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The Basis for Thermospheric Density Improvements Using SET's Solar and Geomagnetic Indices

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Value of indices and proxies

Accurate representation of the thermospheric density environment requires characterization of both solar radiative forcing and geomagnetic energy input, as these drivers directly govern atmospheric heating and expansion. In operational models, these influences are represented through empirical indices and proxies that represent complex physical variability as a continuous time series suitable for operational use. Collectively, solar indices and proxies are considered *surrogates,* i.e., substitutes for measured solar spectral irradiances. An index is a condensed spectral measured quantity indicative of solar spectral activity within a specific wavelength bandpass whereas a proxy is a representative of a spectral range but not spectrally related to the quantity it represents. While these proxies provide a practical and operationally stable means of representing forcing, they also introduce limitations because many traditional proxies are derived from ground-based measurements that only indirectly represent the solar spectral irradiances responsible for thermospheric heating.

Solar forcing is expressed through a set of indices and proxies that capture variability across the far ultraviolet (FUV), extreme ultraviolet (EUV), and soft X-ray (XUV) bands of the solar spectrum. There are distinct solar wavelength bands that are absorbed in specific atmosphere layers, and the power of the solar indices described here is that they are uniquely tailored to provide the driving energies for each of the atmosphere layers. SET leverages space-borne observations to allow these spectral regions to be characterized more directly, since many of the EUV and XUV emissions that drive thermospheric variability are absorbed before reaching the ground.

Indices for geomagnetic activity quantify the magnetosphere's coupling with the thermosphere. The energy deposition from that interaction drives global density changes during geomagnetic storms.

Indices and proxies have differences in cadence, format, and observability, which can introduce complications into thermospheric modeling workflows. The JBH09 (Jacchia–Bowman HASDM 2009) system was developed to unify diverse solar and geomagnetic drivers within a single operational framework, with **JBHSGI.TXT** (Jacchia–Bowman HASDM Solar and Geomagnetic Indices) file serving as its final, integrated data product. The power of this file is that it contains the unique solar and geomagnetic indices/proxies needed for driving the distinct energy variations in the mid–upper thermosphere, lower thermosphere, and magnetically coupled Joule heating and precipitation of electron during storms.

JBHSGI

The JBHSGI.TXT file provides a continuous time series of solar and geomagnetic forcing surrogates (indices and proxies) designed to support both operational forecasting and retrospective thermospheric modeling applications. The public dataset spans an extended historical record that transitions from 1997 into near-real-time (nowcast) values. Advanced operational datasets not only include that time frame but also provide 3-hourly forecasts out to 6-days starting in 2012. This entire data system supporting the operational JBH09 model and HASDM (USSF High Accuracy Satellite Drag Model) systems has performed at Technology Readiness Level (TRL) 9 since 2012 and incorporates redundancy using primary and secondary data sources to guarantee that a valid data product is always available for USSF HASDM operations. The data features are summarized in Table 1.

Solar Forcing

Solar radiative forcing in JBHSGI is represented through four surrogates that describe variability in solar energy input relevant to thermospheric heating. These are produced as hourly and daily values, and reported every 3-hours or daily, to capture short-term variability. 54–day back-smoothed averaged values for JBH09 and 81–day center-smooth values for JB2008 (Jacchia–Bowman 2008) represent the slowly varying, active region background solar conditions. Specific to solar forcing, the S10, M10, and Y10 indices are a unique operational data product produced by SET. Unlike the F10 proxy, these indices are condensed direct measurement indicators of FUV, EUV, and XUV now being reported by GOES satellites. They identify the amount of solar energy being deposited to a particular altitude range of Earth's atmosphere by a specific wavelength range.

F10

F10 is a proxy for activity associated with emission from the solar upper chromosphere and lower corona, which correlates with long-term solar cycle variability and is used to parameterize background thermospheric heating. In JBHSGI, the F10 proxy is derived from the Penticton 10.7–cm radio flux (F10.7) measurement centered on 20 UT and reported daily. Its historical database reaches back to 1947.

S10

S10 represents variability in solar EUV irradiance, which accounts for ¾ of the thermospheric heating and density variations in thermospheric models. The S10 index is a combination of two EUV measurements (28.4 and 30.4 nm) from the GOES satellites, which is the band that is preferentially absorbed by atomic oxygen above 200 km in the mid–upper thermosphere.

M10

M10 is derived from the 280 nm solar MgII core-to-wing ratio and serves as an index for chromospheric and transition-region activity. It captures solar FUV variability associated with solar active region evolution. For JBHSGI, GOES satellite measurements of MgII are used to derive the value for M10, acting as a proxy for the 160 nm Schumann–Runge Continuum solar emission that dissociates molecular oxygen at 110 km in the lower thermosphere.

Y10

Y10 represents variability in solar Lyman-α and soft X-ray emissions, which influence lower thermospheric heating, composition, and ionization of nitric oxide and water, around 85–95 km altitude. The X-ray component is important during periods of enhanced solar activity and flare events while the Lyman-α component is important during solar minimum conditions. With JBHSGI, the Y10 index is derived from a combination of both Lyman-α (121.6 nm) and X-ray (0.1-0.8 nm) measurements from the GOES satellite.

Geomagnetic forcing

Geomagnetic forcing in JBHSGI is represented through indices that describe variability in magnetospheric coupling with the thermosphere through both Joule heating and electron precipitation. These processes are relevant to thermospheric heating and density enhancement during storm periods. These indices are provided at a 3-hour cadence, capturing short-timescale variability associated with geomagnetic activity and storm-time disturbances.

ap

The ap index is a planetary-scale geomagnetic activity index that quantifies the global level of geomagnetic disturbance associated with solar wind–magnetosphere coupling. The 3-hourly index is derived from the K-index provided by NOAA. SET maintains a historical database consisting of hourly ap values dating back to 1947 as well as NOAA–forecasted values beginning in 1997.

Dst

The Dst index provides a measure of the magnetospheric ring current intensity and is a primary indicator of geomagnetic storm magnitude and morphology. Within the JBHSGI framework, the Kyoto Dst is used as the primary data source for historical to nowcast values. Historical values are automatically updated as revised corrections become available. SET's Anemomilos algorithm provides 6–day forecast Dst with 1–hour time granularity starting in 2012. This multi-scale time series enables consistent nowcast and forecast geomagnetic forcing for operational thermospheric and satellite drag applications.

Delta Temperature Correction (DTC)

DTC represents the integrated effects of temperature changes separate from the solar forcing and due to the geomagnetic energy input into Earth's thermosphere. It provides for temperature change in units of K for storm-times. Within JBHSGI, DTC serves as the primary interface between external geomagnetic forcing in the temperature domain that is directly applicable to operational satellite drag models such as HASDM.

Table 1. Summary of JBHSGI indices

INDEX	NOWCAST	FORECAST
F10	Coverage: 1947-present Observation Cadence: Daily	Lead Time: 6 days Coverage: 2012-present Cadence: Hourly
S10	Coverage: 1997-present Observation Cadence: Hourly	Lead Time: 6 days Coverage: 2012-present Cadence: Hourly
M10	Coverage: 1997-present Observation Cadence: Hourly	Lead Time: 6 days Coverage: 2012-present Cadence: Hourly
Y10	Coverage: 1997-present Observation Cadence: Hourly	Lead Time: 6 days Coverage: 2012-present Cadence: Hourly
AP	Coverage: 1947-present Observation Cadence: 3-hourly	Lead Time: 6 days Coverage: 2012-present Cadence: Hourly
DST	Coverage: 1997-present Observation Cadence: Hourly	Lead Time: 6 days Coverage: 2012-present Cadence: Hourly
DTC	Coverage: 1997-present Observation Cadence: Hourly	Lead Time: 6 days Coverage: 2012-present Cadence: Hourly

Forecast Methodology

F10, S10, M10, Y10

To support operational thermospheric and ionospheric applications, SET developed a real-time forecasting capability through the Solar Irradiance Platform (SIP), which produces nowcast and multi-day forecasts of these indices.

The forecasting framework (FGen2/D3.9) is primarily based on persistence and recurrence using a linear predictive approach. In the short term (0-72 hours), forecasts are generated using an autoregressive formulation in which each future index value is expressed as a weighted combination of recent observations plus a residual error term. Predictions out to 48 hours rely on the previous three days of index values, while 48–96-hour forecasts incorporate longer-term recurrence using data from the previous five solar rotations (~137 days).

Although more complex methods based on solar imagery and active region evolution have been explored for intermediate lead times, linear persistence techniques have proven most reliable for short-range (≤3 day) non-flare irradiance forecasting. Because operational solar data streams arrive asynchronously, the nowcast is itself a short forecast generated using the most recent available inputs, which may lag the current epoch. Despite this limitation, validation results show strong near-term predictive skill, with correlation coefficients typically exceeding 0.90 through 72 hours for these indices. Accuracy decreases at longer lead times as persistence assumptions weaken and solar variability increases.

ap

The NOAA SWPC 3–day forecast for Kp is collected by SET and transformed into ap values using a conventional lookup table conversion method. SET then interpolates the 3–day ap forecast into eight 3–hour intervals per day to match the temporal grid for the JBHSGI.TXT files. There is not an independent ap forecast that SET creates aside from this methodology.

Anemomilos Dst

Current Dst forecasts are produced using the data-driven Anemomilos methodology, which links observable solar eruptive events to subsequent geomagnetic storm development. The approach uses solar flare magnitude as represented by a) SET's Xhf flare index, where the X-ray background has been removed, b) integrated X-ray irradiance from start to full-width half maximum, and c) event location on the solar disk as proxies for CME mass, speed, and geoeffectiveness. These parameters are used to estimate the timing, intensity, and evolution of the resulting geomagnetic disturbance. The resulting forecast Dst profile for 6–days into the future with 1–hour time granularity is generated by scaling statistical storm templates derived from historical events with these driver inputs.

Operationally, the method assumes that sufficiently energetic flares, i.e., M5 or larger, occurring near disk center are likely to produce Earth-directed ejecta. For flares nearing the solar East and West limbs, larger flares are needed. The integrated flare irradiance is used to estimate Sun-to-Earth transit speed, which determines arrival time, while flare magnitude and location determine the expected storm strength. This deterministic, event-driven approach produces hourly Dst forecasts out to several days, with cadence and latency suitable for operational thermospheric density modeling and satellite drag applications.

Fusion-Dst

Fusion-Dst is a hybrid science–machine-learning geomagnetic storm forecasting system developed under a NASA SBIR Phase II at SET (PI: Shaylah Mutschler) and is slated for operationalization in late Summer 2026. A key motivation for the development of Fusion-Dst is the performance of SET's legacy science-driven operational storm forecasting algorithm, Anemomilos, which has a high false-positive rate. This limitation arises because the interplanetary magnetic field (IMF) orientation (and associated Bz polarity governing geomagnetic coupling) within an Earth-directed CME cannot be determined until in situ measurements are available only hours prior to arrival at Earth. As a result, accurate prediction of geomagnetic storms at lead times beyond several hours remains fundamentally challenging, while longer lead times are required to support satellite operations and conjunction assessment.

To address these limitations, Andong Hu (SWxTREC, University of Colorado) developed machine-learned (ML) algorithms that provide both a 6-hour deterministic Dst forecast and a 48-hour probabilistic Dst forecast. These ML-based approaches demonstrate improved performance relative to traditional science-driven storm forecasting techniques, including SET's legacy Anemomilos system. When evaluated over the 2018-2025 period, Fusion-Dst's 6-hour deterministic ML-based Dst forecast demonstrates substantial reductions in forecast error under both quiet and storm-time conditions. Specifically, the 6-hour component of Fusion-Dst achieves a root-mean-square error (RMSE) of 7.9 nT during geomagnetically quiet conditions, compared to 18.3 nT for the legacy Anemomilos forecast, and an RMSE of 27.6 nT during storm conditions, compared to 66.4 nT for Anemomilos.

Another component of Fusion-Dst is the introduction of a 48-hour probabilistic ML-based Dst forecast. This probabilistic forecast is designed to provide actionable guidance within Fusion-Dst's operational framework by informing whether the deterministic Anemomilos-based storm forecast should be issued, thereby helping to mitigate the historically high false-positive rate associated with science-driven storm prediction. This 48-hour probabilistic ML-based Dst forecast is currently in development, with ongoing work toward its future integration into Fusion-Dst's operational framework.

SET Data Operations

At SET, we employ multi-core Virtual Machine Servers using RAID backup that are co-located at FirstLink, Inc, in Denver Colorado. This co-host facility has a secure SOC-2-rating with 24/7 network monitoring, redundant internet backbone carrier access, backup services, and backup power. This enables SET to maintain 24/7/365 operations to produce the JBHSGI.TXT files with 99.999% uptime for USSF to access the data. The data regularly acquired are as follows in Table 2.

The JBH index processing pipeline applies automated quality control and statistical filtering to raw solar measurements before generating operational indices. Incoming data are first checked against instrument-defined physical min/max limits, and extreme values are rejected. Additional statistical screening removes outliers exceeding a set number of standard deviations from a historical median (e.g., 3σ for F10.7 and 4σ for S10 and Ly-α), which helps suppress contamination from short-duration solar flares or instrument artifacts. After ingestion, the full historical time series is reprocessed to ensure consistency.

Missing or rejected values are then filled using spline or quadratic least-squares interpolation, and autoregressive forecasting is applied to account for the typical 3- to 4-day data latency. For EUV-based indices such as S10, a multi-day smoothing filter (currently 5-day, transitioning to 3-day) is applied specifically to mitigate flare-driven spikes. Together, these steps ensure the final indices reflect background solar variability relevant for thermospheric density modeling, rather than transient flare enhancements.

Table 2. List of data sources used within the JBHSGI framework

DATA SOURCE	DESCRIPTION
F10.7	SET retrieves F10.7, applies validation and continuity checks, and distributes a single operational value in addition to extrapolating forecasted values. Penticton serves as the primary source with NOAA SWPC as the secondary. **Coverage:** 1947–current **Frequency:** Daily
EUV	SET uses specific wavelength measurements to generate the S10 index, a critical input for JB2008/JBH09 atmospheric models. When data is delayed, SET issues forecast values to preserve operational continuity. NOAA GOES satellites serve as the primary source with LASP SDO/EVE as the secondary. **Coverage:** 1996–current **Frequency:** Hourly
MG II CORE-TO-WING RATIO	SET calibrates these measurements to historic Heath/Donnelly method and provides forecasted interim values due to the 3–4-day latency in data acquisition. NOAA GOES serves as the primary source with Bremen GOME as the secondary. **Coverage:** 1978–current **Frequency:** Hourly
SOLAR LYMAN-A	SET uses GOES measurements to generate the Y10 index and serve as primary inputs to several of our models. Validation is also provided with LASP SDO/EVE and TIMED SEE datasets. **Coverage:** 1996–current **Frequency:** Hourly
GOES XRS 1-8A SOLAR FLUX (XRS)	SET merges GOES-18 and GOES-19 measurements into a single real-time composite time series and improves upon the NOAA SWPC hourly release with a 1-minute composite X-ray flux; these data drive the Flare Initiation Algorithm (FIA) and supports the Xhf flare index and Xb10 background index used in Dst prediction. **Coverage:** 1986–current **Frequency:** 1-minute, Hourly
GEOMAGNETIC INDICES	In addition to maintaining the historical indices, SET generates Ap and Kp indices forecasted for use in atmospheric models based on the NOAA SWPC forecast. **Ap coverage:** 1947-current **Frequency:** 3-hourly **Kp coverage:** 2016-current **Frequency:** 3-hourly
DST	SET uses Kyoto historical and nowcast data as a primary source with automatically updated historical corrections. SET's Anemomilos algorithm provides forecast Dst with hourly time granularity and 6–day forecasts. **Kyoto:** 2007–current **Frequency:** Hourly **SET:** 2012–current **Frequency:** Hourly **Corrected:** 2013-present