Exploring the Sun and its effects on the Earth's atmosphere and physical environment...

HIGH ALTITUDE OBSERVATORY

Challenges in Forecasting the Quiescent Thermosphere-Ionosphere Variability that Underlies Responses to Extreme Space Weather Events

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Scientific Challenge Theme: *Model inputs* from the solar wind *to tidal forcing*, and means of forecasting inputs

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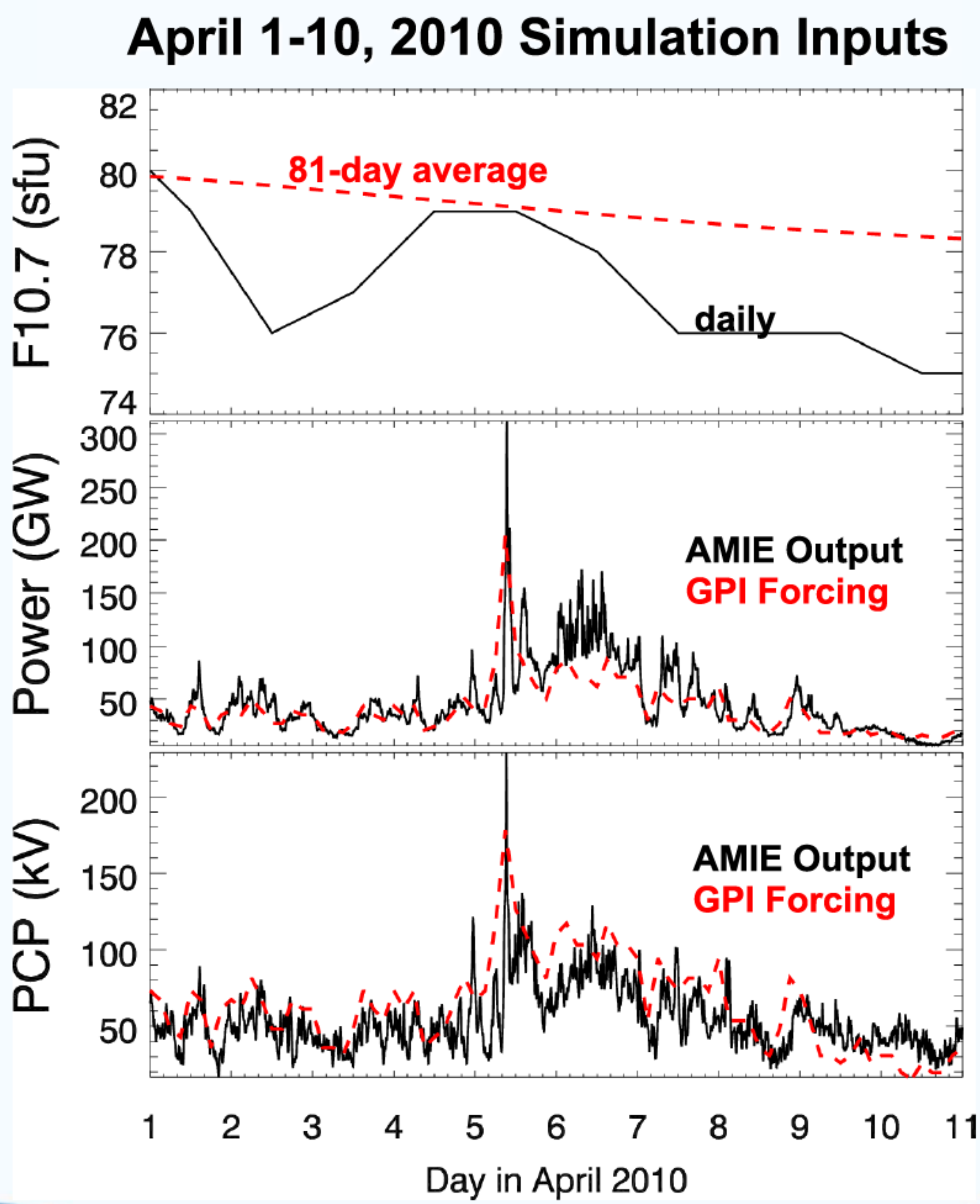
Presentation Overview

- Motivation
- Tidal Primer
  - primary sources
  - signatures
  - effects on the thermosphere-ionosphere (TI)
  - non-negligible secondary sources
- Modeling challenges and “requirements” for accurate tidal prediction
  - middle and upper atmosphere - ionosphere models
  - TI models
  - whole atmosphere models
  - electrodynamics
- Forecasting strategy based on hind-casting successes

Motivation: An Ensemble of TIME-GCM Results



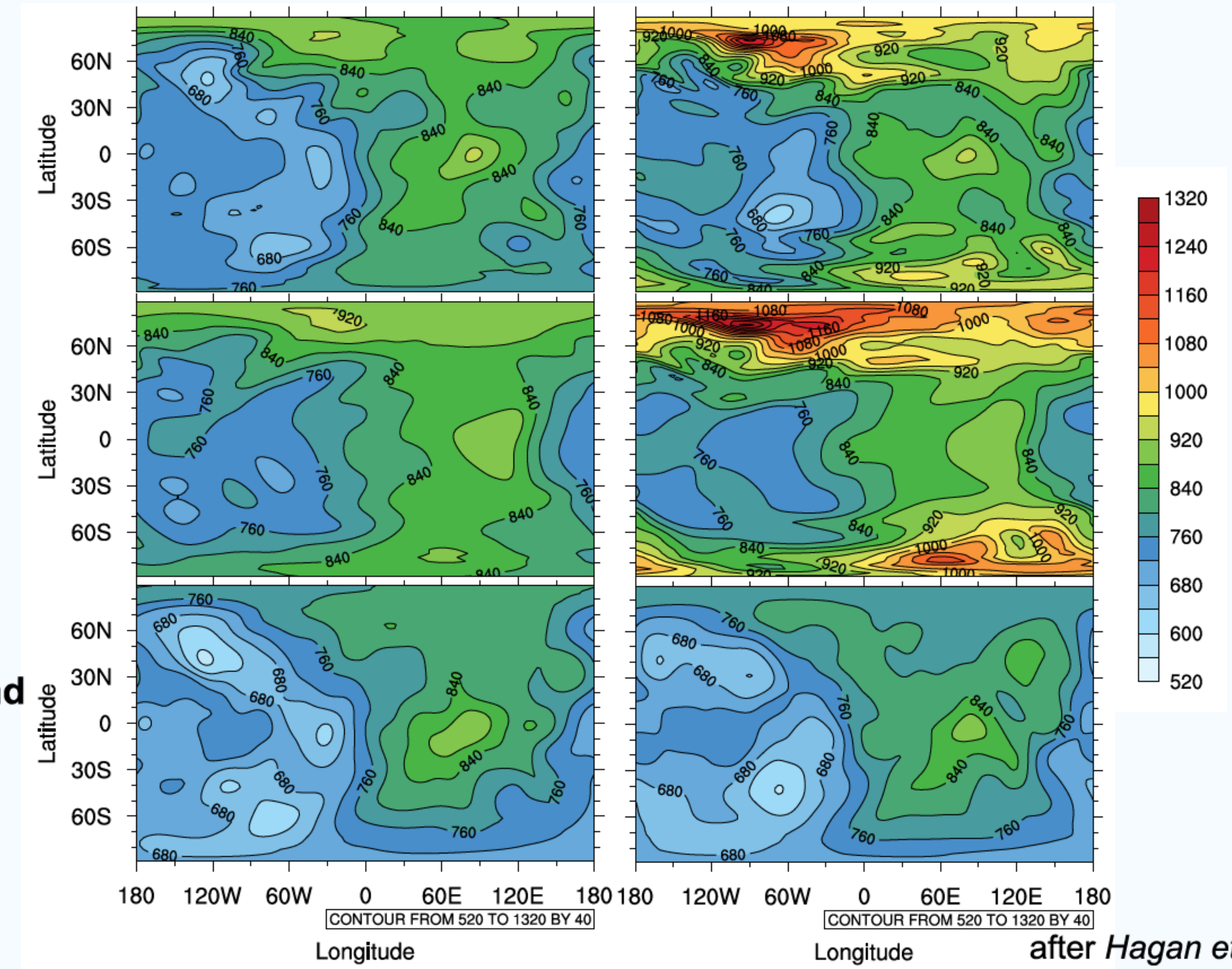
TIME-GCM Hind-Cast: Temperature (K) at 340 km

April 2, 2010 – Quiescent | **April 5, 2010 – Disturbed**

AMIE and MERRA LBC

AMIE and Constant LBC

MERRA LBC and Constant UBC

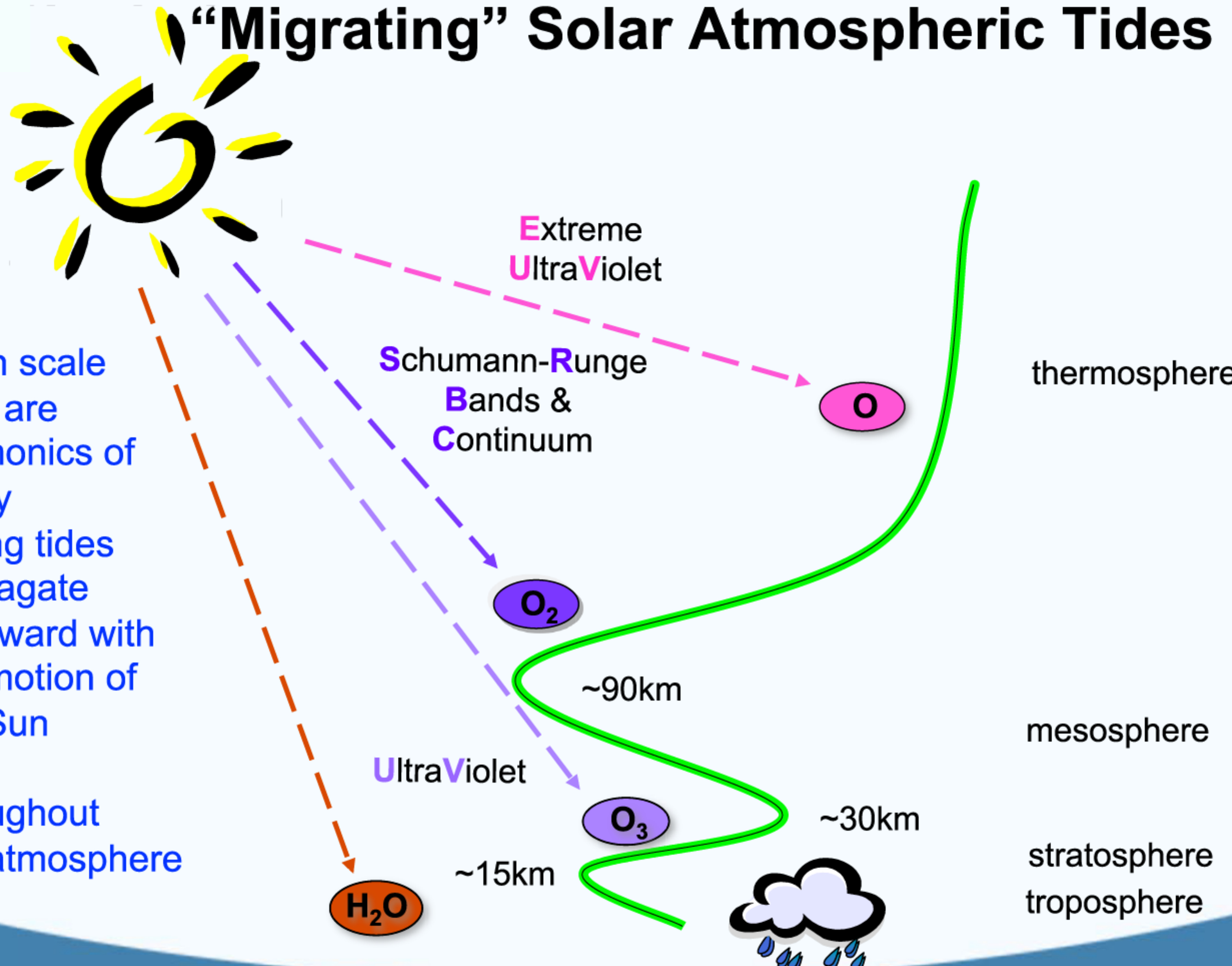


after *Hagan et al.*, 2014

Note variations attributable to MERRA LBC ➔ tropospheric tides

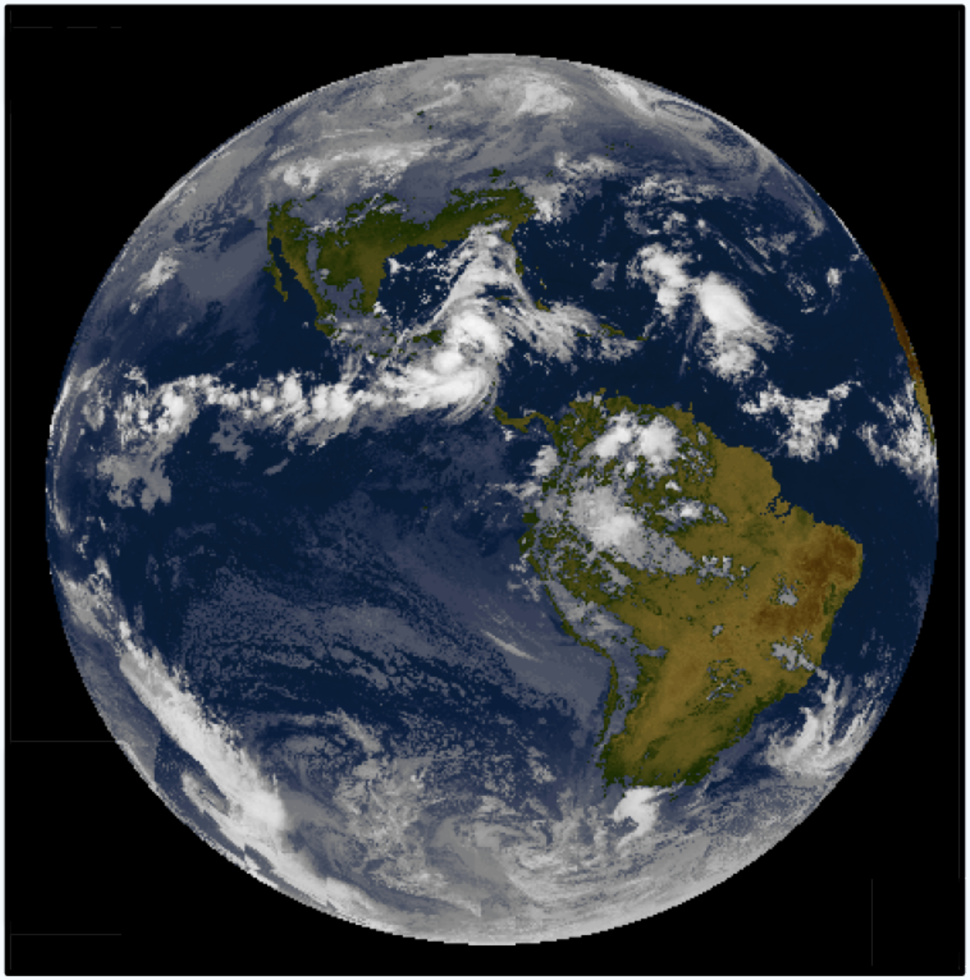
Periodic Absorption of Solar Radiation Excites "Migrating" Solar Atmospheric Tides

- global in scale
- periods are harmonics of a day
- migrating tides propagate westward with the motion of the Sun
- excited throughout the atmosphere



Latent Heat Release of Evaporation When Raindrops Form in Deep Tropical Clouds Excites "Nonmigrating" Tides

- propagate faster or slower than the Sun from the perspective of a ground-based observer
- inherent longitudinal variability of the source

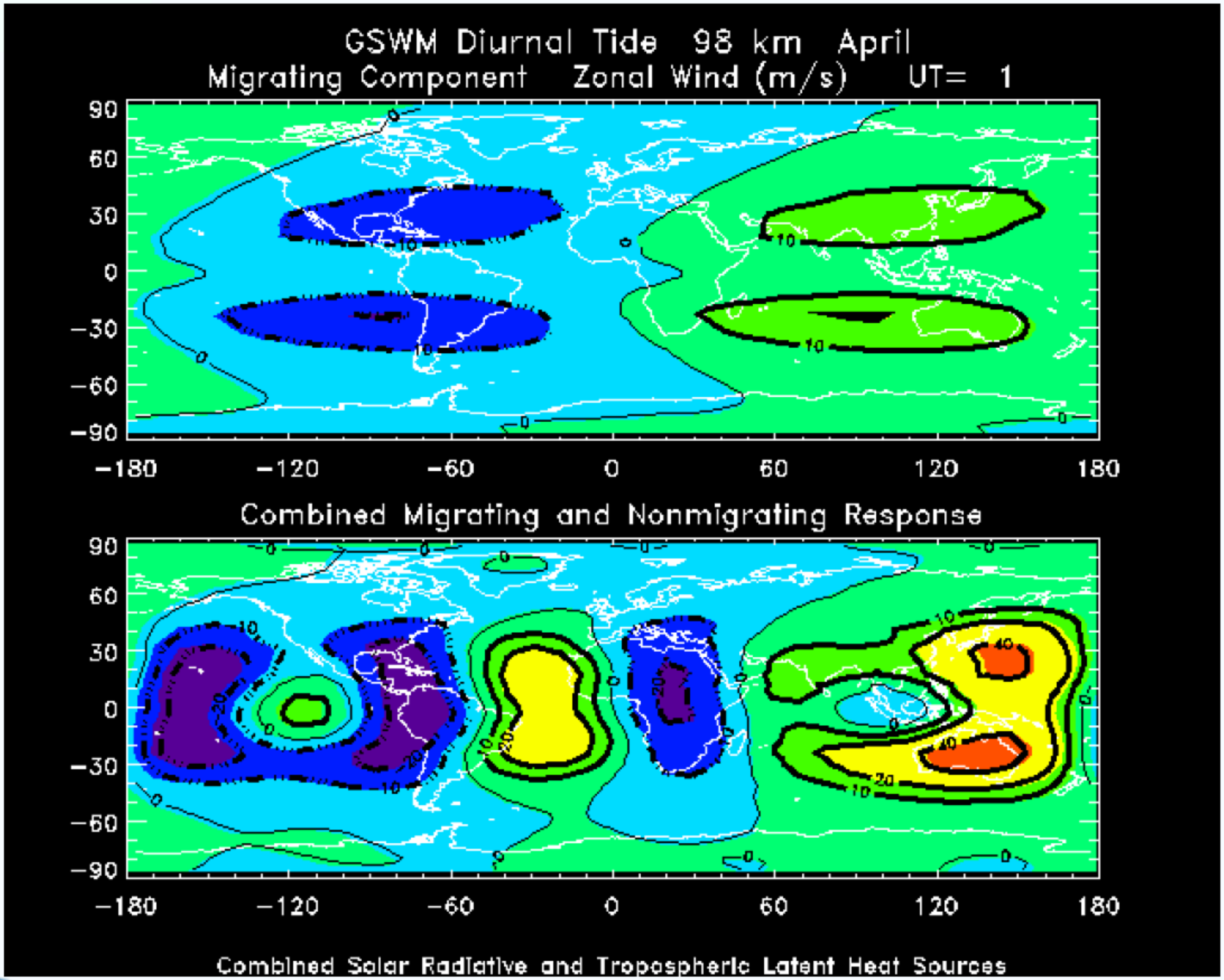


Primary TI Tidal Sources

- In-situ components attributable to
    - absorption of solar EUV radiation
- Components that penetrate the TI from below
    - tropospheric sources
        - absorption of solar infrared radiation
        - latent heat of evaporation due to raindrop formation in deep convective clouds
    - strato-mesospheric sources
        - absorption of solar UV radiation
    - **grow exponentially and evolve as they propagate upward in the increasingly rarified atmosphere**
    - **dominate the dynamics of the upper mesosphere and lower thermosphere ➔ the gateway to the TI**

98-km Zonal Wind Perturbation - Gateway to the TI

Global-Scale Wave Model (GSWM-02*) Diurnal Climatology - April



Migrating tide

- *longitude invariant*
- follows the apparent motion of the Sun

Total migrating + nonmigrating diurnal response

- larger than the migrating response
- evolving *latitude & longitude* variations

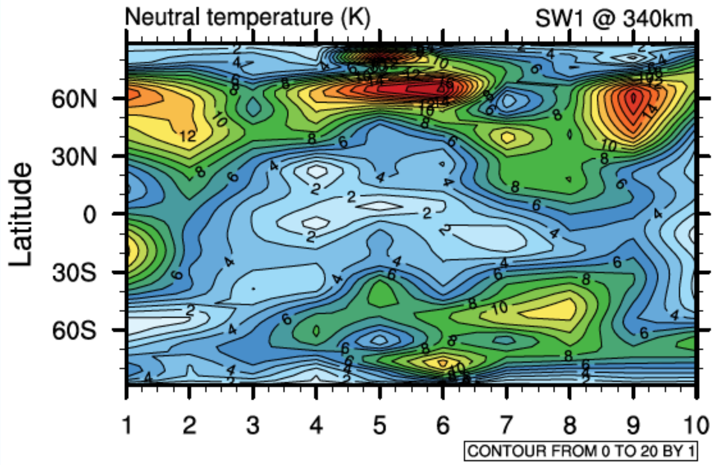
**Hagan and Forbes*, 2002; 2003

Secondary TI Tidal Sources

- In-situ components
  - ion-neutral coupling
    - excite both diurnal and semidiurnal nonmigrating tides
    - the majority of high-latitude nonmigrating tidal components are generated locally in the thermosphere (*Jones Jr. et al.*, 2013)
- Components that penetrate the TI from below
  - strato-mesospheric sources
    - tide-tide and tide-planetary wave interactions
    - tide-mean flow interactions - though not a source - modify upward propagating components
- Electrodynamic effects
  - tidal modulation of the E-region dynamo
  - maps into the F-region
  - convolved with impacts of tides that directly penetrate

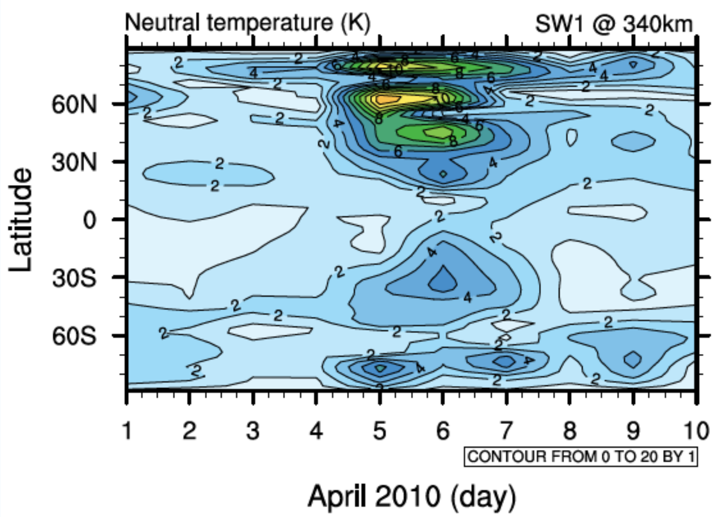
TIME-GCM Tidal Temperature Amplitudes

Realistic Simulation

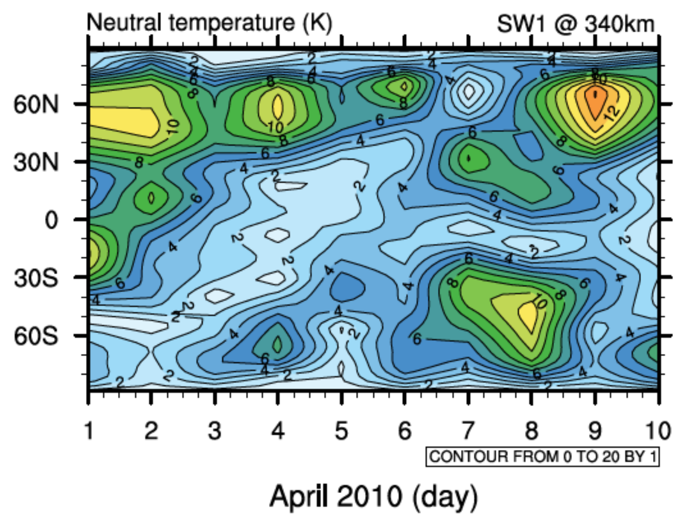


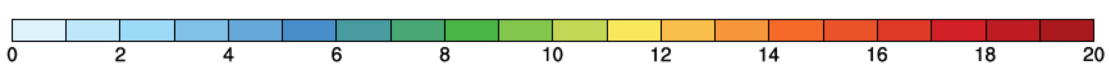
- Nonmigrating Semidiurnal Westward 1 tide (up to 14°K) excited in-situ (ion-neutral coupling) and at the lower boundary
- Enhanced pseudo-tide (up to 12°K) at mid-high latitudes during the disturbance on April 5-7

Constant Lower Boundary



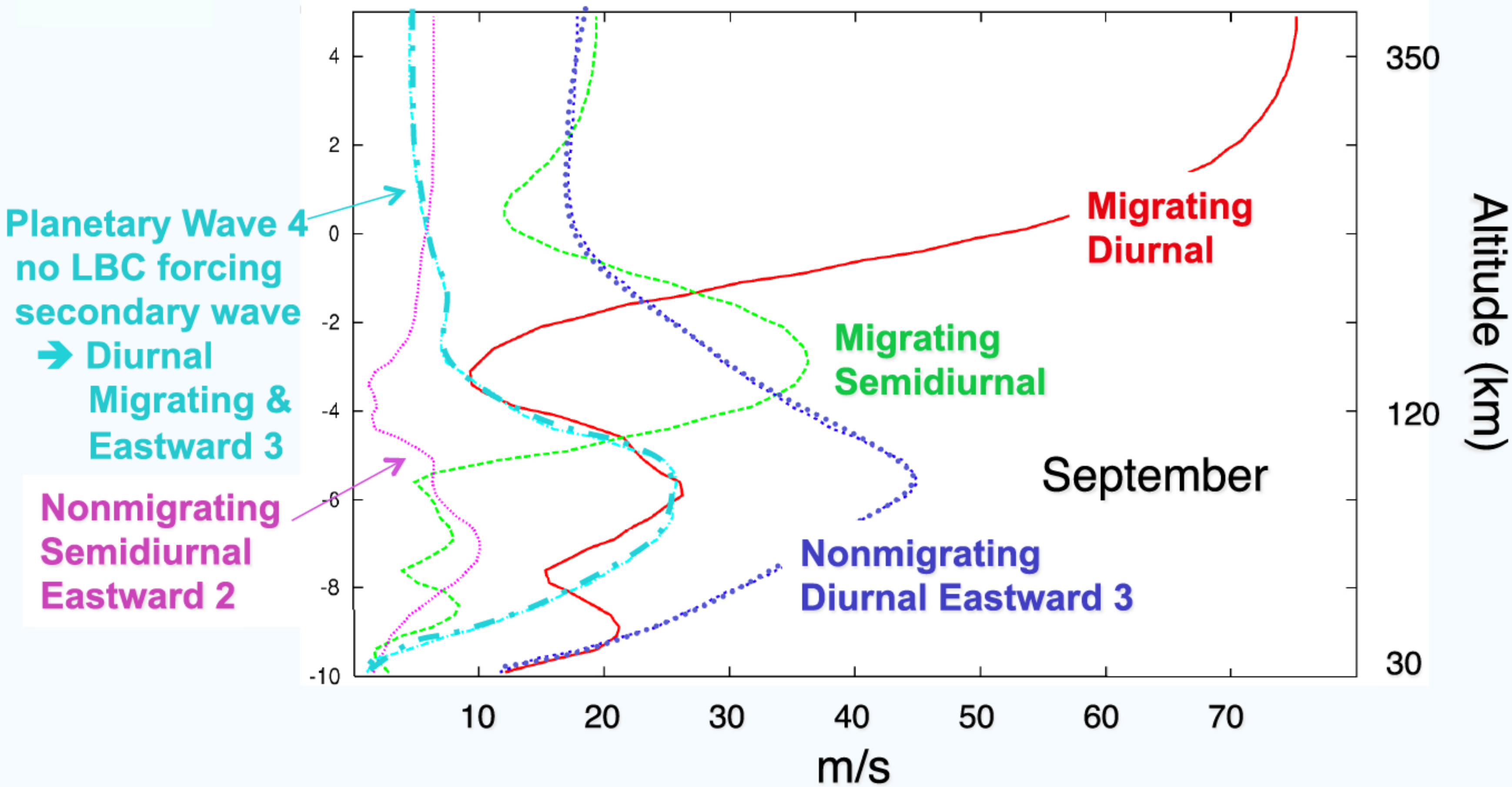
Constant Upper Boundary





after *Hagan et al.*, 2014

TIME-GCM Equatorial Wave Components Zonal Wind Amplitudes (m/s)

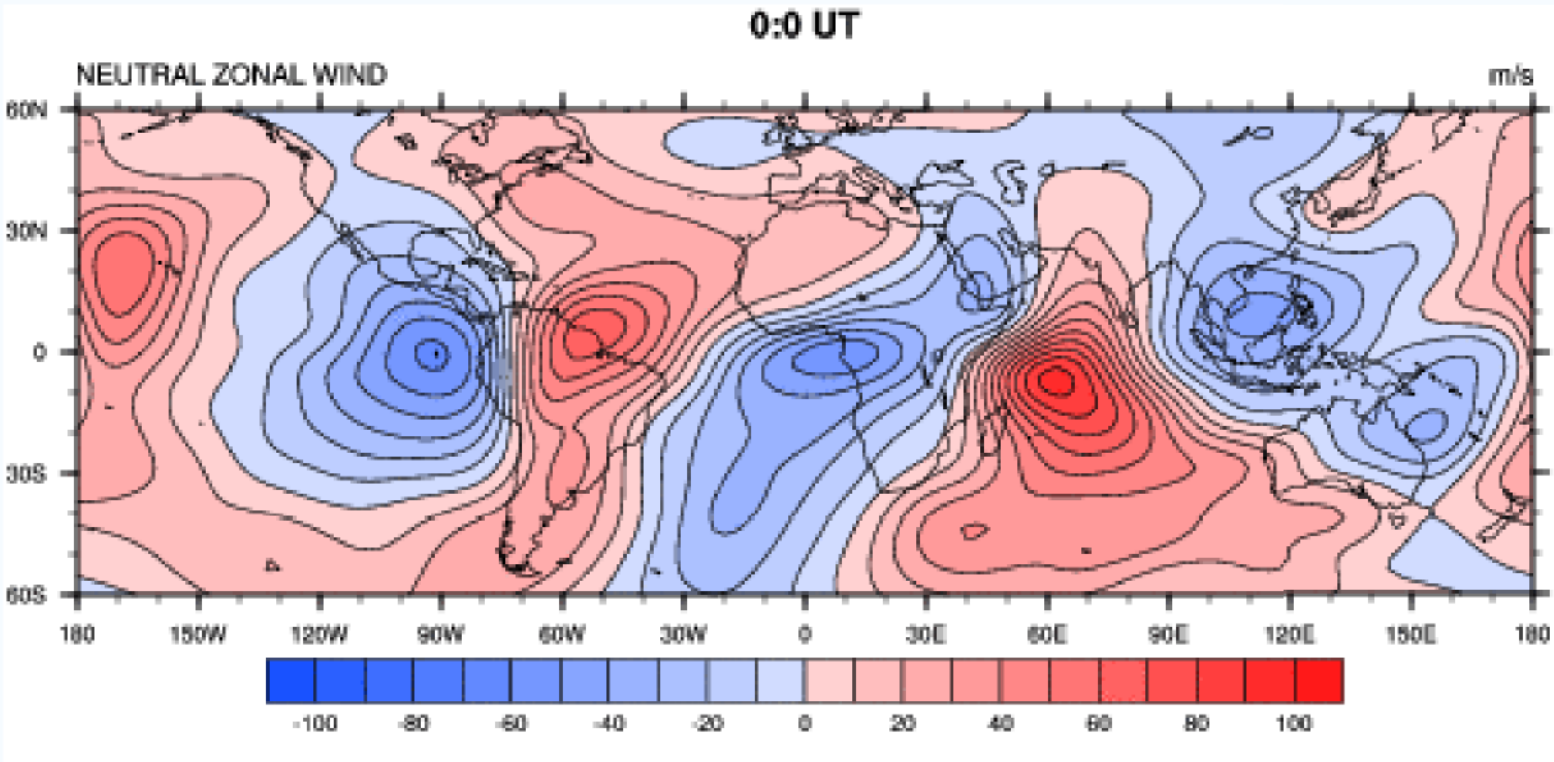


Dominant components in the TI tidal spectrum vary with altitude…latitude…month…and…

Weaker components modulate dominant signatures

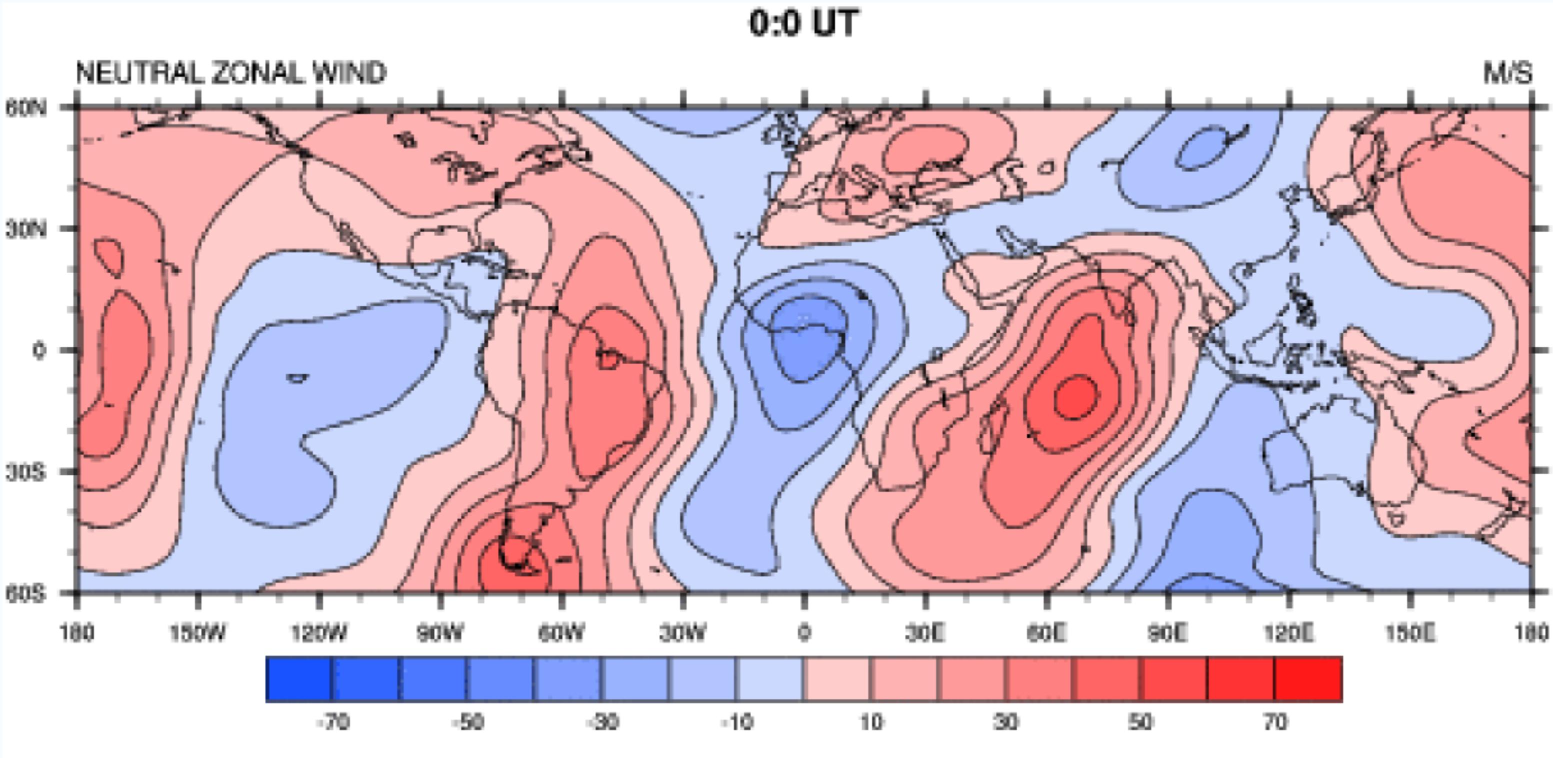
after *Hagan et al.*, 2009

120 km Zonal Wind Differences (m/s) - September all tides - migrating tides



Nonmigrating tides may introduce zonal wind perturbations that modulate the E-region dynamo process and impact the F-region.

325 km Zonal Wind Differences (m/s) - September
all tides - migrating tides



Nonmigrating tides may also penetrate directly into the upper atmosphere and modulate the thermosphere-ionosphere system.

Tidal Forcing – Current Viable Scenarios 1

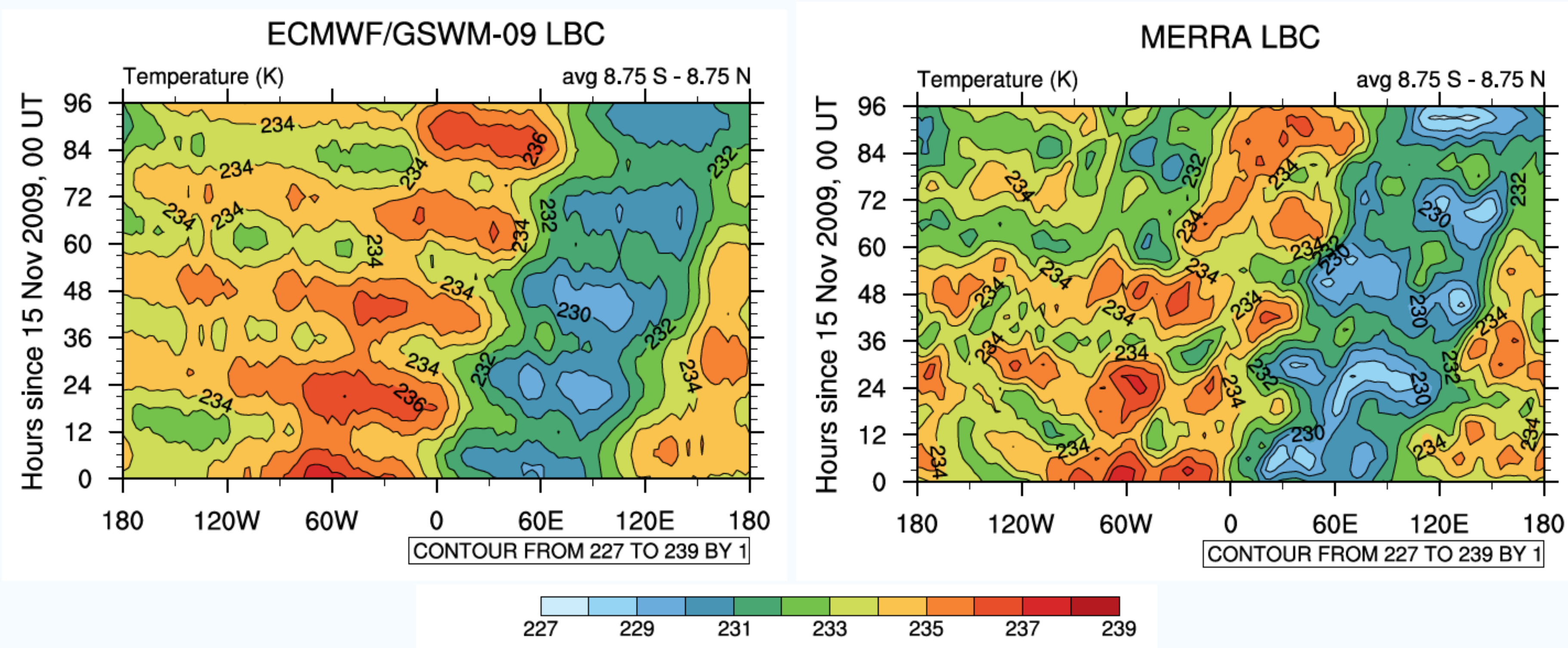
- Lower boundary conditions (LBC) for self-consistent first-principles TI models that include electrodynamics
  - *minimum 3-hourly** temperature, horizontal wind, and geopotential height (or vertical velocity) perturbations (e.g., MERRA Modern-Era Retrospective Analysis for Research and Application)

    *anything less fails to account for semidiurnal harmonics
  - climatological LBC specifications (e.g., GSWM or CTMT Climatological Tidal Model of the Thermosphere)
    - fail to capture day-to-day variability
    - if LBC is above the middle atmosphere ➔ fail to capture
      - ❑ secondary wave sources
      - ❑ tidal impacts of extreme events (e.g., stratospheric sudden warmings) in the low/middle atmosphere
    - addition of ECMWF European Centre for Medium-range Weather Forecasting or NCEP National Centers for Environmental Prediction daily perturbations (if LBC < ~60 km) allows for planetary wave tidal modulation and/or interactions

Tidal Forcing – Current Viable Scenarios 2

- Whole Atmosphere Models
  - self-consistent ionosphere-thermosphere with electrodynamics
  - nudge the free-running model into “realistic” simulation mode

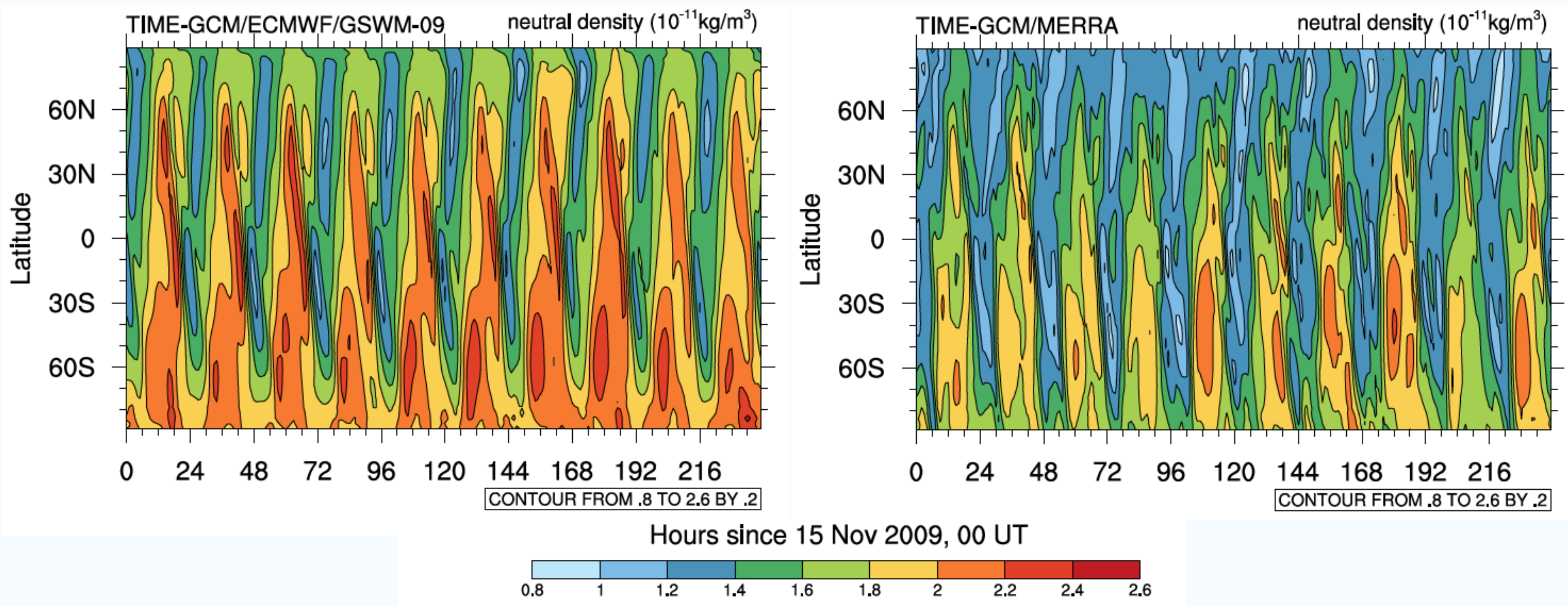
30-km TIME-GCM Lower Boundary Conditions Temperature 15-18 November 2009



- Left - climatological tides (GSWM) plus daily reanalysis data (ECMWF)
- Right - 3-hourly MERRA reanalysis data
- Similar salient features but comparatively more variability in MERRA

after *Häusler et al.*, 2014

TIME-GCM Neutral Densities at 270 km
15-24 November 2009

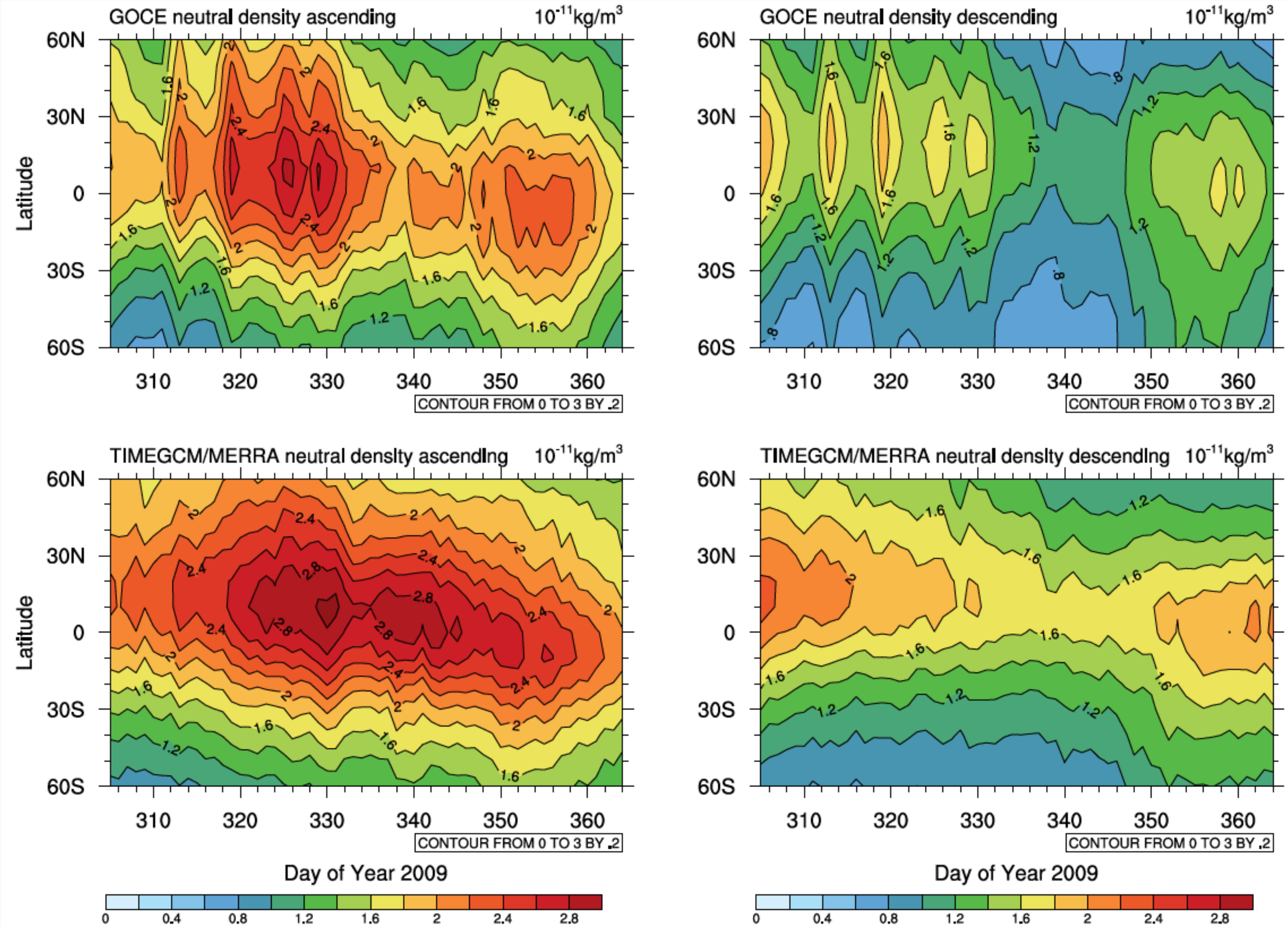


- Left - 10hPa daily ECMWF plus monthly GSWM climatological tidal LBC
- Right - 10hPa MERRA 3-hourly reanalysis LBC
- Day-to-day thermospheric variability due to tropospheric forcing

after *Häusler et al.*, 2014

Reality Check: Neutral Densities at 270 km November - December 2009

TIME-GCM/ MERRA predictions (bottom) capture the salient density features observed by the GOCE satellite (top) but overestimate in-situ tidal forcing (e.g., *Solomon et al.*, 2011)



after *Häusler et al.*, 2014

Tidal Forecasting Challenges/Requirements

- Accurately predict the quiescent conditions that underlie the TI system response to extreme Space Wx events
  - *minimum 2.5º x 2.5º horizontal and ¼ scale height vertical* model resolution to accurately resolve tides
  - spatial and temporal variability in density, temperature, winds, drifts, etc that is attributable to tides

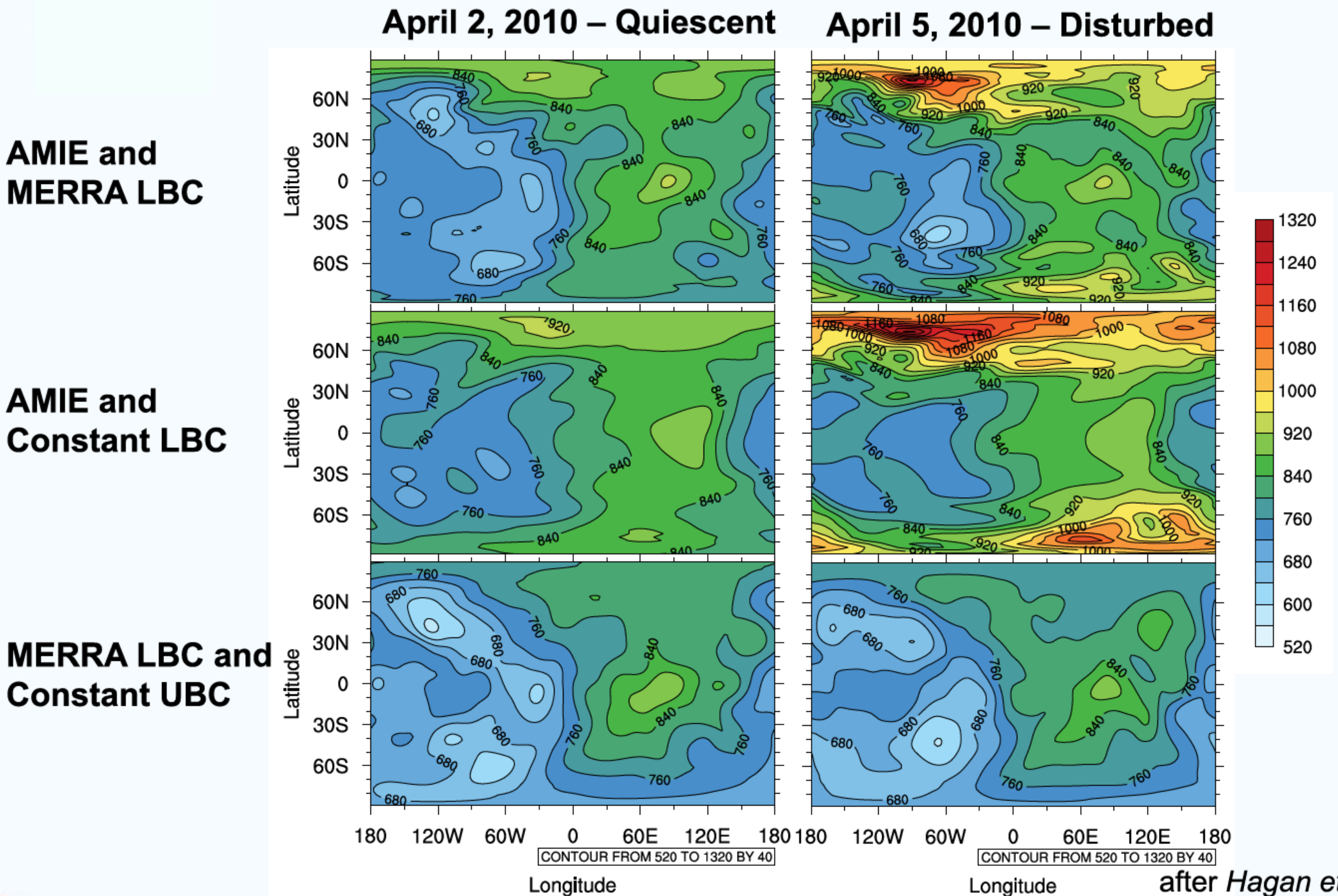
- Fully account for *all* tidal sources
  - in-situ components ➔
    - nonlinear self-consistent TI model with electrodynamics
  - components that originate below ➔
    - self-consistent lower and middle atmosphere

      -or-

    - realistic *minimum 3-hourly* lower boundary specification

- Realistic model initialization
  - ubiquitous and persistent tides
  - day-to-day, month-to-month, year-to-year, and longer-term variability

TIME-GCM Hind-Cast: Temperature (K) at 340 km



after *Hagan et al.*, 2014

Note variations attributable to MERRA LBC ➔ tropospheric tides

TI Tidal Forecasting

Ideas for a Plausible Approach

- In-situ components govern the baseline upper atmospheric response
  - ensure accurate EUV and pseudo-tidal (i.e., ion-drag) forcing
- Bound the upward propagating tidal prediction problem
  - reanalysis data viable for hind-casting ➔ not a forecasting option
  - ensemble of LBCs - quantify variability about climatology
- Invoke persistence assumption
  - upward propagating tidal forcing won't evolve significantly in short term
  - guide/limit the LBC ensembles

Next Steps

- Test the approach
- Community challenge – multiple LBCs and multiple models
- Validate test forecasts with satellite and ground-based data

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