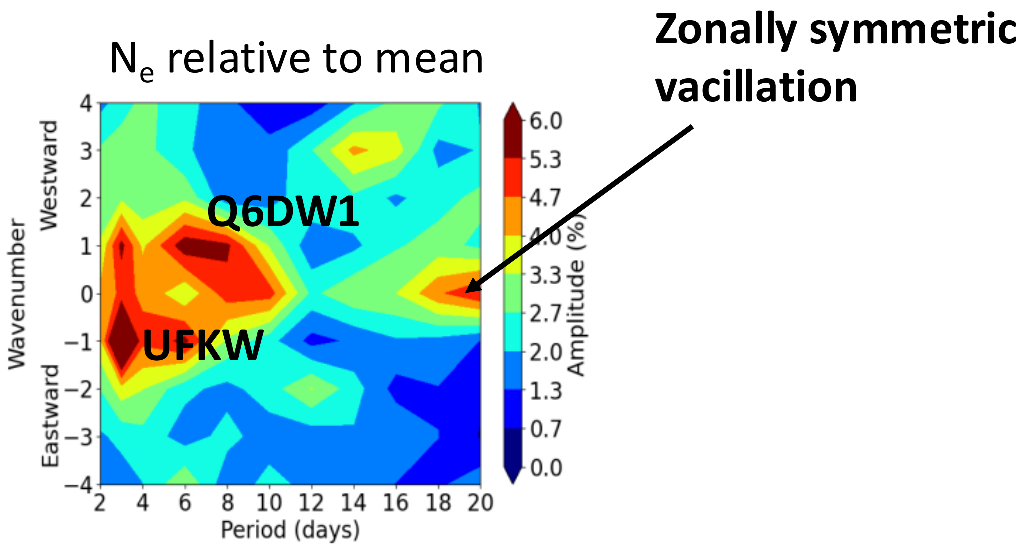
Driven by PW-tide + F10.7 + K_p

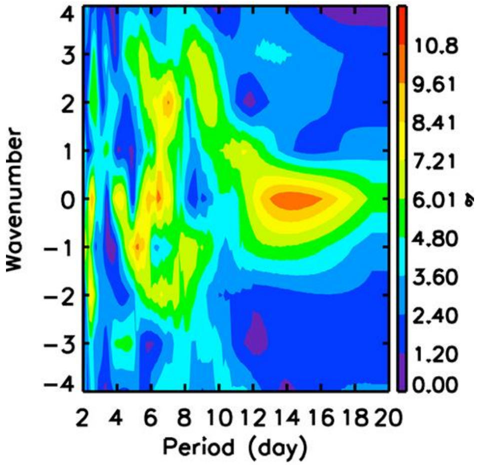


Q16DW1 due to PW-tide interactions

Short-term Variability in the Ionosphere due to Planetary Waves

April 2020 COSMIC-2
300 km, 20°N MLAT





TIE-GCM, 2009
Forbes et al. (2018)

Model and observation show strong zonally symmetric vacillations.

Cannot be E-region dynamo due to lack of current divergence…

Zonal asymmetries in conductivity? *(Liu et al., 2010)*

Courtesy of Sona Baiju
(poster on Tue)

Take Home Points

F-region ionosphere responds strongly to short-term tidal and PW variability

Can conclusively map tropospheric & stratospheric weather into the ionosphere

Radio occultation data from the COSMIC-2 constellation are a powerful tool

Framework for predictability

SSW, NAM, MJO can all be predicted ~1-2 weeks in advance; ML approaches!?

Coupling numerical weather forecast models with whole atmosphere models would open a pathway for ionospheric predictability during low solar activity

VLEO predictability remains a challenge

Tides (and presumably PWs) have a big impact on orbits

No constellations, reliance on assumptions or statistical approaches

Generous support from NASA (HSR, HGIO, LWS) and NSF (ANSWERS) is acknowledged.