Delineating the Migrating Solar and Lunar Semidiurnal Atmospheric Tides in the General Circulation Models

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Comparison of two methods of quantifying lunar contribution to atmospheric tides

In periods of Sudden Stratospheric Warming (SSW), large atmospheric disturbances caused by planetary wave forcing in the winter polar stratosphere propagate upwards to the ionosphere, causing plasma density changes between 50 - 150%[1]. Understanding SSW and the coupling of atmospheric layers is vital for the prediction of space weather. Part of this understanding includes being able to quantify the contributions of the solar and lunar semidiurnal tides. In this study, we first remove the solar contribution before fitting a function to extract the lunar amplitude and phase. We then compare the results of this method to an earlier method used by Maute et al. [2016], using data from TIME-GCM. Results from testing our method for accuracy on known synthetic data show that the percent error of M2 amplitudes is 0.33% for data resolution of 30 minutes, and 1.42% for data resolution of 1 hour. When compared to the results of Maute et al., we see good agreement in amplitudes of M2 in the Northern Hemisphere. However, in the Southern Hemisphere, significant deviation occurs, likely due to unaccounted for background effects from, for example, $F_{10.7}$ data. With further work on phase recovery and incorporation of other factors affecting the Southern Hemisphere, we believe our method has promise as a clear way to extract M2 amplitudes that yields similarly accurate results as existing methods.

How do we characterize atmospheric tides?

Like ocean tides, atmospheric tides are caused by the Sun and the Moon.

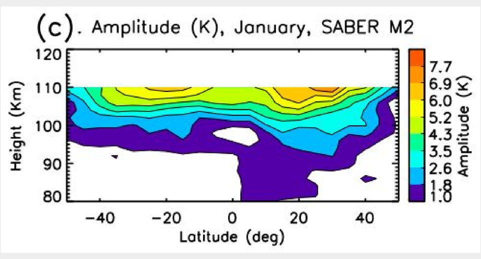


Figure 1. Example of lunar tide data from the SABER instrument onboard NASA's TIMED satellite[2].

Tides depend on:
- Latitude & longitude
- Date and time
- Height

In our study, we focus on the largest contributors to the atmospheric tides:

Semidiurnal migrating tides

	Solar (SW2)	Lunar (M2)
Period	12.00 hours	12.42 hours
Maxima	2/day, 2/longitude	2/day, 2/longitude
Strength	Usually stronger than M2	Much weaker than SW2
Cause	Atmospheric heating (UV, IR)	Gravitational effects
Motion	West at apparent speed of Sun	West at apparent speed of Moon

Why is Sudden Stratospheric Warming important?

Atmospheric layers are not discrete—they are connected!

Sun & Moon affect tides

Planetary wave forcing induces SSW

Resonance frequency of atmosphere matches lunar tide frequency, causes enhanced M2

Disturbances couple to ionosphere, causing plasma density fluctuations

Fluctuations affect operations of radio communication, satellites and other craft

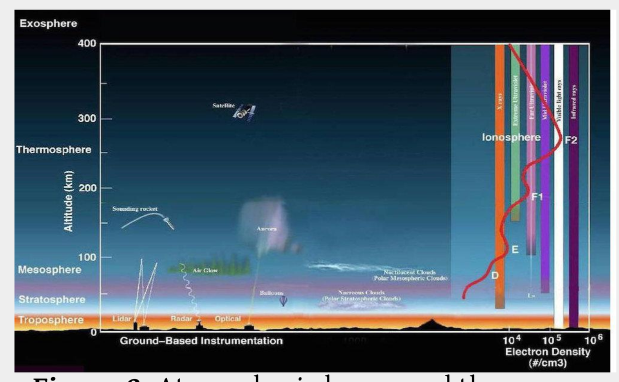


Figure 2. Atmospheric layers and the ionospheric extent. Weather phenomena and certain human crafts are also shown at their appropriate height[3].

Better lunar tide analysis
Better understanding of SSW
Better prediction of space weather

Did you know?

Inability to predict space weather costs the US government an estimated $10 billion per year[4].

Why compare two methods?

M2 and SW2 are difficult to separate because of their similar periods. Long observation windows[2] (see figure) mitigate this problem, but there is a trade off between time to gather enough data and global coverage.

An earlier method used by Maute et al. performs a least-squares fit without initial SW2 removal. We tested how removing SW2 first would affect results compared to the earlier method.

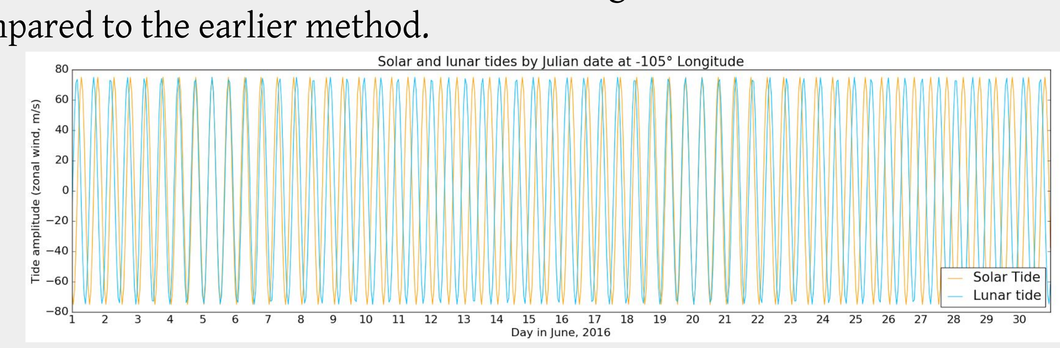


Figure 3. Synthetic example: amplitude of SW2 and M2 over one month. If observations are limited to the few days when the two are highly synchronized (around day 5 and day 20), difficulties would occur in separating the two.

During SSW, the lunar tide, M2, is amplified so that it has almost the same amplitude as the solar tide, SW2. Specific methods and relative accuracies for quantifying the amplitude and phase of M2 have not yet been articulated.

Solar tide removal method

Our goal is simple: remove the average of SW2, and what's left over should be (primarily) M2. We tentatively call it the **Bin-Subtract-Bin-Fit method,** or **BSBF** for short. It relies on two key concepts: **solar local time (SLT)** and **lunar local time (LLT).**

What are solar & lunar local time(s)?

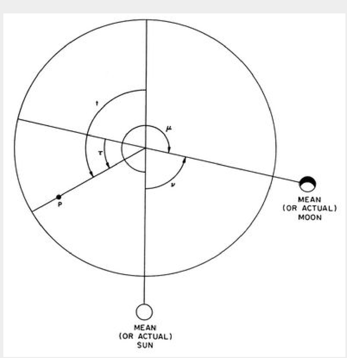


Figure 4. At point P: t is solar local time $t = t_{UT} + \lambda/\Omega$ (λ = long., $\Omega = 2\pi/24$). ν is moon phase, τ is lunar local time, $\tau = t - \nu$. Chapman & Lindzen [1969].

Solar Local Time (SLT): angle between subsolar point and point P.

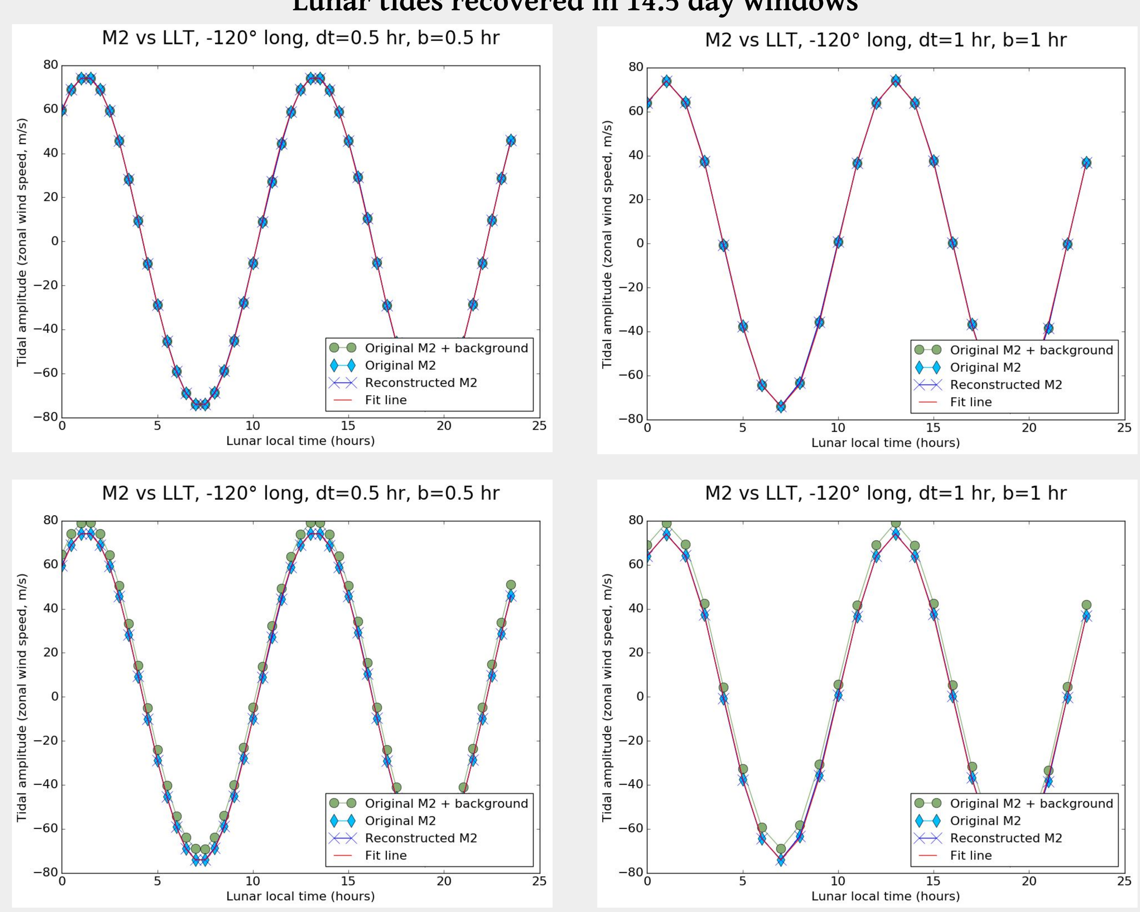
Lunar Local Time (LLT): Difference of SLT and the current moon phase.

BSBF method outline

1. Bin total tidal data by **solar local time** (bin = 1 hour).
2. Calculate average tidal value for each SLT; subtract from the original data.
3. Bin residual data by ***lunar* local time (LLT)**; compute averages.
4. Perform a least-squares (χ^2) fit of the lunar component of the tidal function (shown at right) to the lunar-binned data to recover the amplitude L, phase Φ and vertical offset C (not shown in equation at right).

Testing accuracy using synthetic data

Lunar tides recovered in 14.5 day windows



Figures 5 (left top) and 6 (right top): bin, data resolution = 0.5 hours and 1 hour respectively. Zero background tide, constant M2 & SW2 amplitude, phase.

Figures 7 (left bottom) and 8 (right bottom): lunar tides recovered in 14.5 day windows. In this case, background = 5 m/s and is constant.

In order to test the accuracy of our method, we generated synthetic data using the general tidal equation. This normally involves a sum over wavenumbers and periods, but since we only focus on $n = s = 2$, we omit the sum:

$$\text{tide} = A_B + S\cos\left[\Omega n t_{UT} + s\lambda - \phi_S\right] + L\cos\left[\Omega n(t_{UT} - \nu) + s\lambda - \phi_L\right]$$

(A_B = background tides, Ω = Earth's rotation rate, λ = longitude.)

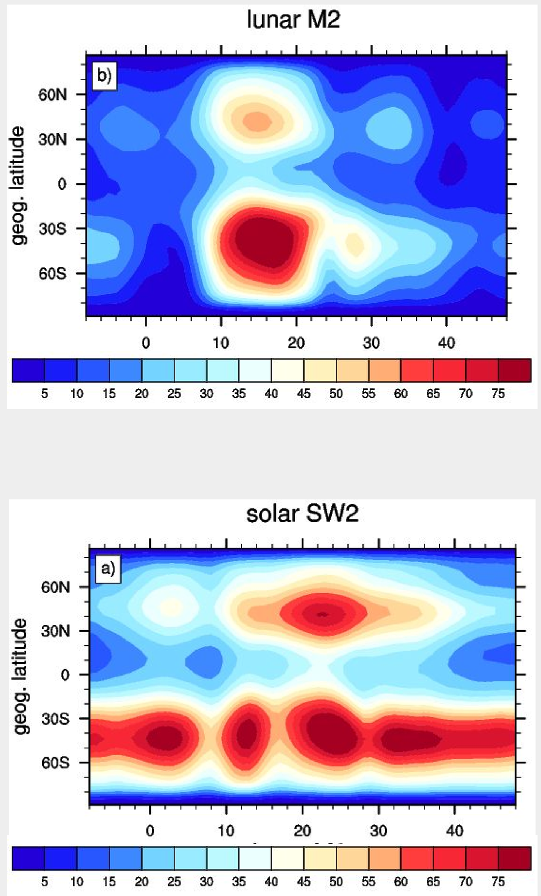
In our study, we found some issues with phase accuracy, which may be related to the use of a greedy algorithm for the fit method. The accuracy values below apply to both trials. Not shown at left is a trial where a planetary wave (period = 16 days, amplitude = 14 m/s) was included. Accuracies were similar for this trial.

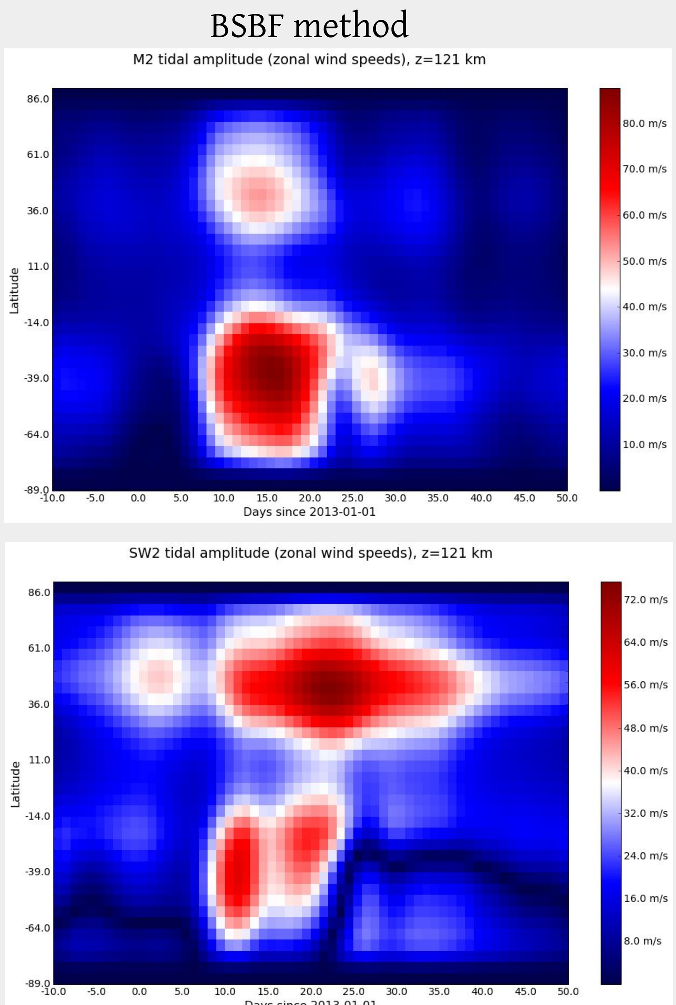
Bin and timestep	Original Amplitude	Recovered amplitude	% error, amplitude	Original phase	Recovered phase	% error, phase
0.5 hour	75 m/s	74.75 m/s	0.33%	$\pi/4$	0.65	16.6%
1 hour	75 m/s	73.94 m/s	1.42%	$\pi/4$	0.53	33.4%

Comparison to results from TIME-GCM model

TIME-GCM (thermosphere-ionosphere-mesosphere electrodynamic general circulation model) is a non-linear atmospheric model. Here we compare amplitude averages over 14.5 day windows for ~50 days from our method to previous results by Maute et al. [2016].

Maute et al. 2016 BSBF method

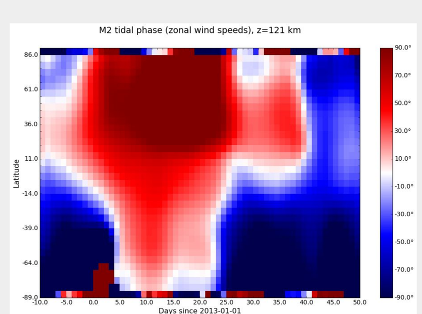




We see good agreement in overall features of M2:
1. Stronger winds in southern hemisphere
2. Strongest peaks around day 15

The minor increase in amplitudes in the Southern Hemisphere with the BSBF method is likely insignificant. We suspect this because the plots of SW2 disagree in the Southern Hemisphere. We would expect peaks of at least 20 m/s to exist along the 45°S latitude line in Southern Hemisphere summer, but instead see values closer to 5-8 m/s.

Phase values depend on local time. Maute et al. plotted phase in SLT, but we are currently unable to compare as the BSBF code obscures SLT information. We can still plot the phase results in LLT, however, as shown at right.



Figures 9 (top left) and **10 (bottom left).** M2 (top) and SW2 (bottom) amplitude averages versus days since 2013-01-01. Averages computed using a sliding window of length 14.5 days (half a lunar cycle)[6].
Figures 11 (top center) and **12 (bottom center).** The same as Figures 9 and 10, using our BSBF method on the same TIME-GCM data.
Figure 12 (right). Reconstructed phase in lunar local time using BSBF method.

Outcomes and next steps

The Good
- Good agreement on general feature extraction in M2
- BSBF is "cleaner" i.e. more controlled than previous methods, produces similar results of comparable magnitudes

The Bad
- Phase recovery: perhaps due to use of greedy algorithm (Scipy curve_fit)
- Phase is difficult to compare due to differences in definition in local times versus universal time

The Hmmm...

In the Southern Hemisphere,
- M2 amplitudes slightly larger than previous results (+5 m/s), because..
- SW2 amplitudes are much *lower* than previous results and what we expect.
  - Could be real, but more likely some background fluctuation is not accounted for (e.g. $F_{10.7}$, the solar radio flux).

Clearly from the notes under "The Hmmm..." above, we have only begun to scratch the surface on implementation of this method! Here is what will be addressed in future work:

- Look closely at Southern hemisphere SW2 results: Is the much lower amplitude a real feature, or is it an artifact due to BSBF not accounting for some background fluctuation?
- Improve code to better recover phase and compare with plots
- Examine other data (tides measured in temperature, density)
- Verify accuracy for situations when tidal amplitudes *themselves* vary (tide is a product of cosines)
- Test with more dates, other SSW periods, solar minimum periods

References

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Sun and Moon images: http://dmf.hr/natjecanja/

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