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©E10.7 USE FOR GLOBAL ATMOSPHERIC DENSITY FORECASTING IN 2001

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ABSTRACT

LEO satellites are affected by dynamic and variable Sun-Earth interactions on short time scales known as space weather. These can be modestly predicted and the first-generation forecast of spherical harmonic temperature coefficients is described which utilizes solar and geomagnetic forecast parameters. A baseline forecast is first performed using the 72-hour forecast E10.7, E10.7-bar, and ap from a linear fit relationship to provide the basic trend. Next, a forecast "seed" is generated that is representative of the detrended dynamics inherent in a temperature coefficient term. Finally, a discrete wavelet transform algorithm is used to help propagate residual statistical information from the past to the future. This ensemble of algorithms provides forecast spherical harmonic temperature coefficients consistent with the two assumptions that underlying solar and geomagnetic forecast trends can provide a baseline state of the atmosphere for the upcoming 3 days and that dynamic trends (winds, tides) exist with scales of variability in their recent history.

BACKGROUND

The Basis for LEO Satellite Orbit Determination Improvement

Low-Earth Orbit (LEO) satellites, located between 100 and 1000 km in altitude, are greatly affected by the dynamic and variable Sun-Earth interaction on short time scales. Space weather, through one of its manifestations in the form of solar extreme ultraviolet (EUV) energy input into the thermosphere, can and does perturb satellite orbits and attitudes. Solar EUV photons are absorbed by neutral atmospheric oxygen and nitrogen which raises the kinetic temperature of the atoms and molecules. The subsequent temperature increase throughout the thermosphere via molecular conduction provides abundant energy for lower altitude atmospheric particles to translate into higher altitudes. This results in a net increase in any particular neutral species' densities for a given altitude layer. The increased neutral atmosphere density is directly proportional to the drag experienced by a LEO satellite and the increased drag can, in a matter of tens of minutes to hours, significantly affect a satellite's orbit parameters or attitude.

Prior to the 1990s, the level of uncertainty in specifying the density of the thermosphere as related to satellite drag was at the 15% level (F. Marcos, private communication, 2002). Part of this uncertainty was due to the coarseness of the solar proxies used to represent the EUV flux and another part was the inability to represent the density variability on time scales of less than a day in which the solar flux was perturbing the atmosphere.

Over the past decade, however, two major advances have occurred. On one hand, techniques pioneered separately by F. Marcos and J. Liu enabled the "calibration" of the global atmosphere. This was accomplished by using a small number of known satellites to derive a better approximation to the global atmospheric density which was then applied to a larger satellite catalog. On the other hand, scientific knowledge about the Sun’s absolute and relative irradiance variability on short time scales, and the ability to characterize it with proxies that could be utilized by legacy code, progressed to the point where space weather products based on space physics models became operational. This paper describes the application in energy content, time resolution, and legacy code use improvements to solar EUV flux which has led to a first-generation capability for forecasting thermospheric temperature parameters directly related to global atmospheric density specification.

E10.7 Solar Proxy from SOLAR2000

Because EUV heating is the major source of uncertainty for satellite drag models, and because there has been a historical scarcity of EUV measurements, the 10.7-cm solar radio flux, F10.7, has been used as a proxy for solar EUV heating. F10.7, as a predominantly coronal low-energy radio emission, is a coarse EUV proxy since it does not contribute to atmospheric heating, ionization, or dissociation processes and is limited to daily time resolution. Despite these limitations, it reflects general solar activity on 27-day and solar cycle time scales and for this reason it became a useful surrogate for solar EUV emissions. It is used as the solar energy driver in several atmospheric density analytical

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and empirical models that are linked with orbit propagators. One example is the modified Jacchia-70 model used by the High Accuracy Satellite Drag Model (HASDM) project.

In order to refine the time resolution and the fidelity of representing the actual EUV energy at the top of the atmosphere available for heating processes, the E10.7 proxy was developed in 1999-2000[1]. By reporting the integrated EUV energy flux from 1-105 nm in the units of F10.7, i.e., $\times 10^{-22}$ W m^{-2} Hz^{-1}, the E10.7 became directly useful for legacy software that used F10.7 as a solar energy input. The 1-105 nm EUV energy flux is provided by the operational grade SOLAR2000 model which, through subroutines, translates that energy flux into the E10.7 proxy. Previous validation studies have reviewed the application of E10.7 to the problem of satellite drag[1,2,3].

SOLAR2000, a collaborative project for accurately characterizing solar irradiance variability across the spectrum[1,4], has the overarching scientific goal to understand how the Sun varies spectrally and through time from the X-rays to the infrared wavelengths. Its irradiance products are fundamental energy inputs into planetary atmosphere models and for modeling or predicting the solar radiation component of the space environment[1]. SOLAR2000 is compliant with the International Standards Organization (ISO) solar irradiance draft standard CD 21348.[5]

METHODOLOGY

E10.7, E10.7-bar, and Ap Forecast

The SOLAR2000 operational grade model is used for operational forecasts. Its inputs are real-time solar irradiance proxies of F10.7 for coronal emissions and Mg II core-to-wing ratio for chromospheric emissions. Starting in 2004, SOLAR2000 will use GOES-N EUV broadband data to produce nowcast and forecast high time resolution solar irradiances capable of capturing flare events. A 3-day forecast daily irradiance product is shown in Figure 1. The E10.7 current epoch forecast is shown in relation to the past 54 days (approximately two solar rotations) in the top panel and is compared with the solar cycle 23 minimum to maximum values in the bottom panel. As used in the HASDM project, E10.7 and its running 81-day average, E10.7-bar, are generated hourly but reported in 3-hour time segments for the past (issued) 24-hours and for the (predicted) next 72-hours. Table 1 shows an example of the reported forecast for the HASDM project. The algorithms for the first-generation operational forecasting of solar irradiances, including the E10.7 and E10.7-bar, are reported in previous work[3]. Table 2 provides a summary of that work for completeness in this paper. Figure 2 shows the forecast covering the period described in Table 1 and beyond the next solar cycle. The time series forecasts in figure 2 show the coronal and chromospheric input proxies into SOLAR2000 that create the irradiances, the E10.7, and the uncertainties associated with both.

The daily Ap and the 3-hourly ap are also reported in this file shown in Table 1. In the first-generation forecasting, these values are directly mirrored from the NOAA Space Environment Center (SEC) and USAF 3-day forecast of the Ap. In second-generation forecasting, the Ap and ap values will be improved using new algorithms now in development at NOAA/SEC.

Dynamics Forecast

A modified Jacchia-70 atmospheric density model uses input parameters of 3 hourly E10.7, E10-bar, and ap to generate a spherically symmetric zeroth-order atmosphere. The solar and geomagnetic indices are only applicable for the overall planetary atmosphere forcing function. In addition to the zeroth-order spherical harmonic temperature terms generated by the solar and geomagnetic inputs, there are first and second order terms in the temperature coefficients that must also be modified in the predicted, forecast space. The forcing function behind these terms is considered to be mostly atmosphere dynamics in the form of tides and zonal winds. However, dynamical processes such as waves that result from large solar/geomagnetic energy pulses, e.g., flares and/or coronal mass ejections, may also occur temporarily within the atmosphere.

In order to achieve a top level, empirical forecast of these dynamical processes over the next 3 days, two assumptions are made. First, it is assumed that the underlying solar and geomagnetic forecast trends will provide the baseline state of the atmosphere in the upcoming period. Second, it is assumed that scales of variability due to dynamic trends (winds, tides) exist in the recent history of the first and second order spherical harmonic temperature coefficient data. If these two assumptions are true, then it is possible to achieve a top level forecast over the next 3 days. Where these assumptions break down, i.e., with changing winds, tides, and dramatically different energy inputs, the forecast will break down.

The forecast of all orders (0,1,…n) of temperature coefficients is performed in an identical manner. A baseline forecast for the nth-order term is first generated using

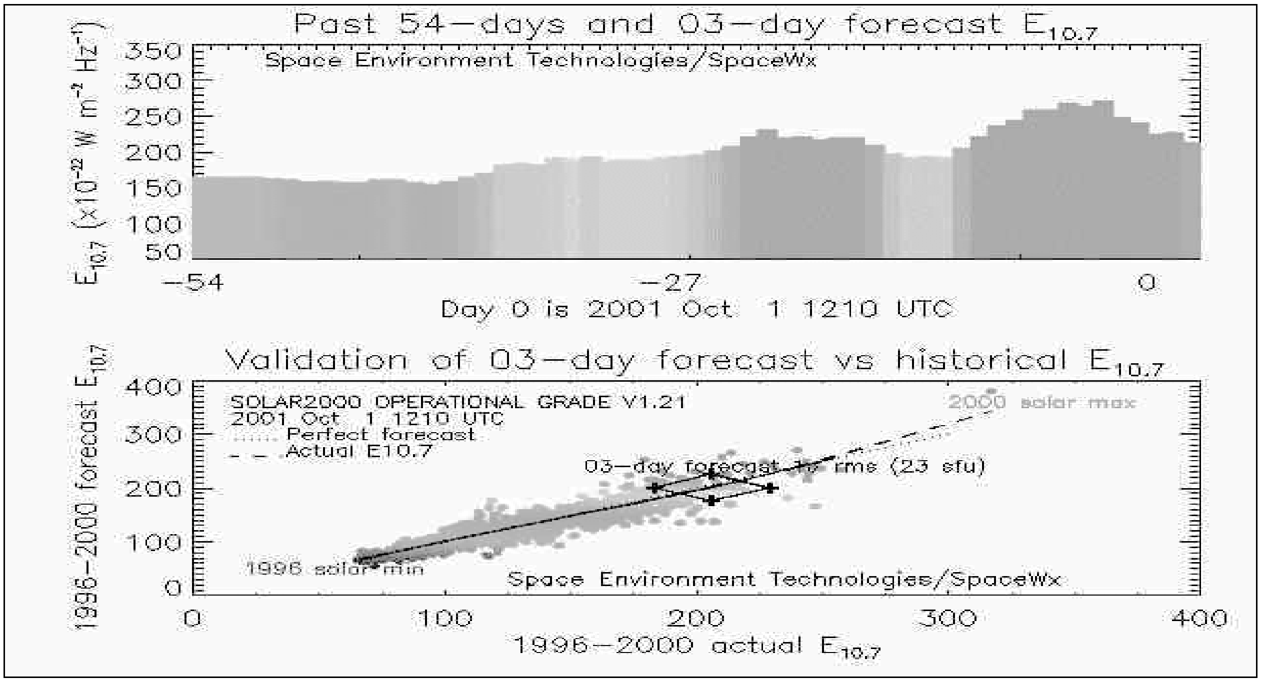

Figure 1: E10.7 for the next 72-hour period from the current epoch compared to the previous 54-days of E10.7 (top panel). Current epoch 3-day forecast E10.7 compared to actual E10.7 for solar cycle 23 minimum (1996) through maximum (2000) (bottom panel).

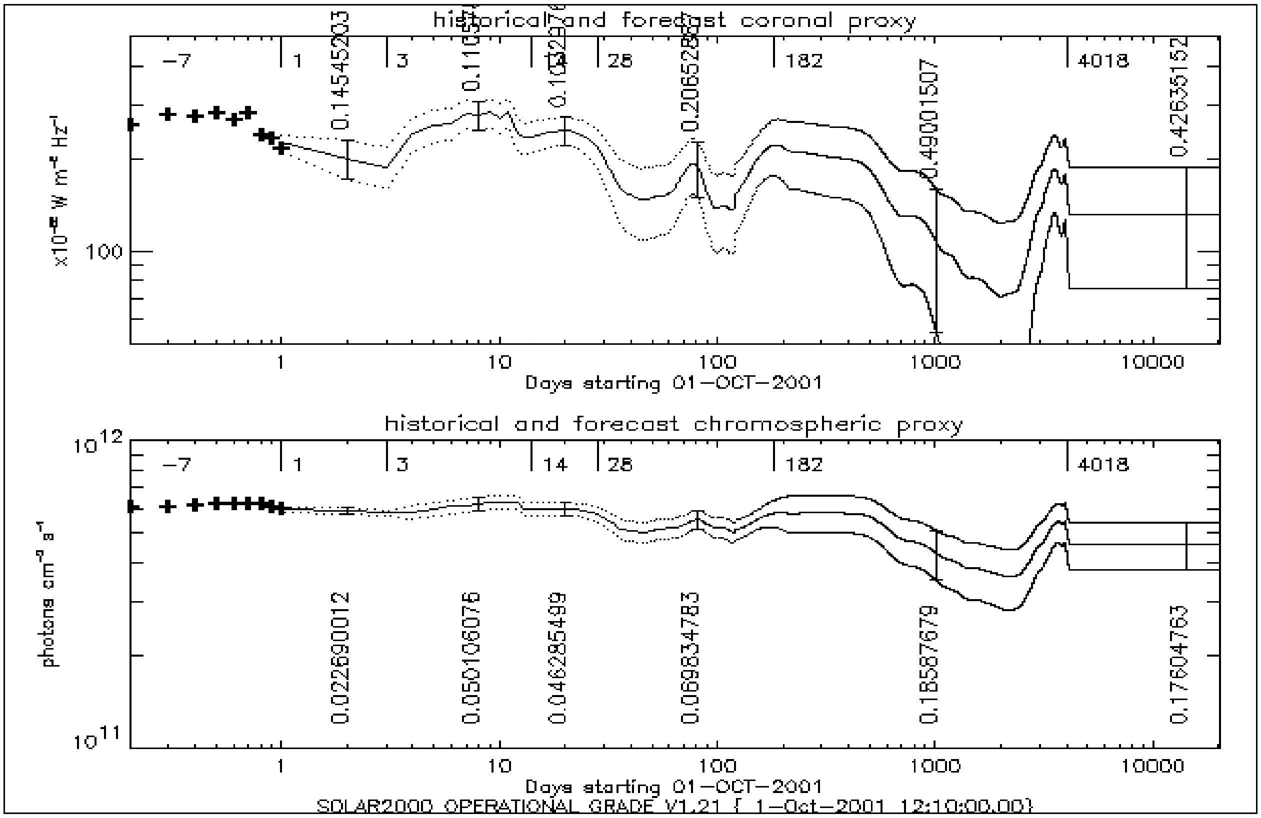

Figure 2: SOLAR2000 forecast proxies for coronal (top panel) and chromospheric (bottom panel) emissions over several distinct time periods. The fractional 1σ rms uncertainty, valid to 2 decimal places, is shown for each period.

TABLE 1. FORECAST BULLETIN FOR SOLAR AND GEOMAGNETIC INDICES

```
:Product: Modified Flux Data              MFD.TXT (Rev. G)
:Issued:   1-Oct-2001 12:10:00.00 UTC
# Prepared by Space Environment Technologies/SpaceWx
# Point-of-contact: W. Kent Tobiska (http://SpaceWx.com)
#
# Metadata:
# Units: Year, Month, Day (YYYY, MM, DD) are UT calendar year,
#          integer month, day of month, hour, minute (hh, mm)
#        S_C is integrated solar spectrum
#          in x10-04 + 1366.05 Watts per meter squared
#        F10, F81 are daily and 81-day solar 10.7 cm radio flux
#          in x10-22 Watts per meter squared per Hertz
#        Lya, L81 are daily and 81-day Lyman-alpha
#          in x10+09 photons per centimeter squared per second
#        E10, E81, E3h, B3h are daily, 81-day, 3-hr, 3-hr-avg E10.7
#          in x10-22 Watts per meter squared per Hertz
#        Ap, a3h are daily mean, 3-hr planetary geomag 2 nT index
#        E1s, a1s are 1 sigma uncertainty of E3h, a3h in proxy units
#        SRC is the data source (Historical, Issued, Predicted)
# Notes: S_C in SOLAR2000 v1.yz is not the TSI variation.
#        E10.7 is unadjusted, integrated 1-105 nm EUV in F10.7 units
#
# Source: SOLAR2000 OPERATIONAL GRADE V1.21
# Location: SpaceWx {PowerMac MacOS IDL 5.5}
# Missing data: -1
#                         Modified Flux Data file
#  CALENDAR
#YYYYMMDDhhmm S_C F10 F81 LYA L81 E10 E81 A_p E3h B3h a3h E1s a1s SRC
#--------------------------------------------------------------------
 200109301200 561 216 238 601 593 226 228  48 226 228  18  11  31   I
 200109301500 561 216 238 601 593 226 228  48 226 228  48  11  31   I
 200109301800 561 216 238 601 593 226 228  48 226 228  67  11  31   I
 200109302100 561 216 238 601 593 226 228  48 227 228  48  11  31   I
 200110010000 561 216 238 601 593 226 228  48 227 228  48  11  31   I
 200110010300 561 216 238 601 593 226 228  48 227 228  80  11  31   I
 200110010600 561 216 238 601 593 226 228  48 227 228  67  11  31   I
 200110010900 561 216 238 601 593 226 228  48 227 228  67  11  31   I
 200110011200 562 216 238 601 593 228 228  52 228 228  32  10  31   P
 200110011500 562 216 238 601 593 228 228  52 228 228  27  10  31   P
 200110011800 562 216 238 601 593 228 228  52 228 228  15  10  31   P
 200110012100 562 216 238 601 593 228 228  52 228 228  48  10  31   P
 200110020000 562 216 238 601 593 228 228  52 229 228  32  10  31   P
 200110020300 562 216 238 601 593 228 228  52 229 228  48  10  31   P
 200110020600 562 216 238 601 593 228 228  52 229 228  67  10  31   P
 200110020900 562 216 238 601 593 228 228  52 229 228  27  10  31   P
 200110021200 561 225 238 595 593 228 228  69 229 228  22  22  31   P
 200110021500 561 225 238 595 593 228 228  69 229 228  32  22  31   P
 200110021800 561 225 238 595 593 228 228  69 229 228  80  22  31   P
 200110022100 561 225 238 595 593 228 228  69 229 228 111  22  31   P
 200110030000 561 225 238 595 593 228 228  69 228 228  48  22  31   P
 200110030300 561 225 238 595 593 228 228  69 228 228  18  22  31   P
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 200110031800 555 199 237 590 593 215 228  17 223 228  39  23  31   P
 200110032100 555 199 237 590 593 215 228  17 221 228  48  23  31   P
 200110040000 555 199 237 590 593 215 228  17 220 228  32  23  31   P
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 200110040600 555 199 237 590 593 215 228  17 217 228  27  23  31   P
 200110040900 555 199 237 590 593 215 228  17 215 228  22  23  31   P
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TABLE 2. EXISTING ALGORITHMS FOR SOLAR INDICES' FORECAST

Time period	Product type	Algorithm
0 – 24 hours	nowcast	Viereck et al., 2001[8]
24 – 72 hours	forecast	autoregression using past 14 days
3 – 14 days	forecast	substitution of past 14 days with no smooth
14 – 28 days	forecast	substitution of past 28 days with 7-day smooth (convolution)
1 – 6 months	forecast	substitution of past 6 months with 30-day smooth (convolution)
1/2 – 11 years	forecast	substitution of past 11 years with 365-day smooth (convolution)
1 – 5 solar cycles	forecast	mean of five solar cycles

the 72-hour forecast E10.7, E10.7-bar, and ap in a linear fit equation where the coefficients are derived from a 16-day (3-hour time center) multiple linear regression fit between the recent history nth-order term and those same solar and geomagnetic parameters. The forecast data are then empirically modified with an exponential weighting function that damps the solar signal after the first day. This step applies the assumption that any persistence in the dynamic trends is generally related to the external solar and geomagnetic forcing and, thus, a baseline can be formed using this information. In reality, this assumption only works part of the time because we don't know the future and the best one can do is determine where the baseline is now plus estimate a future trend. The result of this first step creates a baseline vector upon which detrended dynamical variability information can later be placed.

The methodology of using only a baseline but not the detailed variability in the solar and geomagnetic data is supported by figures 3, 4, and 5. These figures show fast Fourier transform (FFT) plots of the 3-hourly E10.7, ap, and zeroth-order temperature coefficient. It is apparent from the power at specific frequencies that persistence occurs in all three data sets. However, the stronger frequencies in the zeroth-order temperature coefficient are different than either the solar or geomagnetic indices, thus indicating a different source function, i.e., most probably dynamics.

The next step generates a "seed" forecast for the detrended dynamics in the nth-order temperature coefficient term. The previous 4-day history (3-hour time centers) of the nth-order temperature coefficient term is used and the assumption supported by this step is that the actual variability persists only on relatively short time scales of up to a few days. Since the most recent 24-hour period data is likely to be incompletely sampled, the forecast is made for the most recent 24-hour period plus the next 72-hours, i.e., it is a backcast plus a forecast for a total of 32 time steps.

The third step combines the detrended dynamics forecast plus the baseline trend provided by the solar and geomagnetic activity into a single vector. This vector is concatenated with the nth-order temperature coefficient history vector so as to construct a time series that is dominated by and extends from the past and advances into the future.

An important activity at this point is to remove any discontinuities from the vector concatenation process and to propagate into the future any residual historical statistical information about the nth-order temperature coefficient variability. A discrete wavelet transform (DWT) is used to do this and this type of algorithm provides a self-consistent, time-dependent data set of the future nth-order temperature coefficient linked with its past. The transform is initially made of the data set from time space into scale space and then the smaller scale transform coefficient terms are truncated. This truncation removes small-scale variability in the data set but preserves the large-scale variability. The reverse transform is then performed to reform the data set in time space. As a final step, the forecast data is extracted from the new time series data set and returned to a calling algorithm. Figure 6 shows a good forecast result of this algorithm for the zeroth-order temperature coefficient term and figure 7 shows a poor forecast result.

Robust features of this algorithm are that all nth-order temperature coefficients are treated with the same assumptions. In addition, when the details of the dynamics change due to sampling rates, flare activity, or other factors, the routine provides a self-consistent forecast with a time lag that, for higher cadence sampling, is generally consistent with the physics of how the atmosphere actually responds. In addition, the use of the DWT provides a way to characterize and extract information about scales of variability that are not dependent upon an assumption of time series stationarity.

CONCLUSIONS

LEO satellites are greatly affected by dynamic and variable Sun-Earth interactions on short time scales referred to as space weather. The HASDM project uses an operational 3-day forecast of solar and geomagnetic products to mitigate the effects of space weather on satellite orbit determination. Specifically, the solar EUV energy proxy E10.7, its running 81-day average, E10.7-bar, and the geomagnetic index ap that are generated hourly but reported in 3-hour time segments for the past (issued) 24-hours and for the (predicted) next 72-hours, are used. In addition to the highest level of atmospheric density prediction, these three variables help define a baseline upon which the predicted, non-solar, non-geomagnetic variabilities in the spherical harmonic zeroth, first, and second order temperature coefficients are placed. The variabilities in these temperature coefficients represent the delta temperature values by which the modified Jacchia-70 empirical atmosphere must be corrected in order to more closely approximate a calibration-satellite drag-derived atmosphere. The spherical harmonic temperature differences are primarily due to unmodeled atmospheric dynamics such as tides and zonal winds and secondarily due to unmodeled solar and geomagnetic effects.

For a forecast of any order (0,1,…n) temperature coefficient, a baseline forecast is first generated using the 72-hour forecast E10.7, E10.7-bar, and ap in a linear fit equation. Next, a forecast "seed" is generated for detrended dynamics of the nth-order temperature coefficient term. This vector is concatenated with the historical temperature coefficient vector so as to construct a

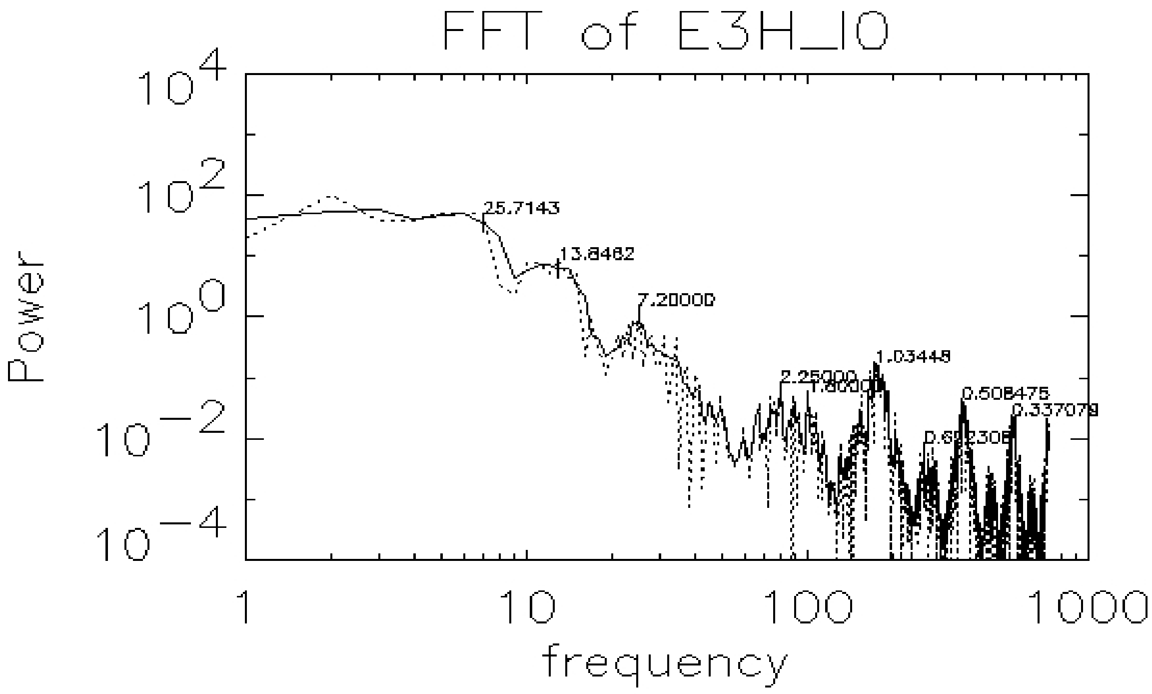

Figure 3: A FFT of the 3-hourly E10.7 showing the power in specific frequencies (labeled in days).

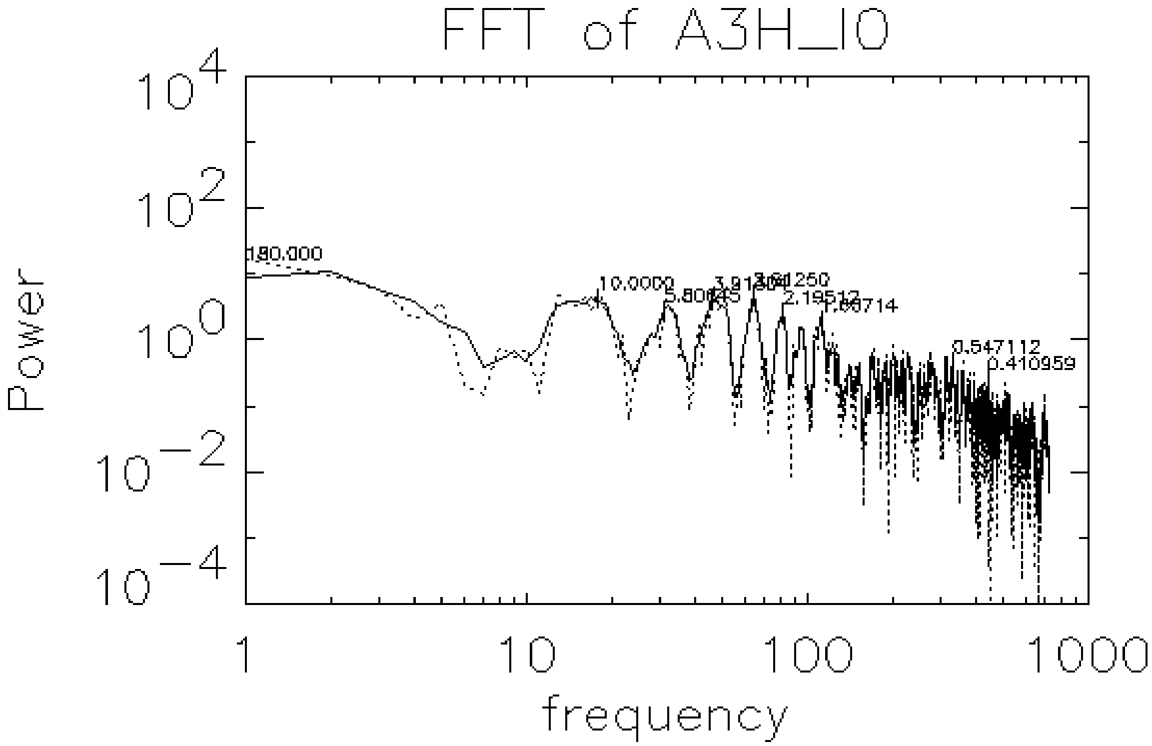

Figure 4: A FFT of the 3-hourly ap showing the power in specific frequencies (labeled in days).

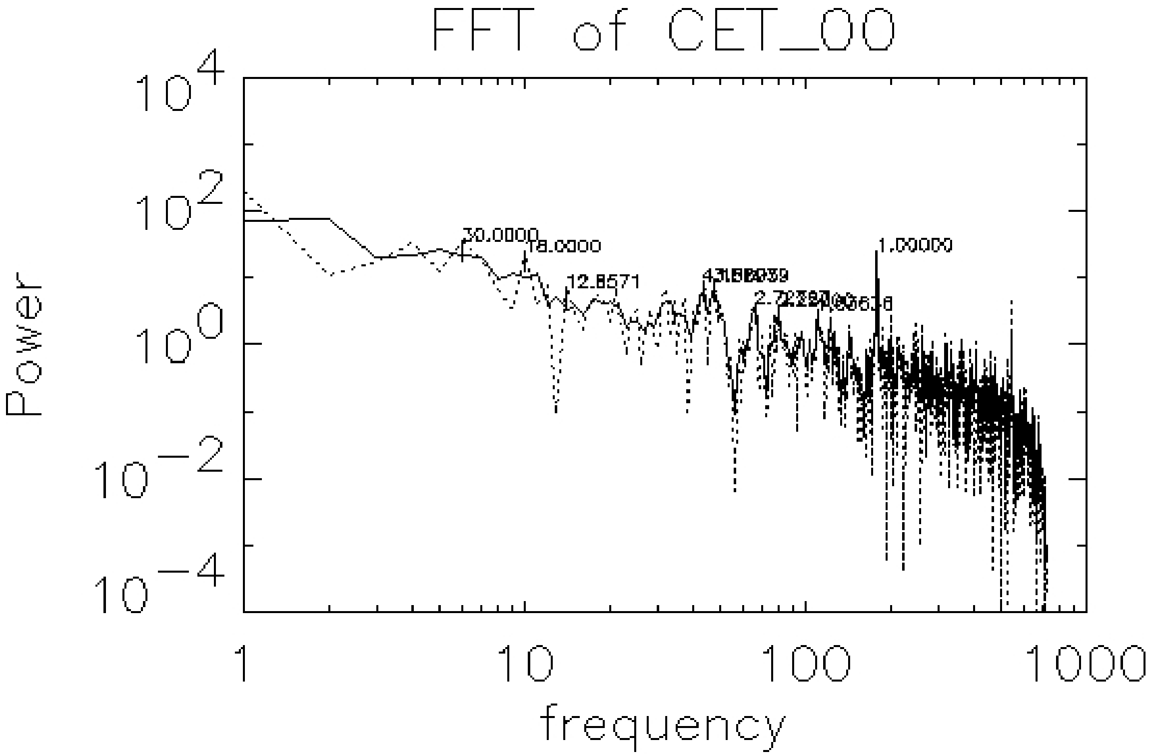

Figure 5: A FFT of the 3-hourly zeroth-order temperature coefficient showing the power in specific frequencies (labeled in days).

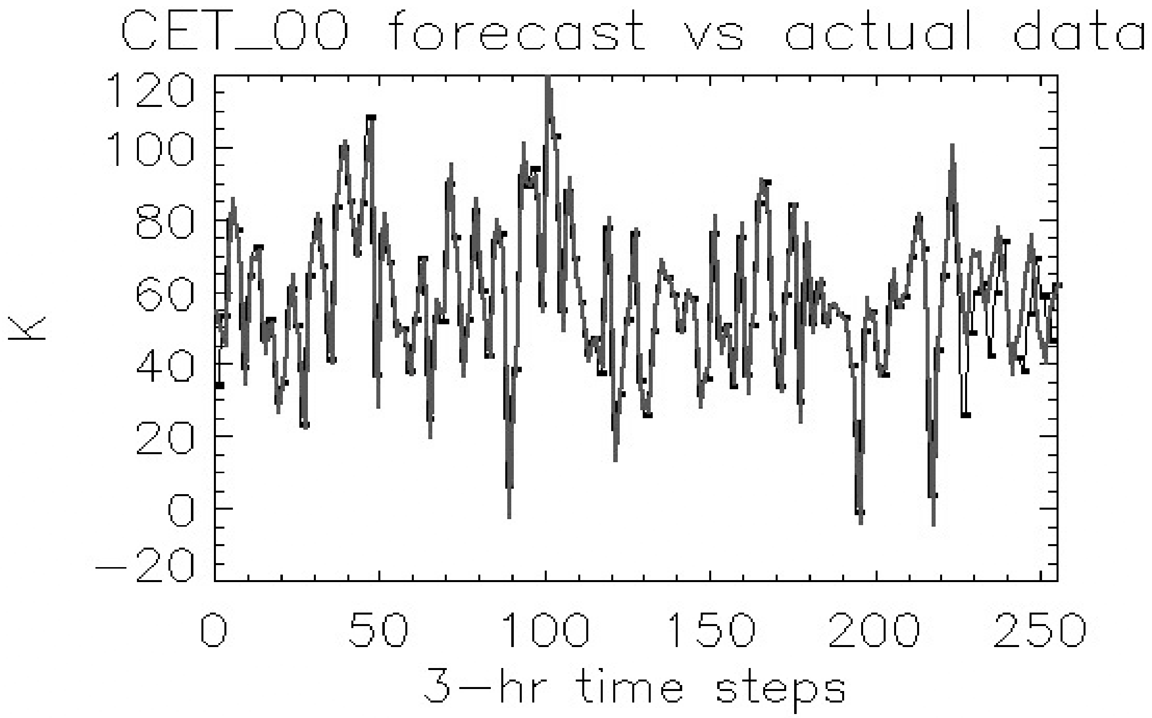

Figure 6: A good forecast of the zeroth-order temperature coefficient term using the ensemble of algorithms described above.

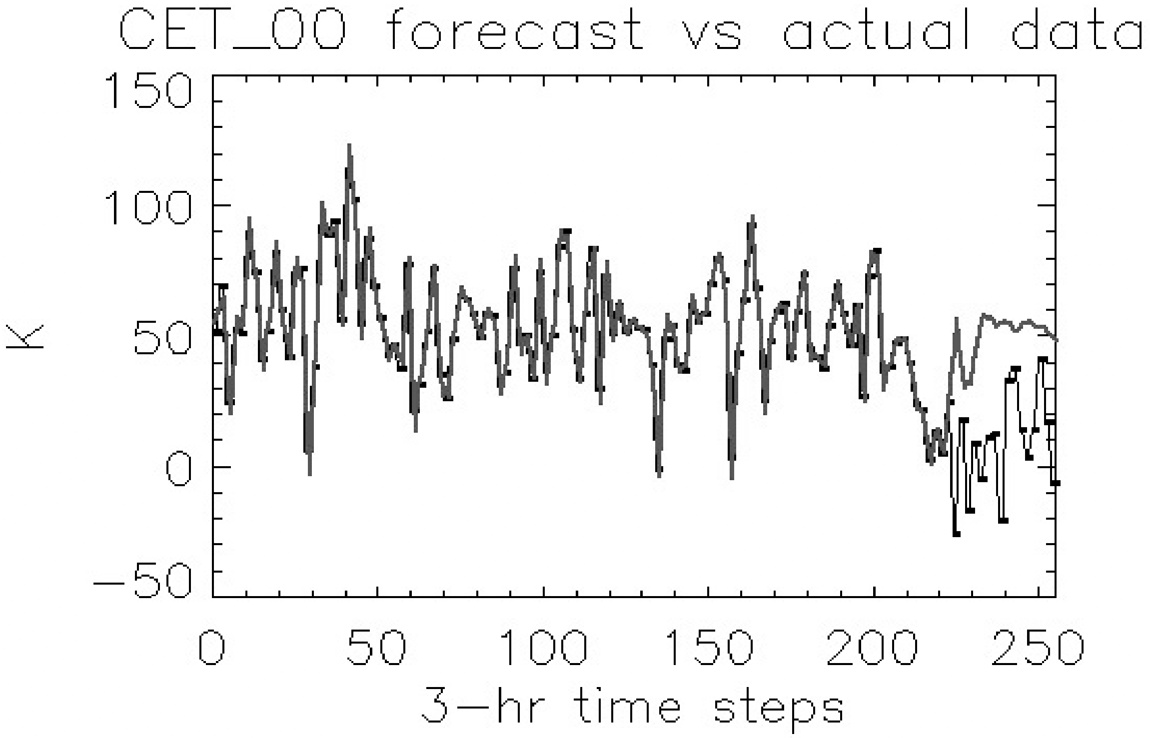

Figure 7: A poor forecast of the zeroth-order temperature coefficient term using the ensemble of algorithms described above.

time series extending from the past and advancing into the future. A DWT is used to remove discontinuities from the vector concatenation process and to propagate residual historical statistical information into the future. The transform is first made into scale space where the small-scale transform coefficient terms are truncated. The reverse transform is then performed to regain the data set in time space and the forecast data is extracted for return to a calling algorithm.

This algorithm provides spherical harmonic temperature coefficients consistent with two assumptions: that the underlying solar and geomagnetic forecast trends can provide the baseline state of the atmosphere for the upcoming 3 days and that dynamic trends (winds, tides) exist with definable scales of variability in their recent history.

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