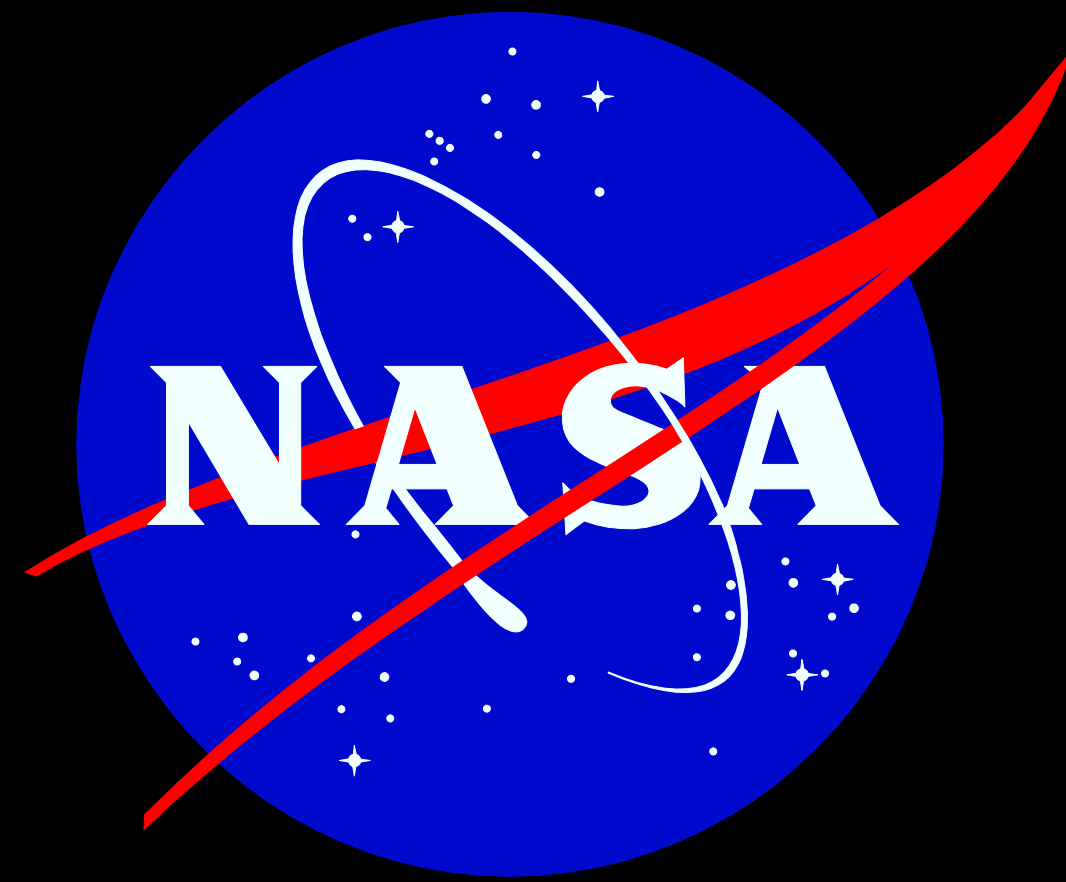




Simultaneous spatial and temporal analysis of SAGE II version 7 ozone data

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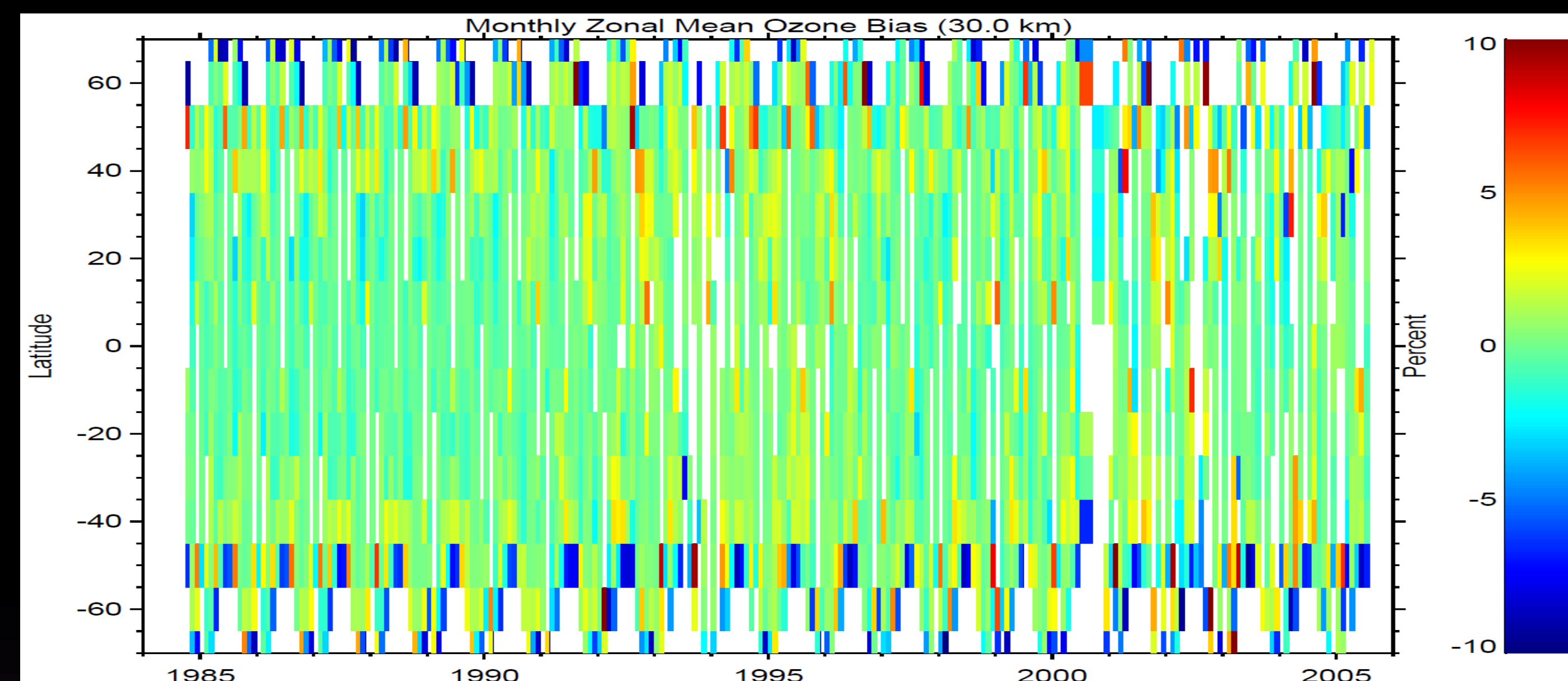
Abstract

SAGE II used the solar occultation technique to measure atmospheric ozone for 21 years between 1984 and 2005 and has continued to play a key role in numerous international assessments. Traditionally, the determination of trends in ozone using SAGE II data has been done via time series analysis of monthly mean data within specific latitude bands. However, given the sparse sampling of SAGE II data, this will introduce temporal and/or spatial biases, particularly in the period after late 2000 when the instrument operated at half-duty cycle. Herein we present a new method for performing time series analysis of unevenly sampled data (in particular SAGE II); namely, we utilize the daily mean data and perform a simultaneous temporal and spatial analysis, making use of a Fourier series to constrain latitudinal variation. This methodology is applied to both the previous (v6.2) and current (v7.0) versions of the SAGE II data. Results are discussed that show the improvements to the data between versions 6.2 and 7.0 that make time series analysis produce reduced residuals as well as the preliminary results of the time series itself, which reveal some of the limitations in currently used proxies for the regression.

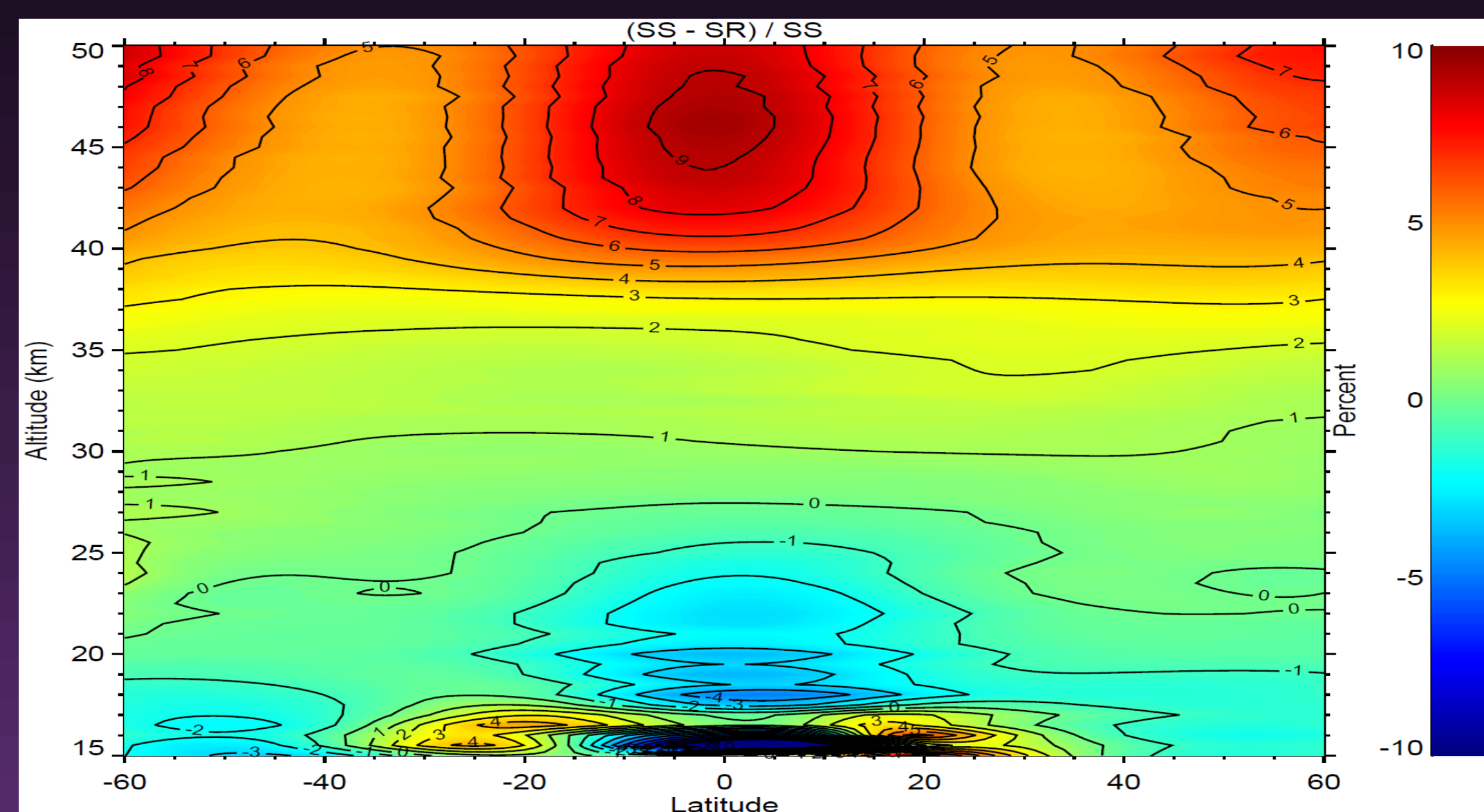
SAGE II Sampling and Biases

SAGE II was launched into a 57° inclined orbit and took two measurements per orbit (one sunrise and one sunset) for a total of about 30 measurements per day. Over the span of a single day, measurement locations for a specific event type would drift a total of about 3° to 10° in latitude for high to low latitudes and ~360° in longitude. This caused SAGE II to take measurements at a particular latitude at roughly the same times of the year, resulting in full seasonal coverage at mid-latitudes, and restricted (or sparser) seasonal coverage at high (or low) latitudes.

Traditionally, time series analysis of ozone data from SAGE II has been done with the use of monthly zonal means. However, due to SAGE II's sampling biases, this method will result in mean measurement latitudes up to half the latitude bin size away from the middle of the bin, and mean measurement times up to two weeks away from the middle of the month. As such, methods using monthly zonal means of a sparse data set will contain temporal and spatial biases. The following plot illustrates the differences in ozone from the regression model due to temporal and spatial sampling biases.



Sampling biases can result in differences up to 10%, and derived trends can be influenced by these biases. This does not consider the further influence on sampling biases as a result of differences in sunrises and sunsets after late 2000 when the instrument operated at half duty cycle, which have the greatest influence at higher altitudes. The following plot shows the comparison of the time-independent mean of sunrise and sunset events from the regression model.



For this analysis, we use daily zonal means that are carefully separated by event type (both local and satellite) to ensure that only collocated events are averaged together. We also use both sunrise and sunset events simultaneously, but allow for a difference in their mean values to account for any potential offset between event types, be it diurnal (i.e. geophysical) or algorithmic (e.g. viewing geometry).

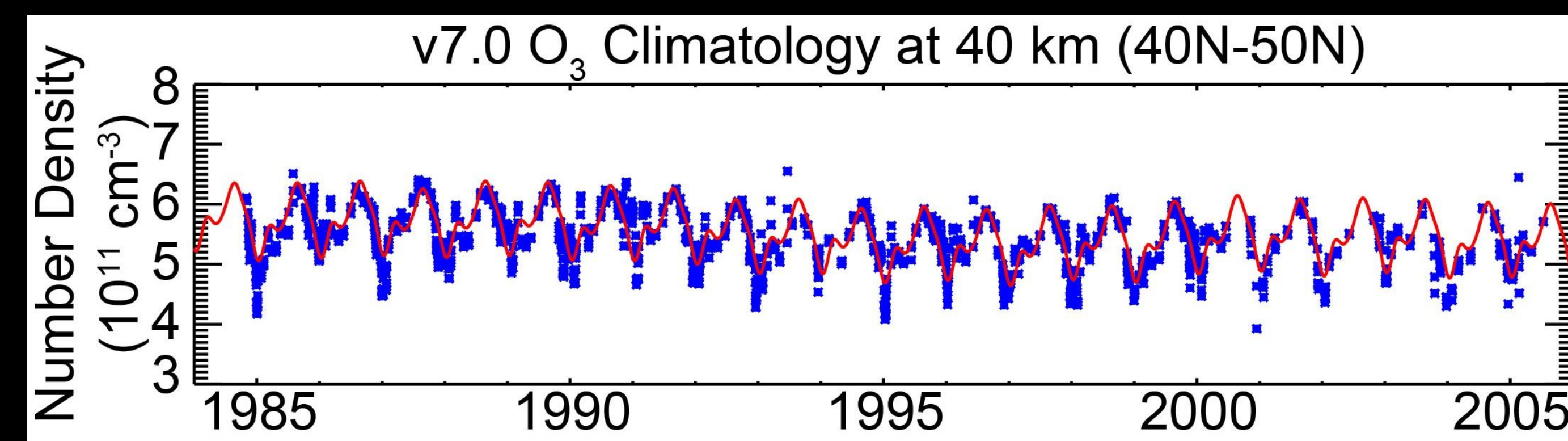
Regression Model

Our regression model makes simultaneous use of both temporal and spatial components. Combined with the use of daily zonal mean data, spatial sampling biases are mitigated and temporal sampling biases are restricted to less than a day. The regression model has the following form:

$$\eta(\theta, t) = \Theta(\theta)T(t)$$

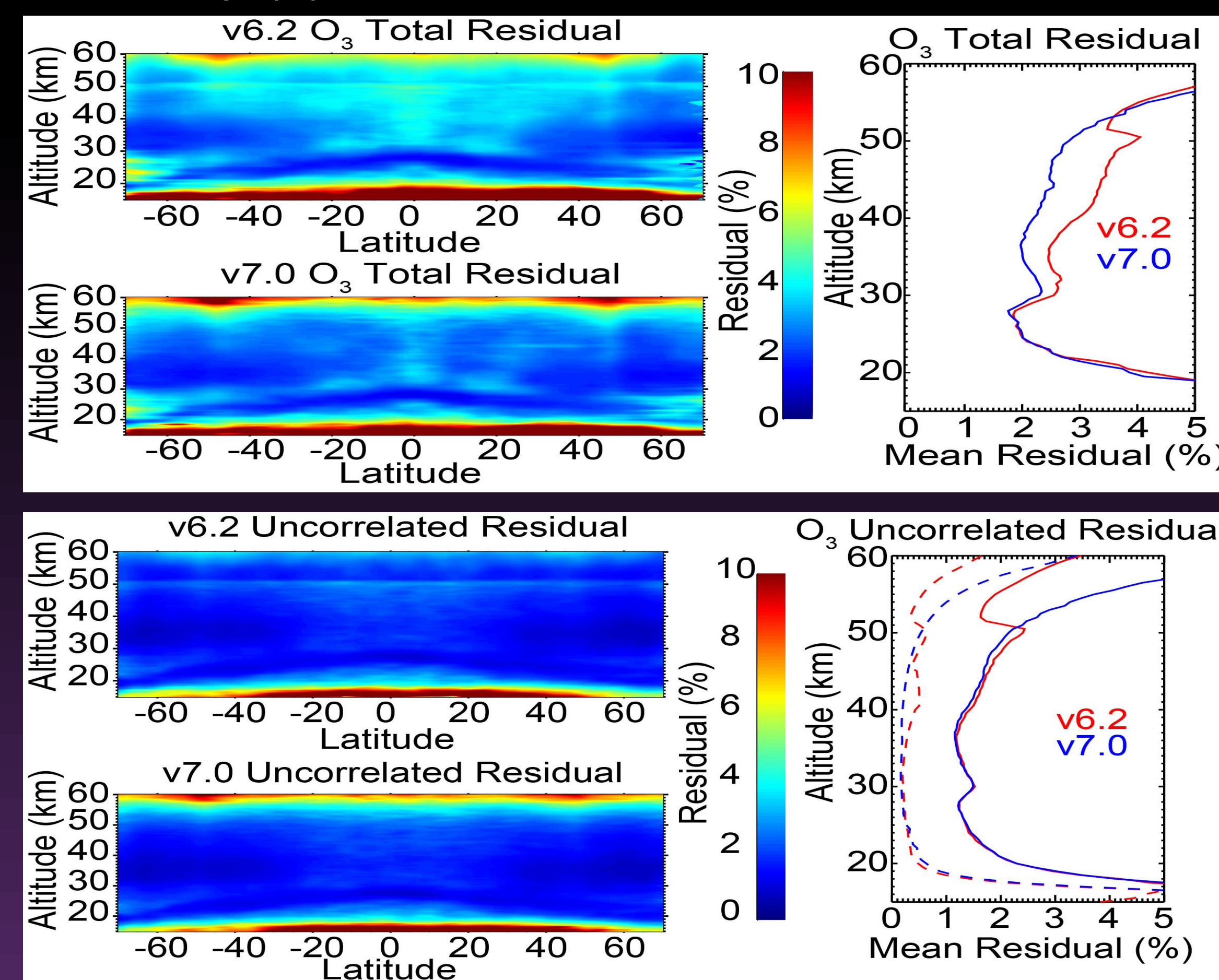
where η is the ozone number density, $\Theta(\theta)$ is the functional form of the latitudinal dependence and $T(t)$ is the functional form of the time dependence. $\Theta(\theta)$ is simply a Fourier series (6 harmonics) with the constraint of zero derivative at the poles. $T(t)$ contains semi-annual (3, 4, and 6 month terms), annual, quasi-biennial oscillation (QBO), El Niño southern oscillation (ENSO), solar cycle, equivalent effective stratospheric chlorine (EESC), and linear trend terms as well as an additional piecewise term to account for any difference in the mean of sunrise and sunset events. Both $\Theta(\theta)$ and $T(t)$ also contain a constant term, which collectively provide the constant for the fit. This fit is performed for each altitude separately.

In order to avoid underestimating uncertainties in the regression coefficients, an autocorrelation correction must be performed. After regression, residuals are computed (total residuals) and an autocorrelation analysis is performed. Given the separation of event types, great care must be taken in ensuring that correlations are analyzed on collocated pairs of points. However, since the model includes a term to remove biases between the different event types, all collocated residual pairs can be used to determine the correlation coefficient. Once determined, correlated residuals can be computed and an autocorrelation correction can be performed like that in Reinsel et al. The subsequent new regression produces the final coefficients as well as an additional set of residuals (uncorrelated residuals). An example of the regression is shown below. (Damadeo et al., 2013)



Data Quality Improvements in Version 7

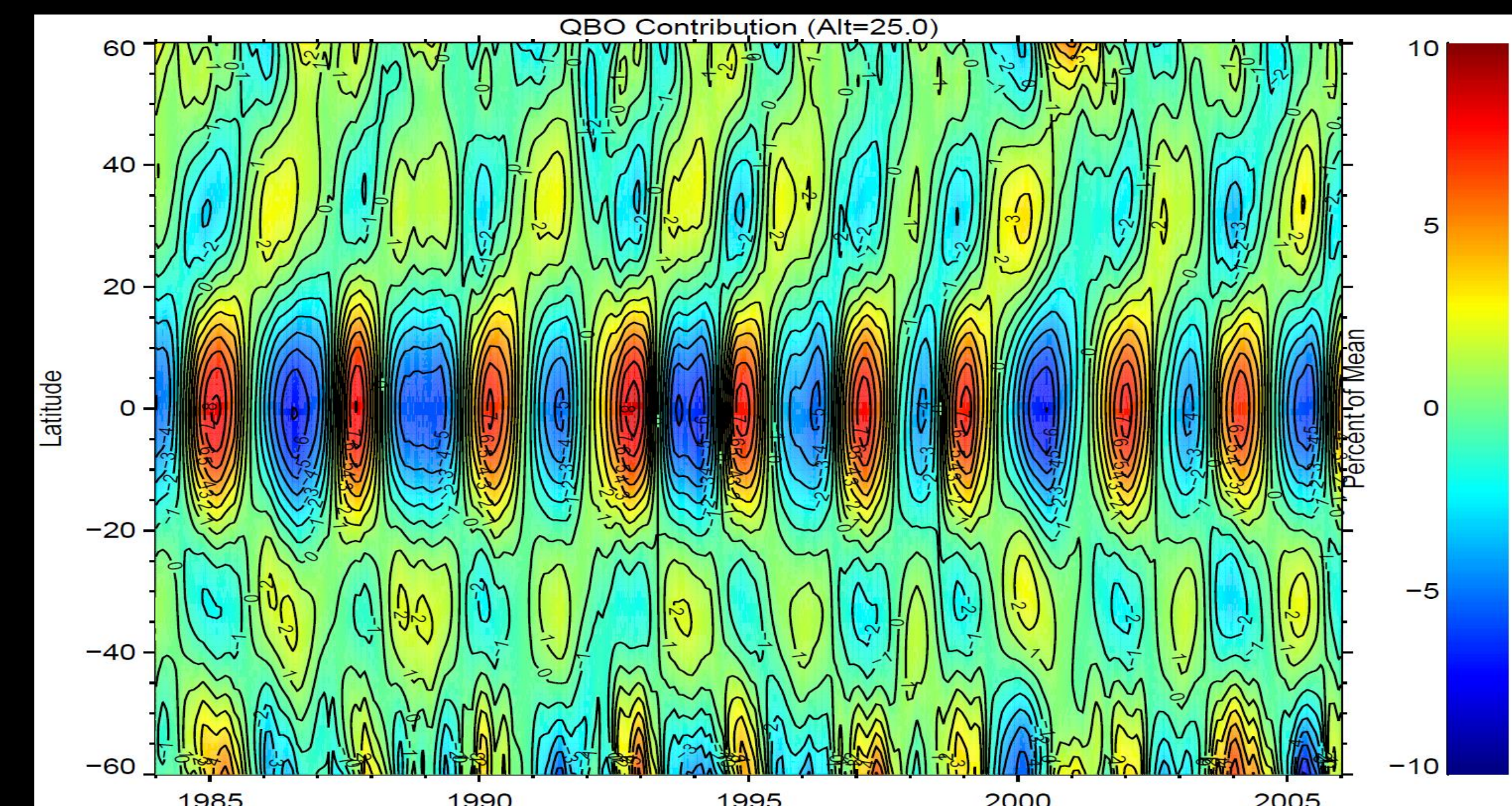
The regression model was applied to SAGE II ozone data from version 6.20 and version 7.00 and the residuals (total, correlated, and uncorrelated) were calculated. The correlated residuals (contained within the total residuals) represent geophysical variability that is well sampled but not well captured by the model, while the uncorrelated residuals represent variability that is not well sampled in addition to geophysical and instrumental noise.



There is a clear reduction in the total (and thus correlated) residuals, except above 50 km where smoothing was performed in version 6.20. The uncorrelated residuals are similar between versions (as expected) and the average uncertainties in the measurements (dashed lines) are slightly (~1%) lower than the uncorrelated residuals, indicating that the uncertainty estimates are reasonable and that the zonally averaged, unresolved geophysical variability is on the order of 1%. All told, version 7.0 data is more consistent, with less correlated noise and smaller total residuals than version 6.2, making the data more robust to work with for time series analysis. (Damadeo et al., 2013)

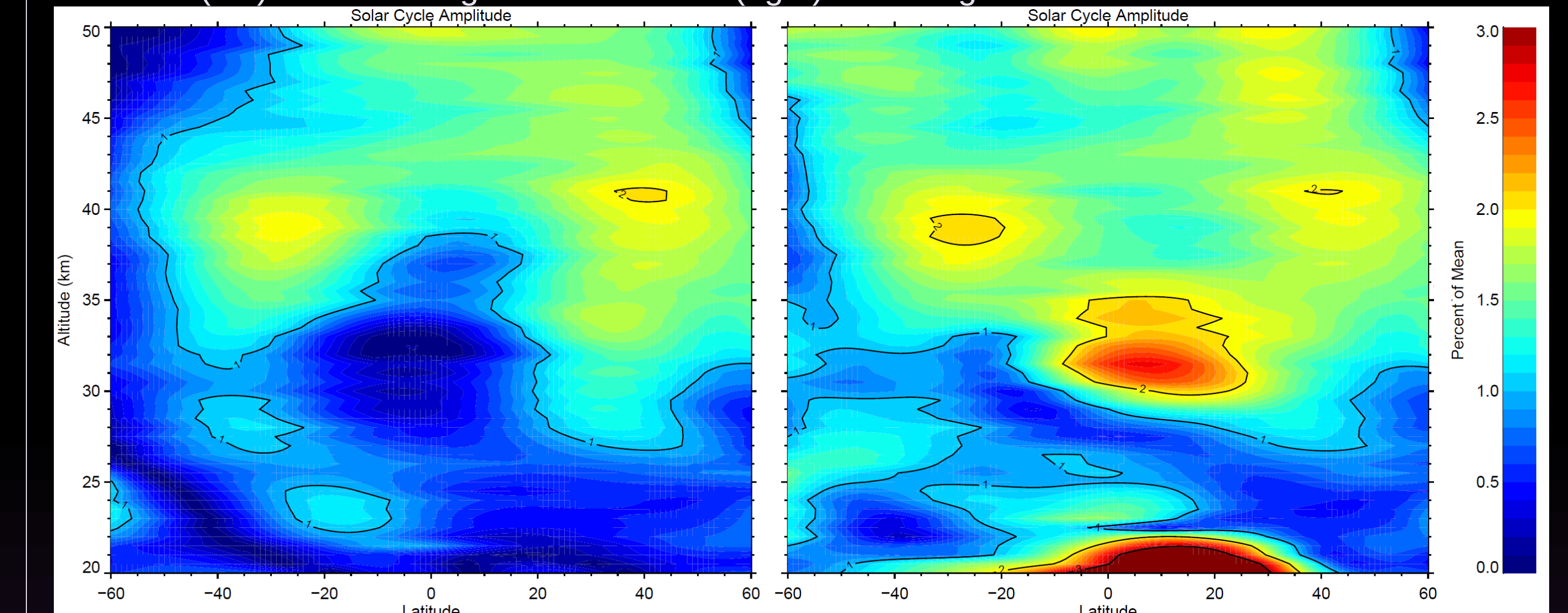
Need for Better Proxies

When applying regression models to long term ozone data, it is common practice to use a proxy for fitting the QBO component (e.g. Singapore wind data). However, while the use of orthogonal functions in the regression can yield the amplitude and phase of the QBO's contribution, it cannot account for the change in frequency at other latitudes (T&Y, 1994) or altitudes above the proxy (R&L, 2010). The following plot illustrates the contribution of the QBO to the ozone signal as a function of time and latitude at 25 km.



While the amplitude and phase vary as expected in the tropics, and the signal at mid-latitudes is mostly out of phase with the tropics (as expected), the frequency of variation in both regions is the same. This is a fundamental limitation of the use of a proxy in regions where the proxy data is not entirely representative of the actual variation.

Another major issue with modeling ozone is the lack of an aerosol proxy. While SAGE II ozone retrievals are sensitive to aerosol, some of the measured variability has non-algorithmic sources (e.g. radiative) and needs to be incorporated into the model. However, no aerosol proxy exists and there does not exist any truly accurate functional form that takes into account time of injection, latitude of injection, and altitude of injection or the subsequent transport. The lack of an aerosol proxy means that the regression model will make an attempt to attribute variability caused by aerosol to other components. The following figures illustrate the difference between using a single solar term (left) or two orthogonal solar terms (right) in the regression.



The large difference seen between 30-35 km in the tropics is actually a result of aerosol effects after the Pinatubo eruption. In the case of a single term, the response is artificially dampened due to the phase offset between the eruption and the peak of ozone increase. In the case of two terms, the phase response is shifted and amplitude artificially increased to account for most of the increase due to aerosol. The lack of an aerosol proxy detrimentally affects the ability to model the data and similar effects are noticeable in other terms (e.g. QBO).

Conclusions

The SAGE II version 7.00 ozone data is of better quality than the version 6.20 data and is more robust to work with for time series analysis. Due to sampling biases, time series analysis of SAGE II data (and other sparse data sets) should be done using a simultaneous temporal and spatial regression with daily zonal mean data separated by event type instead of the traditional way of monthly zonal means. However, there are issues with current (or non-existent) proxies and it would be extremely useful if global QBO and aerosol proxies were available for more accurate time series analysis of ozone data. We continue to refine this methodology and are also investigating the possibility of using SAGE II aerosol data to create an aerosol proxy.

References

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