THERMOSPHERE MODEL EVALUATION AT LOW ALTITUDE WITH GOCE DENSITIES

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ABSTRACT

The COSPAR International Reference Atmosphere (CIRA) thermosphere specification models JB2008, NRLMSISE-00 and DTM2013 are used in satellite aerodynamic drag calculations. Their accuracies at low (120-300 km) as well as high (800 km) LEO altitudes presently are not well documented due to the sparseness of high-resolution and high-accuracy density observations. A relatively new density dataset allows model evaluation for low LEO altitudes.

In the framework of the ESA GOCE+ projects, thermosphere densities were inferred from GOCE observations for the entire Science Mission from November 2009 to 20 October 2013. The exceptional value of the unique low-altitude GOCE density dataset will be demonstrated by comparing it to the CIRA models on three typical time scales: long (annual; mission design, lifetime), medium (monthly; solar rotation), and short (daily; re-entry prediction). Specific model errors, for example as a function of latitude or solar activity, are revealed. The models are evaluated according to the following metric: mean, RMS and standard deviation of the observed-to-modeled ratio (unity for an unbiased model), and correlation. Thanks to the GOCE data, the models' accuracy at low altitude can be established. Analysis of the results reveal the specific weaknesses that require attention in next model revisions.

A new ESA General Study ('PREGO': 4000115173/15/F/MOS) focuses on the last three weeks of the mission, for which a special accelerometer dataset was delivered. The ion propulsion was no longer operating after 20 October and GOCE re-entered the atmosphere over the Falkland Islands on 11 November 2013. The altitude decay rate was very high, but the accelerometers continued to operate up to 8 November down to about 170 km. Densities from 230 km to 180 km could be inferred from the accelerometer data. Results of thermosphere model performance for this last part of the GOCE mission will be presented, and it is compared to results obtained with the Science Mission data at a slightly higher altitude. The model performance remains stable also for the lowest altitudes tested.

1 INTRODUCTION

Semi-empirical thermosphere models are used in the computation of the atmospheric drag force in satellite orbit determination and prediction, as well as in atmospheric studies. They predict point wise temperature and (partial) density as a function of location (altitude, latitude, longitude, local solar time), solar and geomagnetic activities, and season. The Committee on Space Research (COSPAR) selected three thermosphere models in 2012, and these are described in the COSPAR International Reference Atmosphere (CIRA-2012) report. These models, NRLMSISE-00 [1], JB2008 [2] and DTM2009 [3], are also the ISO (International Organization for Standardization) models for the neutral upper atmosphere. The DTM model was updated recently, and the current version is DTM2013 [4]. It was developed in the framework of the Advanced Thermosphere Modelling and Orbit Prediction project (ATMOP; http://www.atmop.eu), which was a European Union 7th Framework project. DTM2013 and the pre-ATMOP benchmark DTM2009 were evaluated by comparing to total density data in order to demonstrate and quantify the significant improvements made, especially in the 250-500 km altitude range [5].

The satellite GOCE (Gravity field and steady-state Ocean Circulation Explorer; ESA, 1999), was the first Earth Explorer mission of the European Space Agency (ESA). It launched in March 2009 in a 96.5° inclination, quasi dusk-dawn orbit. The Science Mission phase, maintained at constant mean altitudes between 275-230 km thanks to drag compensation using ion propulsion, lasted from 1 November 2009 through 20 October 2013. GOCE neutral densities, with a resolution of 80 km along the orbit and a precision of a few percent [6], are made available by ESA (https://earth.esa.int/web/guest/missions/goce/goce-thermospheric-data). Whereas paper [6] compared GOCE densities (data version 1_0) to models mainly for validation purposes of the density data up to May 2012, in this study the validated and complete GOCE density dataset (data version 1_4) is exploited to evaluate the models thoroughly.

The GOCE dataset is the only high-resolution, high-accuracy dataset at low altitude. As such, it is the best dataset for thermosphere model evaluation at low altitude. The Xenon for the ion propulsion was exhausted on 21 October 2013, and GOCE re-entered the atmosphere 3 weeks later on 11 November 2013. The GPS receiver operated almost to the end, and the accelerometers measured the drag acceleration until they

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saturated on 8 November 2013. Density was derived from these measurements, which provides additional information for model testing at altitudes between 230-170 km. This density dataset was compared to the models separately from the ESA density dataset (described in Section 2.1.1), because it was computed with different software as part of this study (see Section 2.1.2), and because the GOCE satellite was no longer in Science mode.

The objective of this study is to quantify the performance of the CIRA models at low altitudes of 270 km and less, i.e. when re-entry of objects in near-circular orbits becomes imminent, using GOCE density data. Performance is evaluated on long time scales of the order of years, which is important in case of mission design and lifetime (i.e. required thrust and fuel), to typical operational time scales of a month, as well as time scales of the order of days, which is important in case of mission operations and re-entry predictions.

2 MODELS AND DATA

2.1 CIRA thermosphere models

The thermosphere varies on global scales with annual, semiannual, solar rotation (about 27-days), solar active region (few months), and solar cycle (11 years on average) periodicities. These variations are represented in current models of the thermosphere. The CIRA models were constructed by fitting to their respective underlying density databases as good as possible in the least-squares sense. They are climatology (or 'specification') models of the thermosphere with a low spatial and temporal resolution of the order of thousands of kilometers and hours, respectively.

DTM2013 is the only model that has partly assimilated the GOCE density dataset, and consequently it is expected to compare best. NRLMSISE-00 has not assimilated any recent total density data. DTM2013 and NRLMSISE-00 can be used for the entire space age (ap, F10.7 and F30 measurements start before 1957), and they predict temperature, density and composition. JB2008 is constructed using a combination of solar- and geomagnetic proxies and indices that are available since 1997 (i.e. it cannot be used before that year), and it predicts temperature and density. An additional weakness of JB2008 is that atmospheric composition, which is required together with temperature to calculate the aerodynamic coefficient of a satellite, is not standard output. The indices are provided on the JB2008 website, but they are regularly modified without warning. Therefore, JB2008 evaluation results are linked to index files downloaded on a specific date (because the version number is *not* unique); in this study, indices are used that were downloaded in June 2016. Fig. 1 illustrates the differences in the S81c index (81-day mean of approximately the HeII line rescaled to F10.7 units; most important index for JB2008), which are very large over the GOCE mission time, and also for the present.

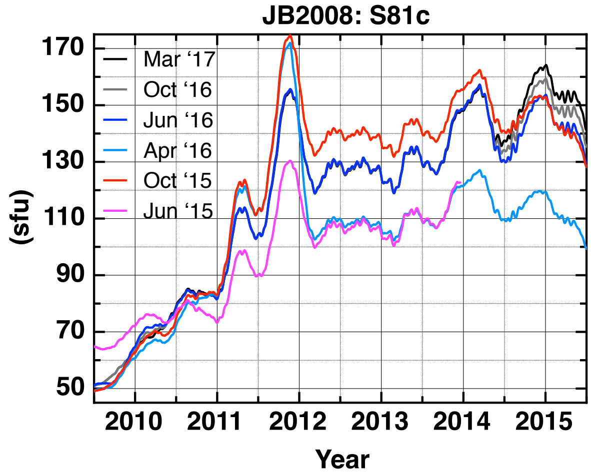

Figure 1. JB2008's S81c index for 6 download dates of the SOLFSMY file.

The 81-day mean F30, F10.7 and S81c (version June 2016), i.e. the proxies used in DTM2013, NRLMSISE-00 (and JB2008), and JB2008, are shown in Fig. 2 for the GOCE mission period. F30 and S81c evolve rather similar after 2012, whereas F10.7 has a slightly decreasing trend. The phase shift between F30 and F10.7 and S81c is due to the averaging method: F30 is averaged using the previous 80 days (causal, and no need for predicted values in an operational environment), whereas F10.7 and S81c are calculated as centered averages.

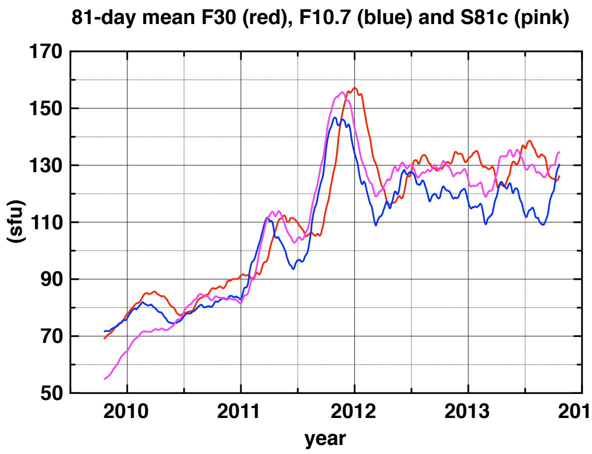

Figure 2. The 81-day mean solar proxies used in the CIRA models for the GOCE mission epoch.

2.2 GOCE total density data

Densities were inferred from thruster data for the Science Mission [7], which lasted from 1 November 2009 through 20 October 2013. The GOCE neutral densities have approximately 80 km resolution along track, with a precision of a few percent at worst and better than 1% after 2010 [6]. Due to the quasi dusk-dawn orbit, their local solar time coverage is limited to 6-8am&pm (slow orbit precession from 6 to 8 at the end of the mission). The density data, excepting the last 3 weeks, is available on the ESA GOCE website (https://earth.esa.int/web/guest/missions/goce/goce-thermospheric-data).

In this study, the GOCE data was scaled by a factor of 1.25, as was done in the ESA Final Report [7], effectively assuming that the High Accuracy Satellite Drag Model of the US Air Force Space Command (HASDM; [8]) is unbiased. This is not necessarily true because the scale of a thermosphere model is closely related to the aerodynamic coefficients that were used in the derivation of atmospheric density.

The last three weeks of the GOCE mission are not part of the Science Mission, and the GOCE accelerometer measurements in a lower resolution mode were provided by ESA as a special dataset. Densities were derived from the special dataset using the methodology described in [9] from 22 October - 8 November 2013, and they also were scaled to HASDM for consistency. Their relative precision was estimated at a few percent, i.e. comparable to the thruster-inferred densities. Daily-mean densities for the entire mission, and the constant mean altitudes thanks to the drag-free control, are displayed in Fig. 3. Starting in 2012, the altitude was decreased in four consecutive steps.

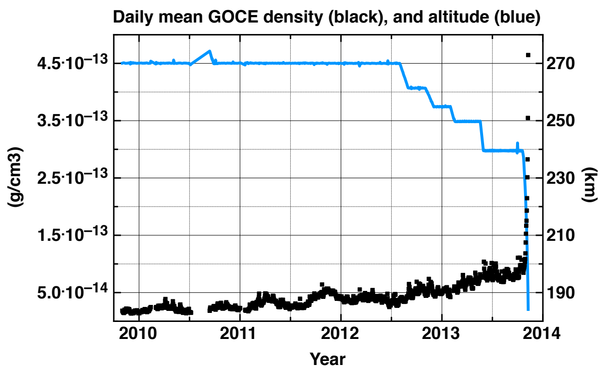

Figure 3. Daily-mean GOCE densities and mean orbit altitude.

3 MODEL EVALUATION RESULTS

The models are evaluated according to the following metric: mean of the density ratios (defined as observed-to-calculated ratios; 'O/C', unity for an unbiased model), standard deviation and RMS of the density ratios, and correlation. The numbers reflect the relative precision of the models; the absolute precision, i.e. in kg/m^3, is rather difficult to interpret due to the orders of magnitude differences as a function of altitude or solar cycle. Model bias (i.e. the mean of the density ratios minus 1) is most damaging in orbit extrapolation because it causes position errors that increase in time. The standard deviation represents a combination of the ability of the model to reproduce the observed variations and the geophysical and instrumental noise in the observations, inclusive of bias in case of RMS. The correlation coefficients R, contrary to RMS, are insensitive to model bias and R^2 represents the fraction of observed variance captured by the model. Fig. 4 gives an example of densities for a descending profile (1/2 orbit revolution), and the model results.

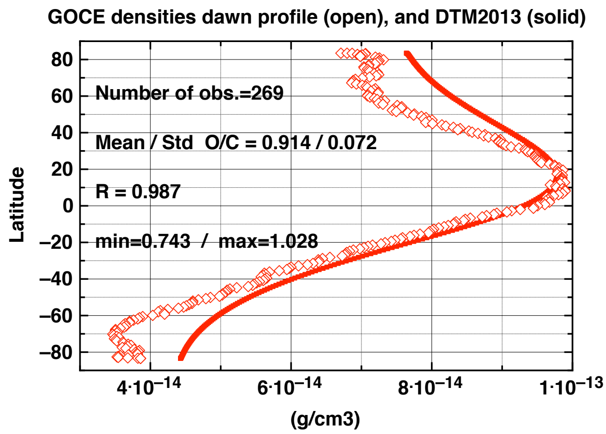

Figure 4. GOCE and DTM2013 densities for a descending profile.

The model performance on long time scales is evaluated by computing the density ratios averaged over the entire GOCE Science Mission of nearly 4 years, as well as per calendar year. The bias of the models over the entire Science Mission is small, less than 5% for all three models. This remains true only for DTM2013 when the averaging is done over 1 year intervals (biases are 2% or less), whereas the NRLMSISE-00 bias is 11% for 2013. This can be seen in Fig. 5, which presents the mean density ratios for the three models for the five time scales. The correlation coefficient of the models is 0.97 or larger for the entire Science Mission. DTM2013 has rather similar correlations (not shown) per year, whereas NRLMSISE-00 presents the largest variations in annual correlations. JB2008 has the smallest correlation in 2010, confirming its worst performance when solar activity was low.

Evaluation at the monthly period is done because it is an operational time scale (mission planning) as well as a physical one: it is close to the solar rotation period of approximately 27 days. The errors are not random, even if a recognizable pattern is only visible in the DTM2013 density ratios: a quasi semi-annual periodicity. The performance of the models is expected to decrease when averaging is done over shorter time spans. This is clearly visible in Fig. 5, in which the scatter and minimum and maximum deviations increase when the averaging is done over shorter periods.

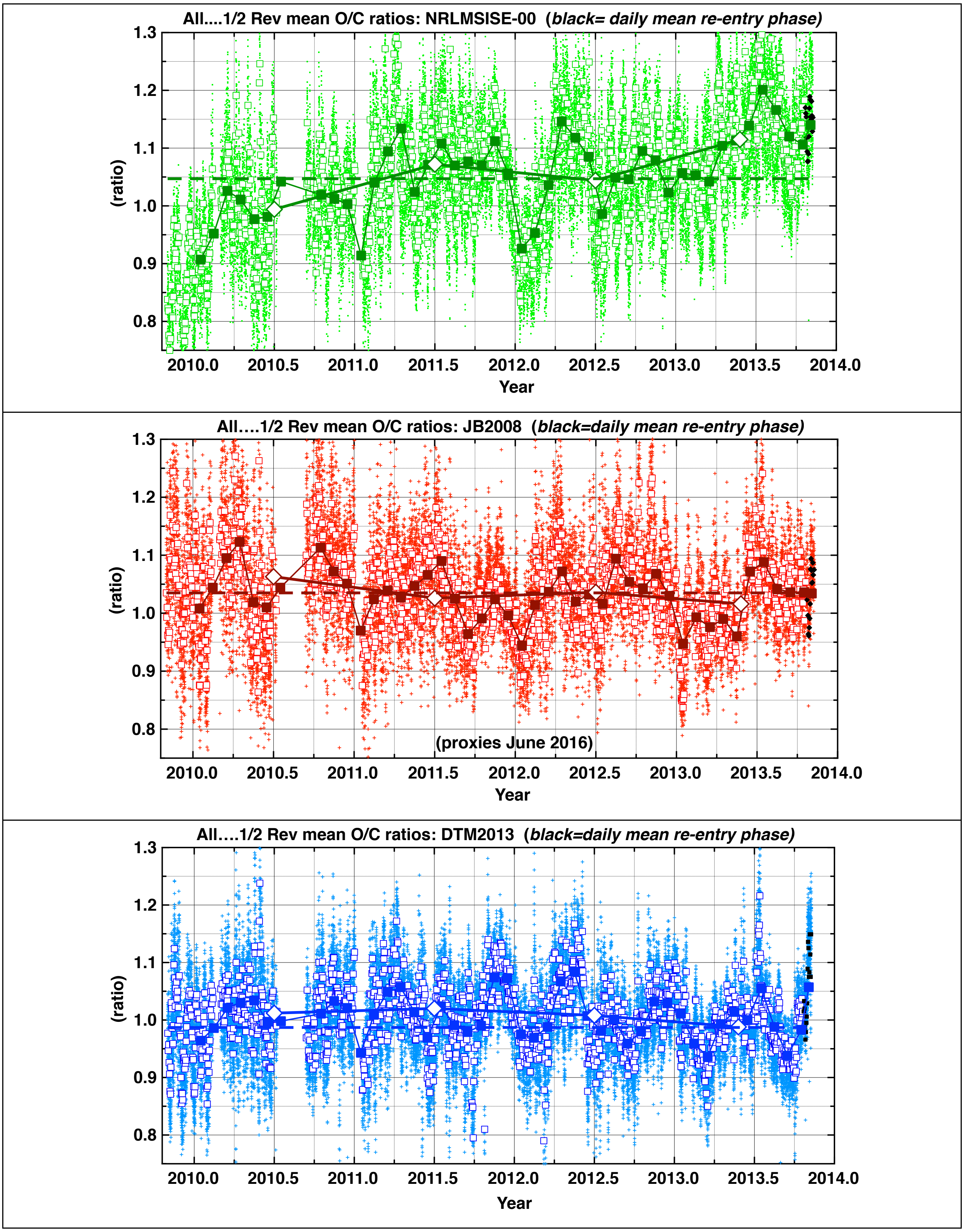

Figure 5. Mean density ratios for NRLMSISE-00 (top), JB2008 (middle), and DTM2013 (bottom). Averaging over the entire period (dashed line), annual (large open symbol), monthly (large solid symbol), daily (small open symbol), and ½ revolution of about 50 minutes (cross).

The standard deviation of the time series of the mean density ratios for a specific time scale, i.e. of the density ratios shown in Fig. 5, is used here to quantify model performance. Fig. 6 displays the standard deviations for the three models and annual down to hourly (1/2 revolution: ascending and descending arc, which is why there are two values) on a semilog scale. The performance is approximately twice better on monthly versus hourly time scales, and again twice better on annual time scale.

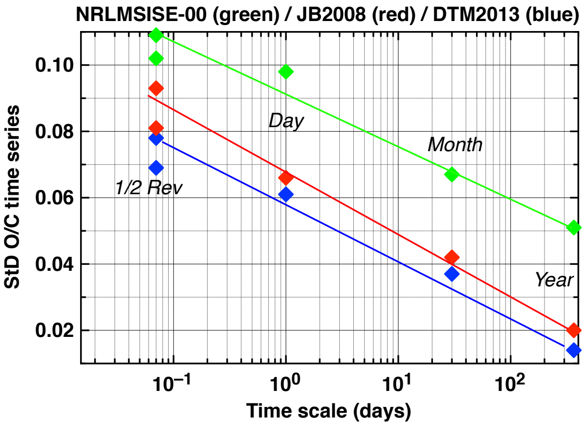

Figure 6. Standard deviation of the mean density ratio time series on 4 time scales.

The observed and modelled densities are also compared spectrally. Daily-mean densities were calculated for the period 12 February 2011 through 31 January 2013; this period of 720 days was selected because it has fewest and short data gaps. The gaps were linearly interpolated before computation of the power spectrums. JB2008 densities were computed with two versions of the solar activity proxy files, the first from June 2015, and the other from March 2017, in order to evaluate if performance improved on specific time scales.

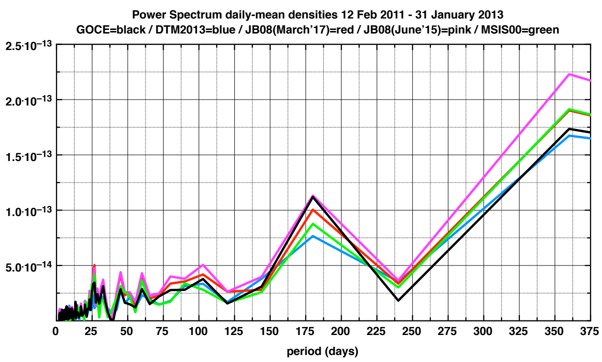

Figure 7. PSD of GOCE-inferred (black) and model-predicted daily-mean densities.

The Power Spectral Density (PSD) for periods of 2-375 days is displayed in Fig. 7. Annual, semi-annual, and harmonics of the approximately 27-day solar rotation period are visible, and overall the models reproduce variations on all the time scales rather accurately.

The PSD of the proxies, just F10.7 and F30, together with the NRLMSISE-00 and DTM2013 densities is displayed in Fig. 8, in order to show the difference in spectral content of the proxies. The semi-annual variation in density is not due to the solar EUV emission, but the solar wind, i.e. geomagnetic activity. Both models under estimate the amplitude, whereas JB2008 (Fig. 7) predicts more accurate on that time scale.

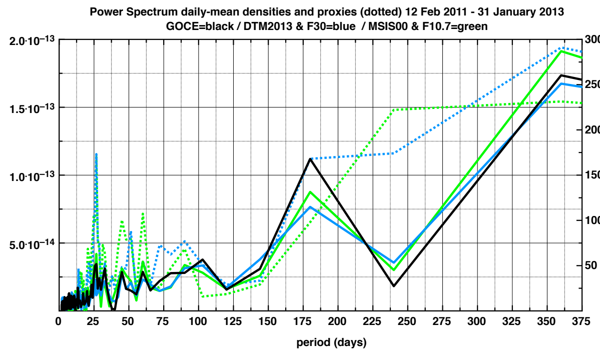

Figure 8. PSD of GOCE-inferred and model-predicted daily-mean densities, and the daily F10.7 and F30 proxies (dotted lines).

HASDM is the only operational model that assimilates density data inferred from some 60-70 spacecraft in near-real-time, which results in bias-free densities. This is demonstrated in Fig. 9, which only shows periods up to 3 weeks. Notice the accuracy around 14-15 days in particular, compared to JB2008 and DTM2013. Errors around these periods are due to shortcomings in the solar proxies, but HASDM can remedy that kind of error too. The semi-annual and annual amplitudes are also nearly identical to the GOCE-inferred densities.

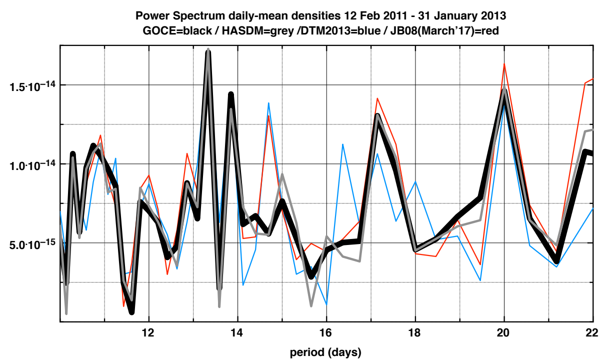

Figure 9. PSD of GOCE-inferred, HASDM, and model-predicted daily-mean densities

4 SUMMARY AND CONCLUSIONS

Evaluation of the CIRA models at altitudes from 270-170 km, on long (years) and short (hours) time scales, shows the diminishing performance of these mean, climatological models when the weather contribution becomes larger. Averaged over one year or longer, DTM2013 and JB2008 are nearly unbiased; when the averaging is done over one orbit or ½ an orbit (i.e. time scales of 1-2 hours), biases can become large (8-10% 1σ). NRLMSISE-00 is trailing a little bit due to its underlying density database without recent total neutral density datasets, and its use of the F10.7 proxy (see figs. 5 and 6). The thermosphere model error is not white, as can be gleaned from the variability of the density ratios displayed in Fig. 5. Consequently, uncertainty in drag predictions also cannot be modelled using white noise, but should be based on the observed error (the density ratios). A significant part of the model error is still due to the solar proxy, which has the largest impact for NRLMSISE-00, which uses the F10.7 proxy. Even if the ground-based F30 proxy is less representative of solar EUV heating than the HeII line measured in space (S proxy in JB2008), it is more robust and always accurately and identically calibrated.

There is room for improvement of the semi-empirical models, but more density data is needed, and robust and if possible more representative solar (and geomagnetic) proxies. However, best results will be obtained with a model that can assimilate density data in near-real-time, on the condition of good quality, coverage and continuity.

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