JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, B03103, doi:10.1029/2005JB003831, 2006

Local time stacking of geomagnetic solar daily variations

M. E. Everett[1]

Received 11 May 2005; revised 25 October 2005; accepted 20 December 2005; published 23 March 2006.

[1] Regular geomagnetic solar daily variations, the *Sq* signal, is used in electromagnetic induction studies to investigate the electrical conductivity structure of Earth's upper mantle. Traditionally, *Sq* induction studies employ observatory magnetic data from a few quiet days in which the overprint on the regular *Sq* ionospheric current vortices from various irregular disturbances is minimal. Active days are typically discarded, a procedure which results in a gappy time series that is difficult to analyze. Furthermore, the quiet day selection is largely arbitrary since daily geomagnetic activity levels range continuously from very quiet to very active. This fact precludes the establishment of rigorous quiet/active thresholds. The average local time variation on active days resembles typical quiet day variations except for a multiplicative scaling factor. A multiyear stack of yearlong geomagnetic time series aligned with respect to local time incorporates "regular active" days while greatly attenuating the effects of irregular geomagnetic disturbances. External and internal current systems that rise and fall in step with the Sun's transit across the sky above an observatory contribute coherently to the local time stack. All other current systems are incoherent and tend to stack out. An exact 1-year-long stack preserves the seasonal variation. The resulting stacked time series contains no gaps, is dominated by regular solar daily variations, and can be used for improved *Sq* induction studies and comprehensive geomagnetic field modeling. Hourly geomagnetic values from Niemegk, Boulder, Mbour, and Meanook observatories between 1970 and 2002, along with the *ap* index, are used in this study.

Citation: Everett, M. E. (2006), Local time stacking of geomagnetic solar daily variations, *J. Geophys. Res.*, *111*, B03103, doi:10.1029/2005JB003831.

1. Introduction

[2] Regular solar daily geomagnetic variations are generated by thermospheric winds advecting photoionized ions and electrons across main geomagnetic field lines. The resultant ionospheric dynamo action [*Volland*, 1984] powers the dayside *Sq* current vortices. The day-to-day variability of the *Sq* current vortex strength is governed largely by fluctuations in solar EUV irradiance. The ground magnetic signature of the *Sq* current system and its induced counterpart [*Campbell*, 1989] constitutes the regular part of daily geomagnetic variations measured at observatories or by low-Earth orbiting satellites. Irregular daily variations caused by various ionospheric disturbances overprint the *Sq* signal.

[3] The central objective of geomagnetic induction is to separate the causative sources of magnetic spatiotemporal variations into external and internal components and to study how the spatially heterogeneous electrical conductivity of the solid Earth generates the internal contribution to the total observed geomagnetic variations. To do this, it is essential to have firm knowledge of the external source distribution. Induction studies have traditionally attempted to distinguish geomagnetic quiet days from disturbed, or active days [*Schmucker*, 1999]. The underlying assumption is that the external source operating during the quiet days is simple enough to be understood and represented by a small number of spherical harmonic terms. A reliable separation of external and internal sources during quiet days can then, in principle, be accomplished.

[4] However, a major challenge to successfully carrying out the above procedure lies in the identification of the quiet days. Also, removal from consideration of active days results in a gappy time series that is difficult to analyze. We show in this paper, using both local and global measures of daily geomagnetic activity, that geomagnetic activity level ranges continuously from very quiet to very active. There is no distinct cutoff or threshold value below which a day can be declared unambiguously as geomagnetically quiet. Furthermore, we show that the average local time variation on active days resembles typical quiet-day variations except for a multiplicative scaling factor.

[5] In view of the above results, we suggest that daily variation induction studies could benefit from a continuous 1-year time series of multiyear stacked data in which all days contribute to the stack regardless of the level of

---

[1] Department of Geology and Geophysics, Texas A&M University, College Station, Texas, USA.

0148-0227/06/2005JB003831$09.00

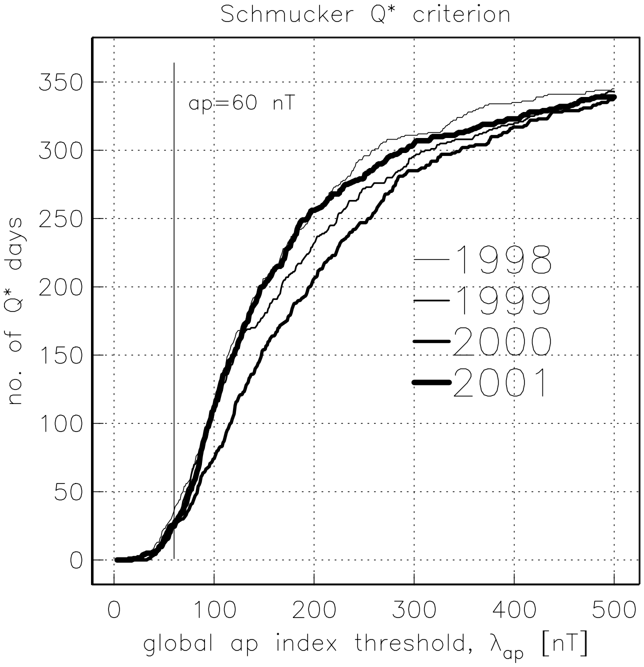

Figure 1. Number of Q* days in each year from 1998 to 2001 as a function of the global *ap* index threshold λ_{ap}. The solid vertical line corresponds to λ_{ap} = 60 nT.

geomagnetic activity. The advantages of local time stacking are that a continuous time series without gaps is obtained and it is not necessary to distinguish between quiet and active days. Furthermore, geomagnetic variations caused by physical mechanisms that are organized with respect to local time stack coherently, while geomagnetic variations that are incoherent with respect to local time are stacked out. This provides a powerful means of isolating the regular solar daily variation signature while rejecting geomagnetic disturbance variations, such as storm-related and other events, that are not organized with respect to local time.

2. Quiet-Day Analysis

[6] *Schmucker* [1999] recently introduced an algorithm for identifying geomagnetic quiet days. His procedure, termed Q*, was applied to worldwide observatory data from the particularly quiet years of 1964 and 1965. A day is declared as quiet under the Q* criterion if a certain 2-day summation of 3-hourly global *ap* index values is less than a specified threshold value, λ_{ap}. *Schmucker* [1999] chose a threshold value of λ_{ap} = 60 nT. The sum spans the last half of the previous day, the entire day itself, and the first half of the following day, to make a total of 16 *ap* index values. The *ap* index is a global indicator of geomagnetic activity level [*Langel and Hinze*, 1998].

[7] The Schmucker Q* procedure is applied to 1998–2001 and the results are shown in Figure 1. For each year, the number of Q* days (i.e., quiet days under the Q* criterion) is plotted against the *ap* index threshold, λ_{ap}. Schmucker's choice of λ_{ap} = 60 nT is shown as the solid vertical line and it can be seen that for this choice, 1998–2001 would each contain some 35–45 Q* days. An inspection of Figure 1 indicates, however, that the number of Q* days is a smooth, monotonically increasing function of λ_{ap}. In other words, there is no sudden jump in the number of Q* days as the threshold λ_{ap} surpasses any particular value. The smoothly varying nature of the Q*(λ_{ap}) curves in Figure 1 suggests that a rigorous justification for choosing a particular *ap* threshold value does not exist and, indeed, the designation of a given day as quiet under the Q* criterion is largely arbitrary. The utility of specifying days as either quiet or active is called into question by this plot.

[8] The previous discussion pertains to the *ap* index, which is a global geomagnetic activity level indicator. To investigate whether individual quiet days can be rigorously identified on the basis of a local observatory indicator of geomagnetic activity, we define the total daily variation (TDV) as the sum of the absolute values of the differences between adjacent hourly geomagnetic values recorded at a specified observatory. Thus

$$TDV = \sum_i |B_{i+1} - B_i|, \tag{1}$$

where B_i is the observatory hourly value of a given geomagnetic element $B = X$ (north), Y (east) or Z (vertical) recorded at the local hour $i = 1,\ldots, 23$, where $i = 1$ is local midnight, $i = 13$ is local noon, and so forth. Therefore high

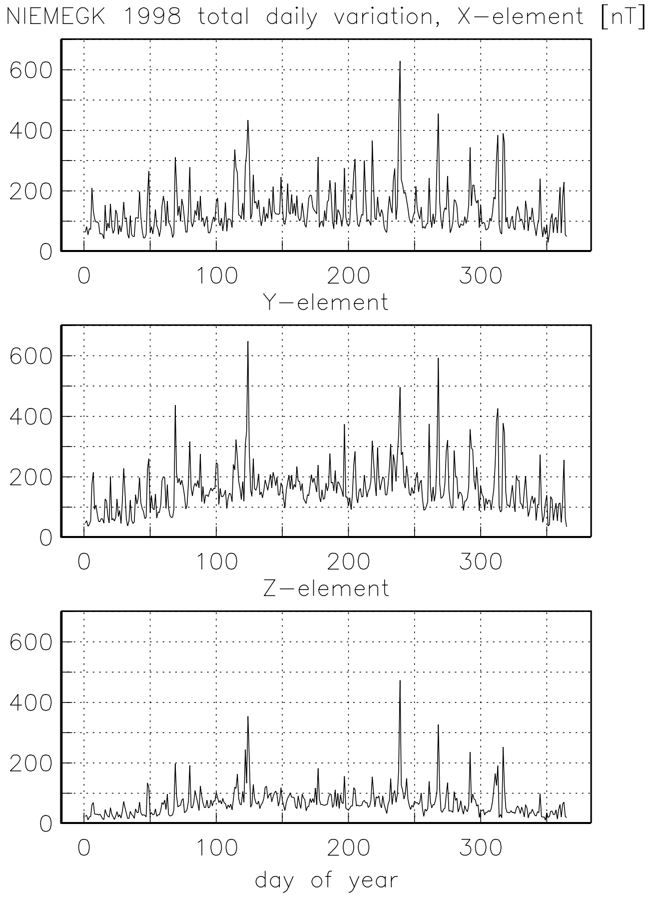

Figure 2. Total daily variation (TDV) of geomagnetic (top) X, (middle) Y, and (bottom) Z elements throughout 1998 at Niemegk Observatory.

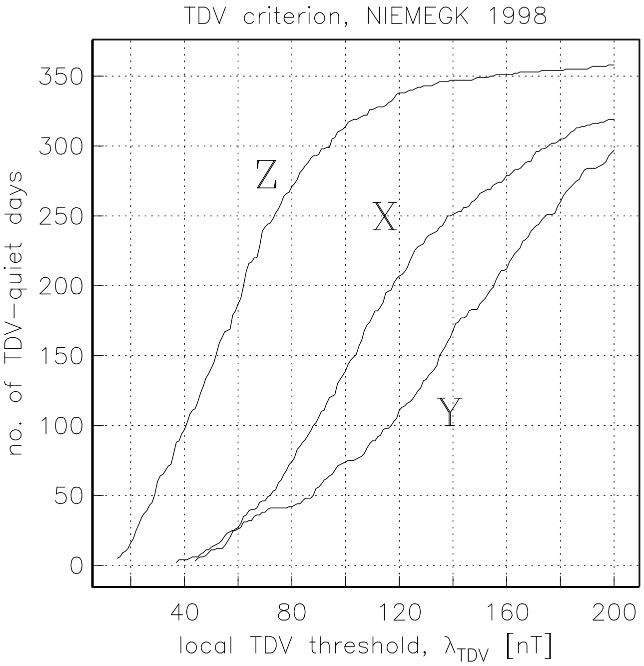

Figure 3. Number of TDV quiet days in 1998 as a function of the local activity threshold λ_{TDV}, for each of the geomagnetic elements *X*, *Y*, and *Z* recorded at Niemegk Observatory.

TDV values are associated with active days, i.e., those characterized by large hour-to-hour fluctuations of the given geomagnetic element. Low TDV values correspond to quieter days with smaller hour-to-hour fluctuations. The TDV for geomagnetic elements *X*, *Y*, and *Z* at Niemegk Observatory (52.07°N, 12.68°E) during 1998 is shown in Figure 2. Notice that an annual variation is evident in this plot, marked by a significant increase in TDV during the summer months. There is significantly less TDV in the geomagnetic *Z* element than in the horizontal geomagnetic elements *X* and *Y*. The differences in the magnitude of the TDV signals for the *X*, *Y*, *Z* components, and that of their respective annual variations, is a function of the latitude of the Niemegk Observatory, i.e., its position with respect to the causative *Sq* current vortices in the ionosphere.

[9] The TDV activity level shown in Figure 2 also reflects, to a great extent, global-scale geomagnetic storm activity as recorded by the *Dst* index. The period of time January to mid-February and mid-November through December were quiet months according to the *Dst* index. The largest 1998 storms with $|Dst| > 200$ nT occurred in early May (about day 125) and late September (about day 269), with additional moderate disturbed activity, $|Dst| > 100$ nT, in late August (about day 240) and early to mid-November (about days 313–319). The *Dst* index for 1998 therefore explains most of the peaks in the TDV plot.

[10] As in the Q* analysis, a threshold λ_{TDV} value can be explored. If the TDV on a given day is below λ_{TDV}, that day is declared to be quiet under the TDV criterion. For example, it can be seen in Figure 2 that most days are TDV quiet if λ_{TDV} is set to, say, 400 nT. Conversely, most days are TDV active if λ_{TDV} is set to, say, 20 nT. The number of TDV quiet days in 1998 is shown in Figure 3 as a function of λ_{TDV}, for each of the geomagnetic elements *X*, *Y* and *Z*. It is clearly seen that the number of TDV quiet days increases smoothly and monotonically with the local geomagnetic activity level. As in the global Q* analysis, there is no sudden jump in the number of quiet days for any critical TDV activity level. Again, the distinction between quiet and active days is ill-defined. For a given choice of λ_{TDV}, there are more TDV quiet days for the *Z* element than for the other elements because *Z* element TDV levels are generally quite low in the Niemegk Observatory time series, as shown in Figure 2.

[11] It has been established from the foregoing analyses of the global *ap* and the local TDV indicators that there exists a smooth, continuous variation in the level of daily geomagnetic activity from very quiet to very active. In other words, there exists no distinct threshold value of geomagnetic activity that obviously separates a quiet day from an active day. Given this continuum in geomagnetic activity, how does the typical daily variation on a quiet day differ from that of an active day?

[12] To explore this question, we looked again at the Niemegk Observatory time series from 1998. For each geomagnetic element, the yearlong hourly time series is broken into separate days extending from local midnight to 2300 LT. The TDV of each day is then computed. Upper λ^{+}_{TDV} and lower λ^{-}_{TDV} thresholds of TDV are then determined such that one-third (121 or 122) of the days, identified as Q (quiet) days, have TDV less than λ^{-}_{TDV}; one-third, identified as D (disturbed) days, have TDV greater than λ^{+}_{TDV}; and the remaining third (nominal, or N days) have TDV falling in the intermediate range $\lambda^{-}_{TDV} < \mathrm{TDV} < \lambda^{+}_{TDV}$.

[13] The result of this analysis is quite remarkable and is shown in Figure 4. It is seen that, for each geomagnetic element *X*, *Y* and *Z*, the general shape of the local time dependence of the daily variation is roughly the same, regardless of the geomagnetic activity level. In other words, the Q, N and D curves for a given geomagnetic element are similar apart from a multiplicative scale factor. The Q day curves show the smallest amplitude variation while the D day curves show the greatest amplitude variation, as expected. The similarity in the local time dependence of the Q, N and D curves suggests that a single physical mechanism operates at all levels of geomagnetic activity and repeats every day, generating the coherent stacks seen in Figure 4.

[14] Some of the active days are likely characterized by enhanced solar EUV irradiance and consequently powerfully built *Sq* vortices. Other active days can result from the energization of various non-*Sq* ionospheric and magnetospheric current systems [*Xu and Kamide*, 2004]. Large disturbances such as geomagnetic storms are caused by fluctuations in the magnetospheric ring current as a result of unsteady solar wind or interplanetary magnetic field conditions. Geomagnetic storms are episodic in nature and are therefore incoherent with respect to local time stacking. Geomagnetic pulsations are rapid enough that they are averaged out during the construction of the hourly observatory *X*, *Y* and *Z* means. On the other hand, solar EUV irradiance stacks coherently with local time, being strongest close to local noon and smallest close to local midnight.

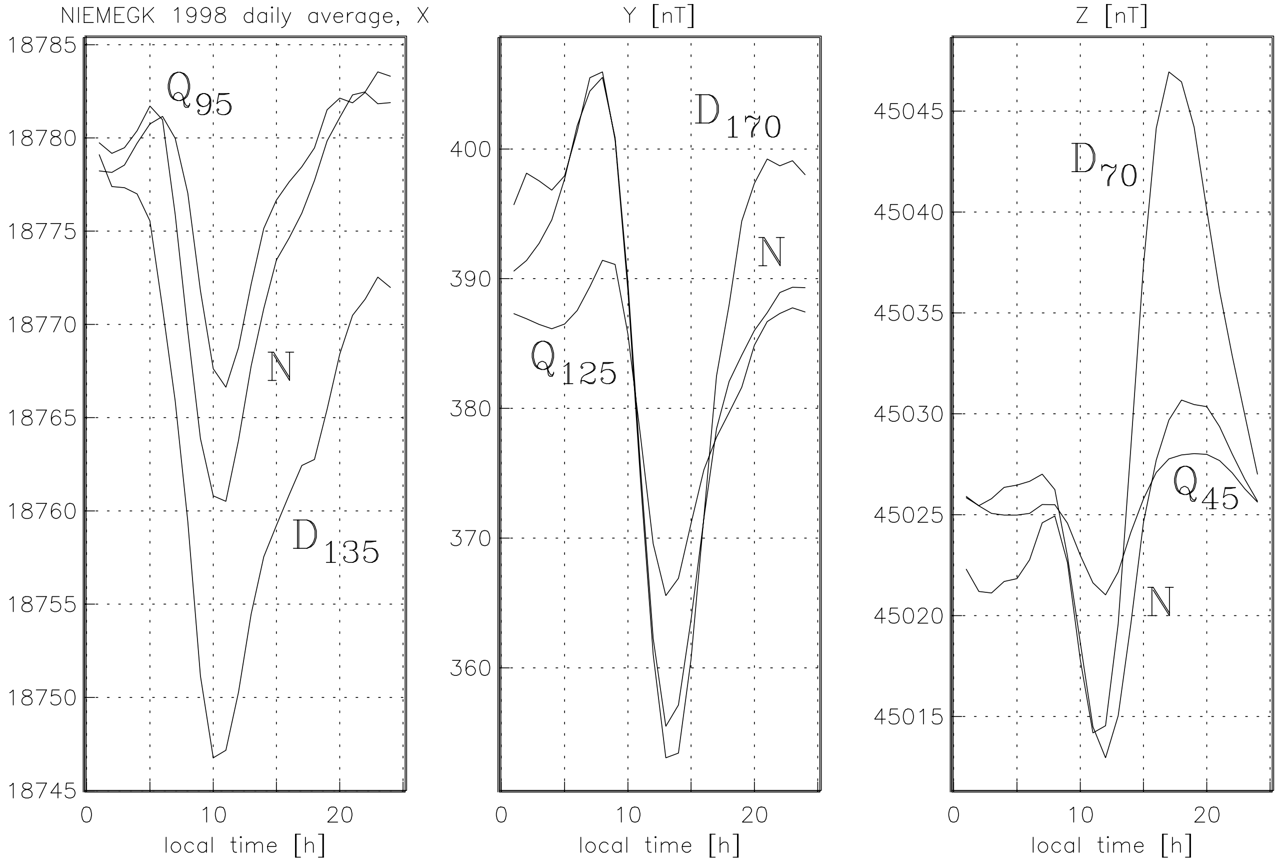

Figure 4. Average daily variation in geomagnetic elements (left) *X*, (middle) *Y*, and (right) *Z* for 1998 at Niemegk Observatory, sorted into quiet (Q), nominal (N), and active (D) day activity categories. The subscripts on the Q and D labels refer to the upper λ^{+}_{TDV} and lower λ^{-}_{TDV} threshold values in nT that separate the geomagnetic activity categories.

[15] The daily 10.7 cm solar radio flux index $F_{10.7}$ is sometimes used as a proxy for solar EUV variations [*Floyd et al.*, 2005]. For example, the ionospheric contribution to the comprehensive geomagnetic field model of *Sabaka et al.* [2002] is directly scaled to the $F_{10.7}$ cm radio flux index. While solar EUV irradiance is the dominant global energy source that creates the ionosphere, the limitations of the $F_{10.7}$ cm radio flux index as a proxy for the much shorter-wavelength 30–120 nm EUV radiation have been widely discussed in the literature. An in-depth study of the correlation between daily geomagnetic variations and solar EUV irradiance variations would provide valuable insight into the cause of the former but this exceeds the scope of the present article. Such a study is now feasible due to recently available measurements from the solar EUV experiment (SEE) which acquired irradiance data as part of the NASA TIMED spacecraft mission [*Woods et al.*, 2005].

3. Local Time Stacking

[16] Regular daily geomagnetic, or *Sq*, variations that are generated by ionospheric currents flowing in response to solar EUV irradiance should add coherently to local time stacks of geomagnetic time series acquired at any given ground-based magnetic observatory. The coherence is due to the fact that the observatory rotates once per day beneath the Sun-stationary *Sq* current vortices, which are energized primarily by the day-to-day varying solar EUV radiation input. In general, any current system that has a regular everyday pattern that waxes and wanes in step with the Sun's daily apparent trek across the sky above the observatory will add coherently to a local time stack. The *Sq* vortices and their below ground induced counterparts, to first order, will satisfy this requirement.

[17] Though the *Sq* vortices have the same general spatial configuration each day, their strength and the location of their focal points are modulated by both the day-to-day solar EUV variability and also the longer-term seasonal variation caused by inclination of Earth's orbit with respect to the ecliptic. The irregular solar daily disturbance, or D, field is generated by EUV radiation but it energizes non-*Sq* ionospheric electric currents that shift the regular pattern of the *Sq* vortices. The geomagnetic D field, owing to its irregular nature, should average to zero in a multiyear local time stack.

[18] The local time stacking procedure is very simple. First, hourly observatory magnetic *X*, *Y*, *Z* values from the observatory of interest are downloaded from the U.S. National Geophysical Data Center Web site http://spidr.ngdc.noaa.gov. Second, the data series are separated into calendar yearlong sequences, each non-leap-year sequence nominally consisting of 365 days/year × 24 hours/d =

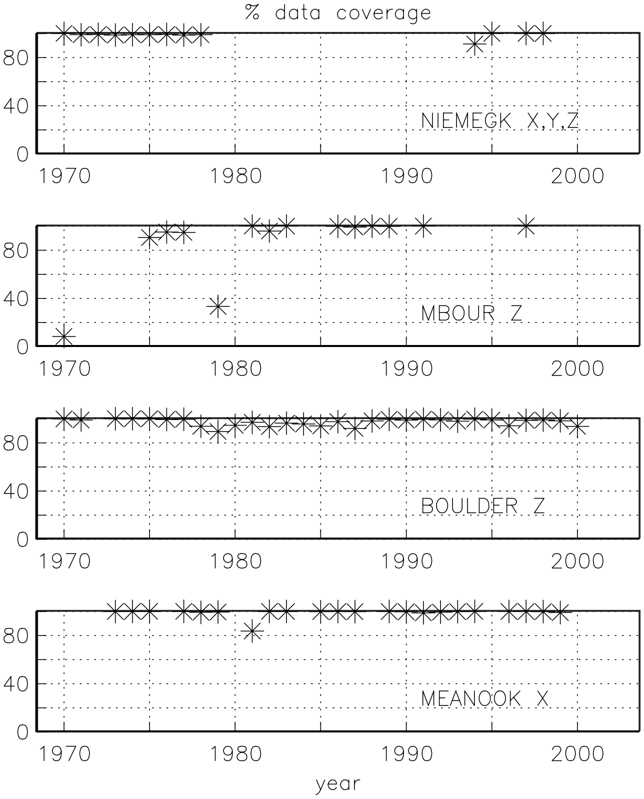

Figure 5. Data coverage for the geomagnetic data at Niemegk, Boulder, Mbour, and Meanook observatories between 1970 and 2002. The value 100.0 is full set of 8760 data points; 0.0 is no data.

8760 hourly values/yr, provided no data are missing. Third, the various yearlong time series are aligned beginning at New Year's Day, local midnight. Fourth, the mean of each yearlong time series is computed and subtracted. Fifth, each zero-mean, yearlong time series is detrended by fitting and removing a straight line. Finally, the different yearlong time series are summed together and averaged. This completes the local time stacking procedure.

[19] The most prominent multiyear trends in geomagnetic data are due to the 22-year solar cycle and main field secular variation [*Sabaka et al.*, 2002]. It is assumed that the year-by-year linear trend correction removes any bias in the stacked signal caused by these long-period geomagnetic variations. The detrended yearlong signals are assumed to be stationary and therefore gaps should present no particular problem. A gap simply reduces the number of data points used to compute the average signal at a particular local time. Leap years of 366 days are handled by simply excluding data from 31 December of that year. The leap-year effect is quite negligible since Earth returns every 4 years, less one day, to within 1 angular degree of the same position along the ecliptic and geomagnetic daily variations are not anticipated to be significantly dependent on Earth's position along the nearly circular ecliptic. The local time stacking procedure was applied to the X, Y, Z magnetic elements from Niemegk Observatory. The data coverage spans 1970–1978, 1994–1995, 1997–2000, see Figure 5.

[20] The multiyear local time stacked series is shown in Figures 6a–6c, broken down into separate months for convenient display since a 1-year hourly time series has far too many (8760) data points to show as a single continuous plot. The stacked signals clearly show the regular daily variation which presumably is caused by solar EUV irradiance along with induction in the solid Earth. Each 1-year series is zero-meaned and detrended prior to stacking. This procedure is important in order to remove bias associated with the geomagnetic secular variation, which at Niemegk between 1970 and 2002 amounts to some 25 nT/yr in the Z element, for example. As a result, the stacked 1-year series also has an overall zero mean, although the separate month-long series shown in Figures 6a–6c; do not necessarily have zero mean. The data coverage at Niemegk between 1970 and 2002 is only 38% complete, with 62% gaps. However, the final stacked series is 100% continuous, with 0% gaps, since over the course of 1970–2002 every hour of every calendar day featured at least one observation (actually, 7 or more) of a magnetic X element, similarly for Y and Z.

[21] Episodic disturbances such as geomagnetic storms stack incoherently with respect to local time, as noted above, which is why their oftentimes dramatic geomagnetic signature is conspicuously absent from Figures 6a–6c. There were two large storms and several moderate storms in 1998, as noted earlier in the text.

[22] As mentioned above, the signals that will stack coherently are those that have a peak and fall of exactly 1 solar day or its harmonics, observed at the Niemegk Observatory. Certainly the geomagnetic variations associated with the *Sq* current system (both external and induced) qualify. The lunar daily geomagnetic variation (so-called L signal) is of gravitational origin, rather than thermal origin as the solar daily variation. The L signal has a dominant semidiurnal period and a much smaller amplitude than the *Sq* signal [*Malin and Chapman*, 1970]. The L signal depends on lunar time so that it is out-of-phase with the *Sq* signal, which depends on solar time. Since the phase of the moon does not track with the transit of the Sun, the L signals do not stack coherently in local solar time.

[23] The seasonal variation, because it has exactly the 1-year period, also appears in the stack (see Figures 6a–6c). The seasonal variation stays in the data because the stack is based on exact, 1-year-long series. A 300-day or a 400-day stack, for example, would have stacked out the seasonal variation. Finally, the 11-year solar cycle should add a small quasi-DC bias to the stack, but this is of no great concern because the means are zeroed prior to stacking. Essentially, the solar cycle effect is removed along with the secular variation.

4. Analysis of the Stacked Time Series

[24] To check the robustness of the stack, several partially stacked, month-long segments from August are shown in Figure 7. Figure 7 shows that a 4-year stack (Figure 7 (middle), in gray) is not sufficient to accurately represent solar daily variations to within 5 nT of the full stack (Figure 7, in black) at all times during the day. The 9-year stack (Figure 7 (top), in gray), on the other hand, shows small <5 nT deviations from the full stack, with the

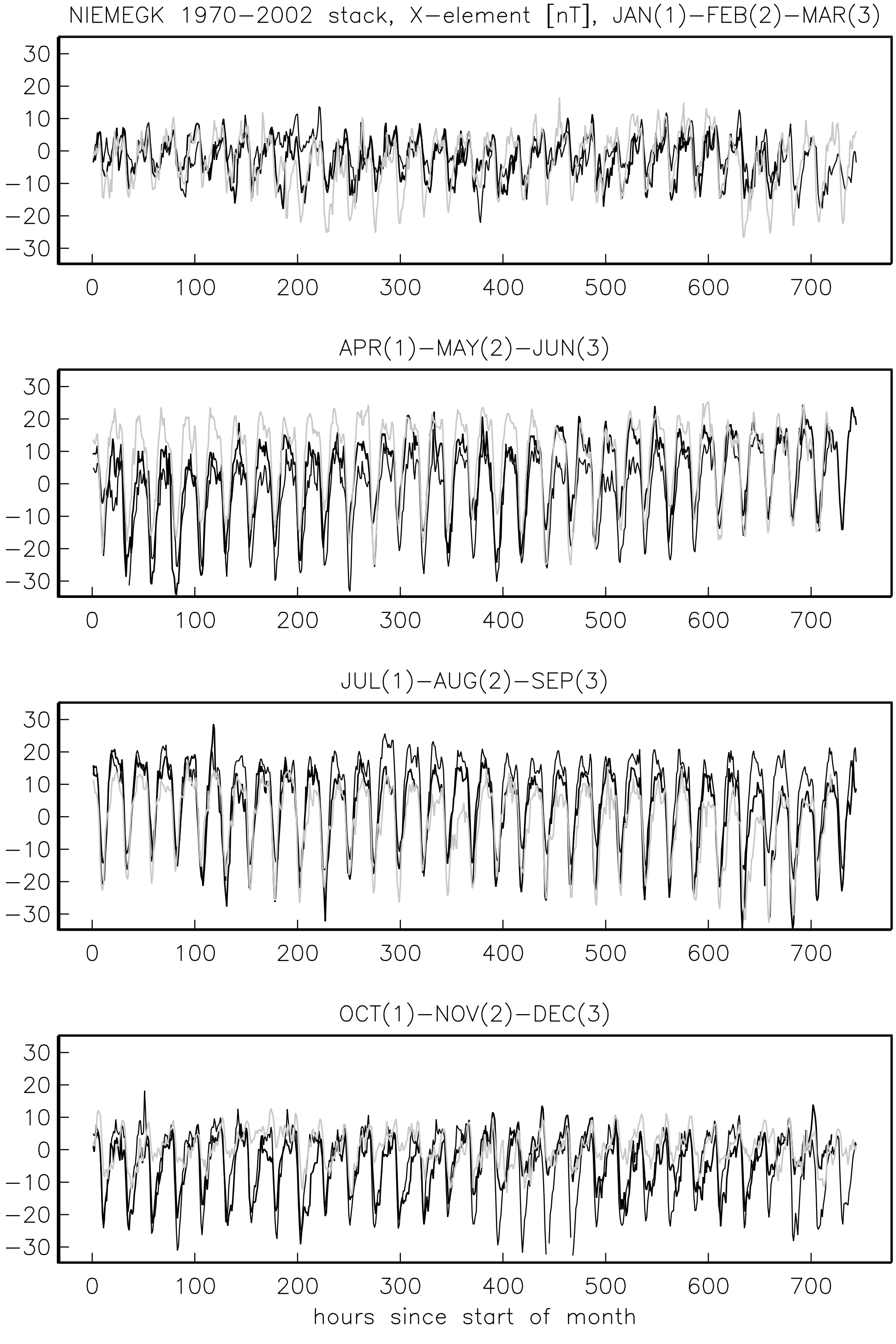

Figure 6a. A continuous 1-year-long times series of hourly geomagnetic *X* element values [nT] obtained by stacking zero-mean detrended time series from individual years, as recorded at Niemegk Observatory between 1970 and 2002. Labels 1, 2, and 3 in parentheses after month names refers to the thin black, heavy, and gray curves, respectively. The time series is displayed month-by-month for the convenience of display. To highlight how well geomagnetic storms are removed, notice that the effects of the two largest geomagnetic storms of 1998 with *Dst* > |200 nT|, occurring in early May and late September, are not evident in the stack.

largest deviations occurring during the late afternoons at which the *Z* element reaches its daily maximum value. A high-quality coherent stack of solar daily variations can result when data from alternate years are used, as shown in gray in Figure 7 (bottom). Figure 7 (bottom) confirms that the quality of the stack does not depend fortuitously on a data selection from a contiguous period of years.

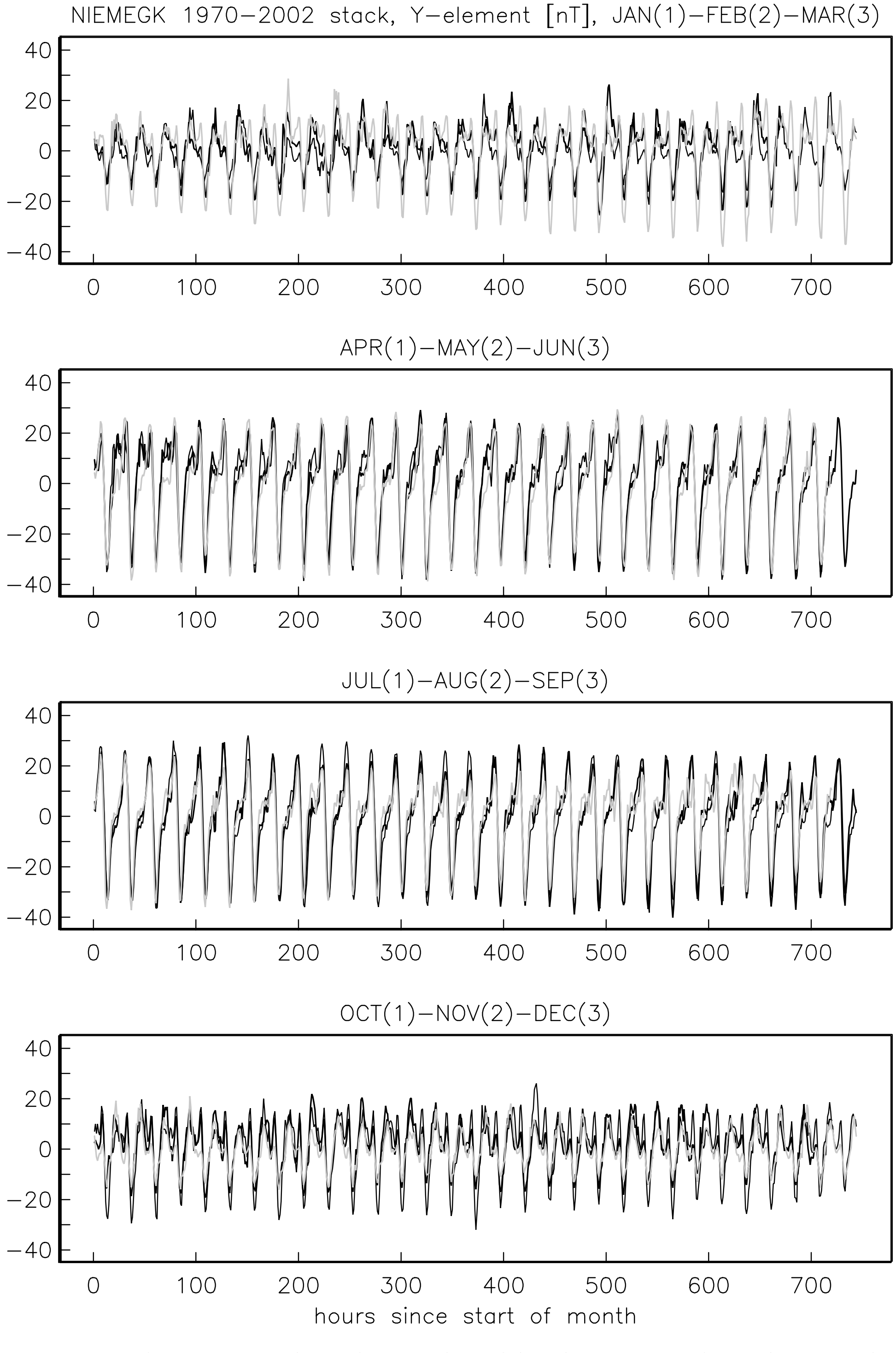

Figure 6b. A continuous 1-year-long times series of hourly geomagnetic *Y* element values [nT] obtained by stacking zero-mean detrended time series from individual years, as recorded at Niemegk Observatory between 1970 and 2002.

[25] The power spectra of unstacked 1-year time series from 1998 (Figure 8, top) and 1999 (Figure 8, bottom) and the fully stacked time series from 1970 to 2002 are shown in Figure 8. Strong lines in the spectra are seen at the 1-day period and its harmonics. The diurnal line occurs at frequency 0.042 cph; the semidiurnal line is next at 0.083 cph, and so forth. The stacked spectrum has a much greater signal-to-noise ratio compared to the 1998 or 1999 spectrum, as measured by the amplitudes of the diurnal and harmonic lines with respect to the background continuum. The diurnal line and up to 7 harmonics are readily detected as the black lines in the stacked spectrum whereas only 3–4 harmonics are visible in the 1998 or 1999 spectrum before the spectral lines are lost within the background continuum.

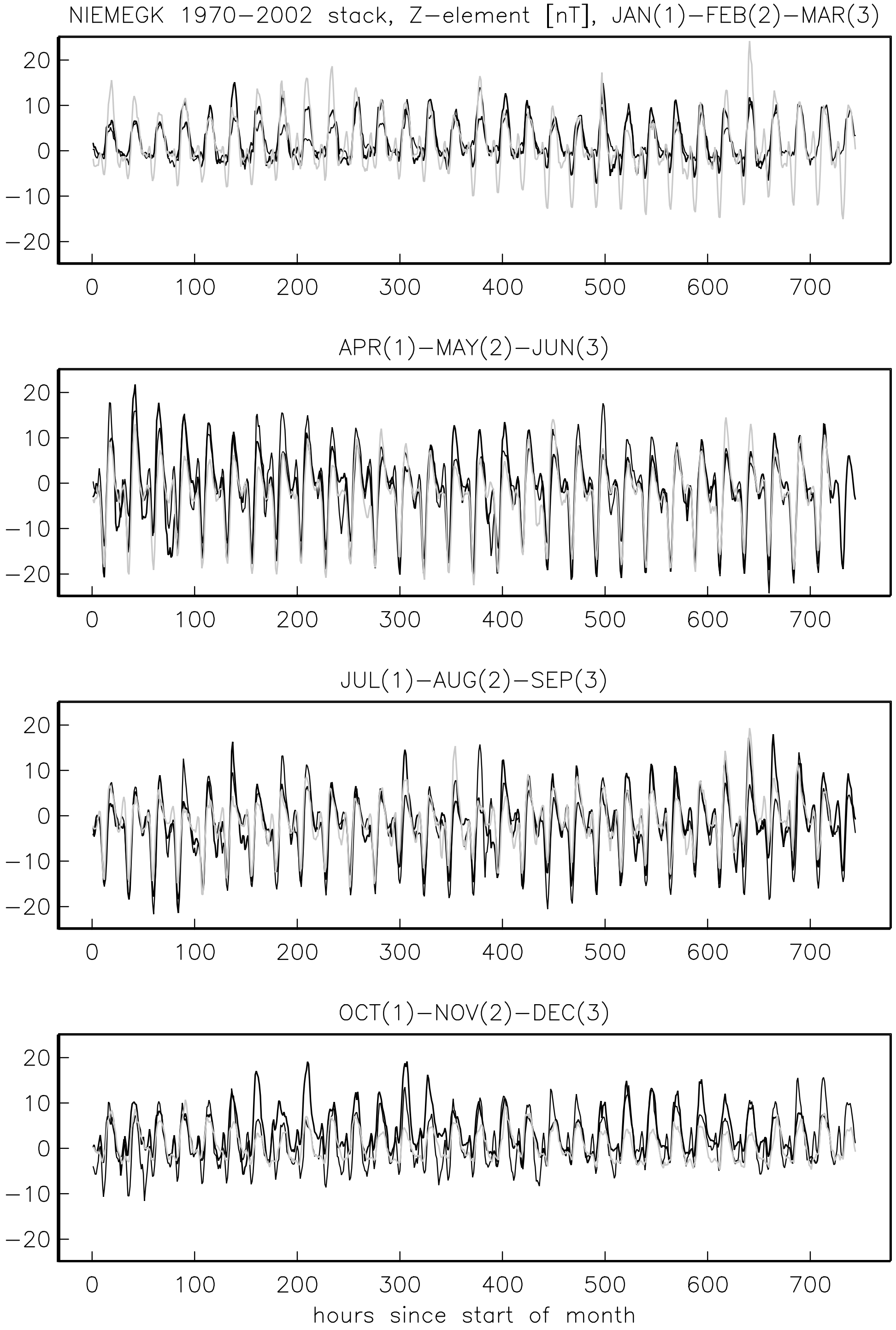

Figure 6c. A continuous 1-year-long times series of hourly geomagnetic Z element values [nT] obtained by stacking zero-mean detrended time series from individual years, as recorded at Niemegk Observatory between 1970 and 2002.

[26] A good illustration of the effect of local time stacking on attenuating irregular daily geomagnetic variations is shown in Figure 9. Figure 9 (top) shows hourly time series of the magnetic Z element at Niemegk for 2 months in 1998. Each monthly segment appears to have a regular daily variation overprinted by irregular fluctuations of 100 nT or more. The Schumcker Q* days (*ap* threshold of 60 nT) are indicated by the asterisks; there are 7 Q* days in January 1998 and just two Q* days in August 1998. The remaining days are classified as active and the data on these days traditionally would be discarded. However, as shown in Figure 9 (bottom), the full 1970–2002 stack has largely

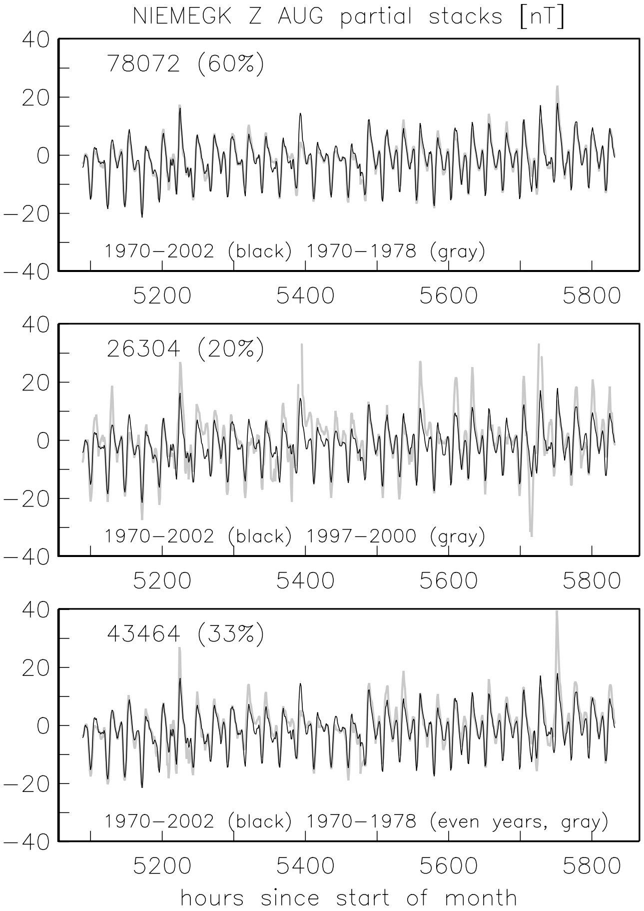

Figure 7. Partial stacks of the Niemegk hourly magnetic *Z* element time series, shown for the August month-long segment. The numbers at the top left indicate the data used, both as the number of values and as a percentage of the full data set. (top) Full 15-year stack (black) compared to a 9-year partial stack (gray) for 1970–1978. The partial stack used 78072 data values, or 60% of the entire data set. (middle) A 4-year partial stack for 1997–2000, which used 20% of the entire data set. (bottom) A 5-year partial stack for alternating years beginning with 1970, using 33% of the entire data set.

attenuated the 1998 irregular variations. The stacked day-to-day variations are much more regular in appearance and do not exceed ±20 nT.

[27] The regular nature of the full yearlong stack is examined in Figure 10. The Niemegk TDV signal for 1998 is shown in gray. The large spikes up to almost 500 nT are caused by irregular geomagnetic fluctuations of various causes including day-to-day solar EUV irradiance and episodic solar wind variability. The full-stack Niemegk TDV signal, shown in black, has a greatly reduced day-to-day variability, with no large spikes exceeding 100 nT. In effect, Figure 10 shows that multiyear local time stacking has the potential to "turn every day into a quiet day." Note that the seasonal variation of the single-year TDV signal is preserved in the full-stack TDV signal, as expected, since TDV is tied to EUV irradiance which stacks coherently in local time and is largest during the summer months.

[28] To ensure that the local time stacking concept applies to geomagnetic observatory data in general, and not just Niegmek, we stacked yearlong time series of the magnetic *Z* element at Boulder (40.14°N, 254.76°E) and Mbour (14.40°N, 343.02°E) and the *X* component at Meanook (54.62°N, 246.27°E); the data coverage between 1970 and 2002 for these stations is shown in Figure 5. The results are shown in Figures 11a–11c. As in the case of Niemegk Observatory, the multiyear local time stacked *X* and *Z* element time series are dominated by regular solar daily variations. The shape of the average solar daily variation is different at each station, relecting its relative positioning with respect to the causative *Sq* current vortices. A seasonal variation can also be discerned in the stacked time series; as expected, the seasonal variation is larger at Boulder and Meanook compared to Mbour. The latter observatory is situated closest to the equator. There are few irregular

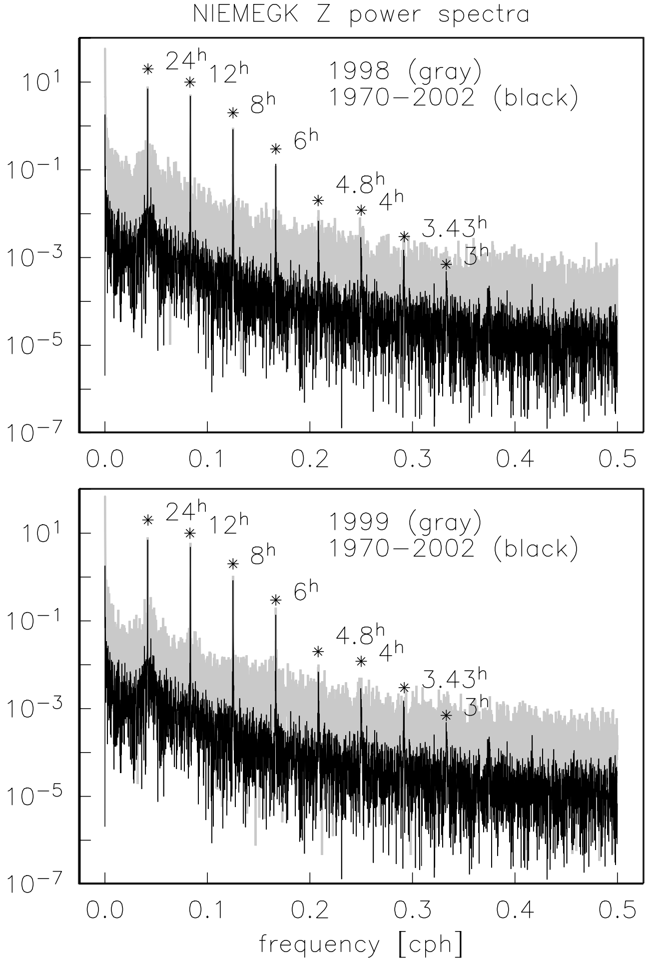

Figure 8. Power spectra of the Niemegk hourly magnetic *Z* element time series for the single year of (top) 1998 (gray) and (bottom) 1999 (gray) and for all available data between 1970 and 2002 (black). The harmonic lines at 24, 12, 8, and 6 hours in the single-year spectra have approximately the same amplitude as those of the full-stacked spectrum, although the gray lines are difficult to see behind the black lines in this plot.

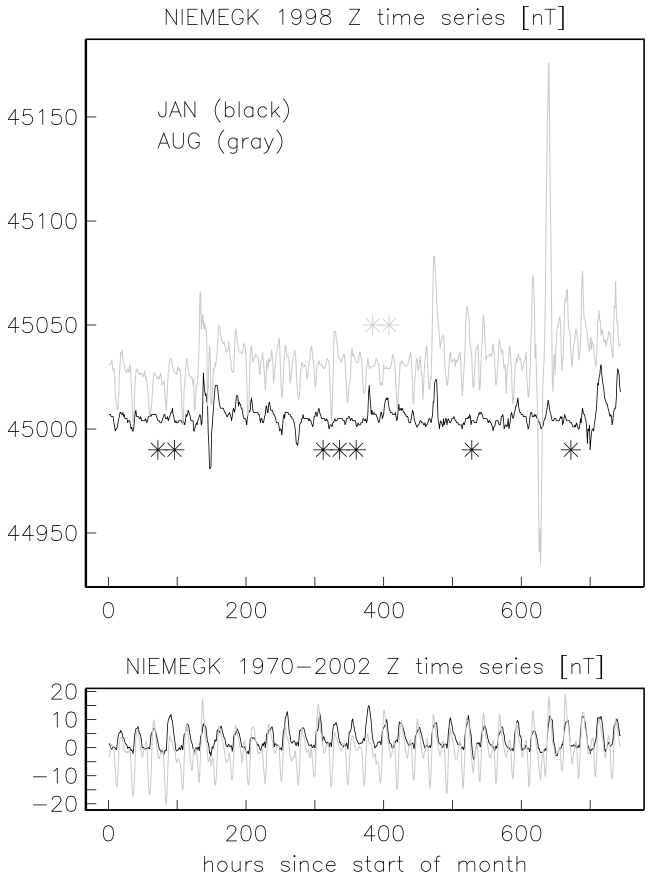

Figure 9. (top) Magnetic *Z* element at Niemegk for months January and August in 1998. The asterisks denote Q* quiet days. (bottom) January and August monthly segments of the fully stacked Niemegk 1970–2002 time series.

fluctuations of any periodicity in the local time stacks at the three observatories.

5. Discussion

[29] The major assumption underlying the validity of the multiyear local time stacking concept is that irregular geomagnetic variations get stacked out and that the *Sq* signal stacks coherently. The analysis in this paper shows that irregular geomagnetic variations are greatly attenuated by long-term local time stacking.

[30] The internal signal caused by induction of electric currents in the solid Earth owing to irregular external fluctuations should be stacked out along with the external irregular signal. Remaining in the stack, however, should be the internal signal owing to the regular external variations. This is the induced *Sq* signal.

[31] The electric currents induced in the solid Earth by the external *Sq* current vortices have a complicated spatiotemporal morphology that is largely unknown due to its dependence on the underlying 3-D electrical conductivity distribution down as far as lower mantle depths beneath a given observatory. The regular daily variation is essentially a geomagnetic tide. Just as the spatially complicated hydrodynamic interaction between the shallow ocean floor and ocean tides has a regular component that repeats every day, to first order, so too should the pattern of induced electric currents repeat daily in response to the regular solar geomagnetic daily variation. There will be additional currents induced in the solid Earth caused by irregular external variations and regular variations of other periodicities. However, the superposition principle states that electromagnetic induction is linear with respect to the source distribution. This implies that the total internal signal shall be the sum of the internal signal due to regular source variations plus the internal signal due to irregular source variations. Therefore it is anticipated that the induced regular signal stacks coherently while the induced irregular signal stacks out.

[32] The foregoing discussion is not meant to indicate that the induced regular signal is always in-phase with the external regular signal. To the contrary, the basic physics of electromagnetic induction in conductive media shows that there is always a definite phase lag between the external and induced currents. The important facts to keep in mind are that the induced currents flow in the same basic pattern that reproduces itself each day and that the induced signal has the same one-solar-day periodicity as the *Sq* external signal. Under the above mentioned pair of conditions, the induced *Sq* signal should stack coherently in local time. A determination of the underlying mantle electrical conductivity structure that causes the induced *Sq* signal can be investigated in the frequency domain using 1-D and 3-D forward modeling codes [*Kuvshinov et al.*, 1999; *Velimsky and Martinec*, 2005] that have recently been published.

[33] We have shown that local time stacking has greatly attenuated the amplitude of irregular geomagnetic time variations, while the regular solar daily variations stack

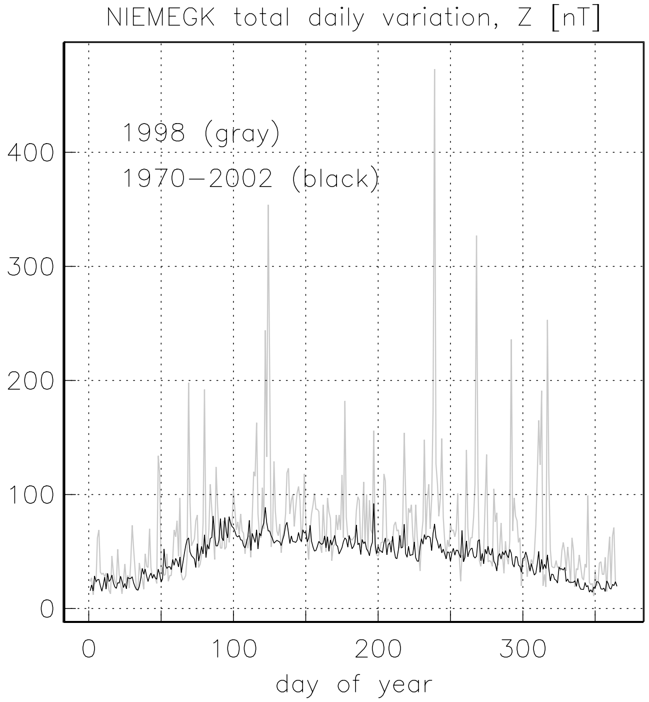

Figure 10. Total daily variation of the Niemegk *Z* element for single year 1998 (gray) and the full 1970–2002 stack (black).

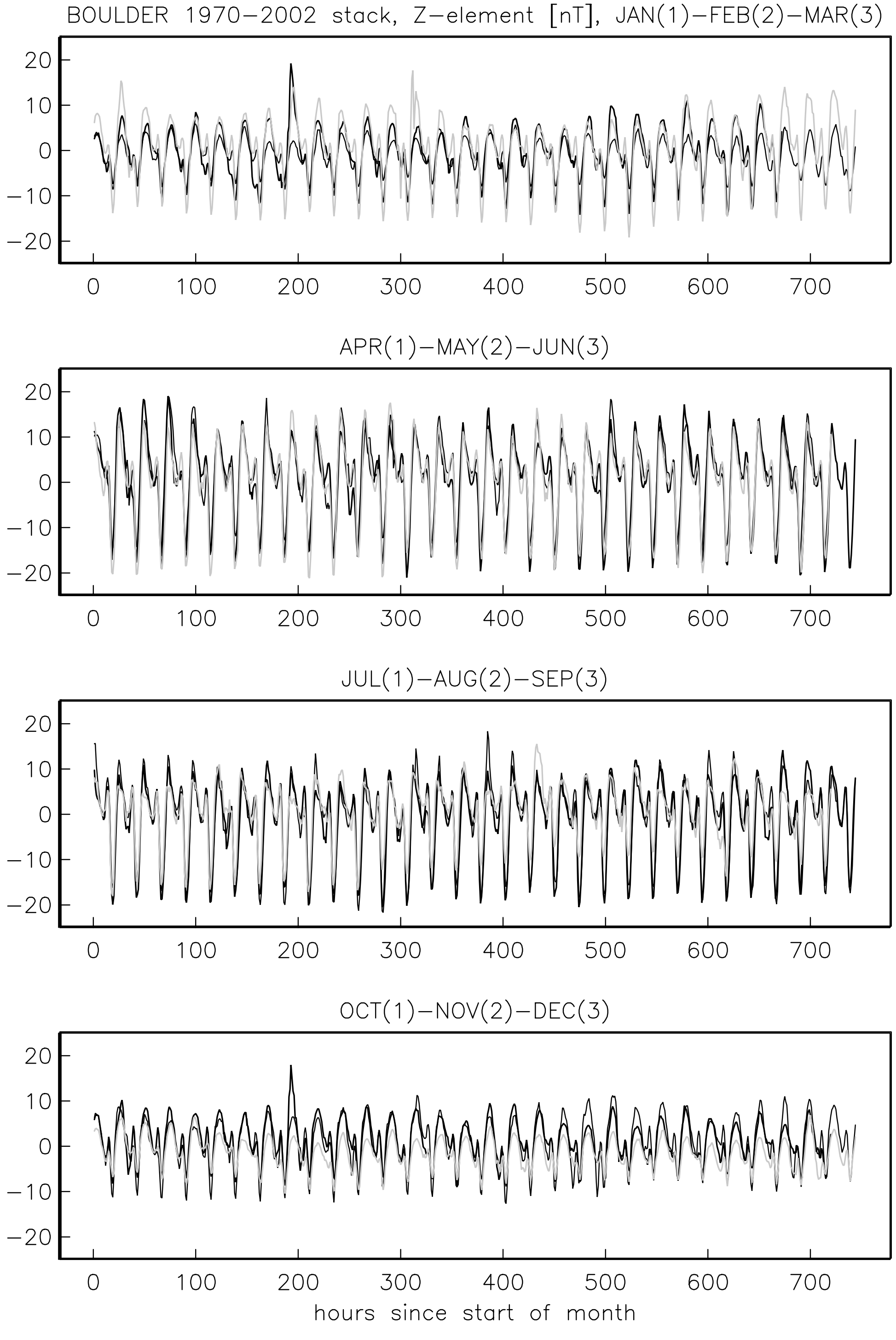

Figure 11a. A continuous 1-year-long times series of hourly geomagnetic Z element values [nT] obtained by stacking zero-mean detrended time series from individual years, as recorded at Boulder Observatory between 1970 and 2002. Labels 1, 2, and 3 in parentheses are as in Figure 8. The time series is displayed month-by-month for the convenience of display.

coherently. It can be assumed that the irregular variations are randomly distributed in local time since they do not repeat themselves every day, nor do they necessarily track the rise and fall of the sun in the sky above a given observatory. Under this assumption, the amplitude of the irregular variations should decrease with $\sqrt{n}$, where n is the stack number. In this paper we stacked hourly sampled data series, each series being nominally 1 year long. The benefit of such local time stacking scales with the square root of the number of years in which geomagnetic observatory data are available to contribute to the stack. A factor of two reduction in the signal-to-noise (S/N) ratio of the regular

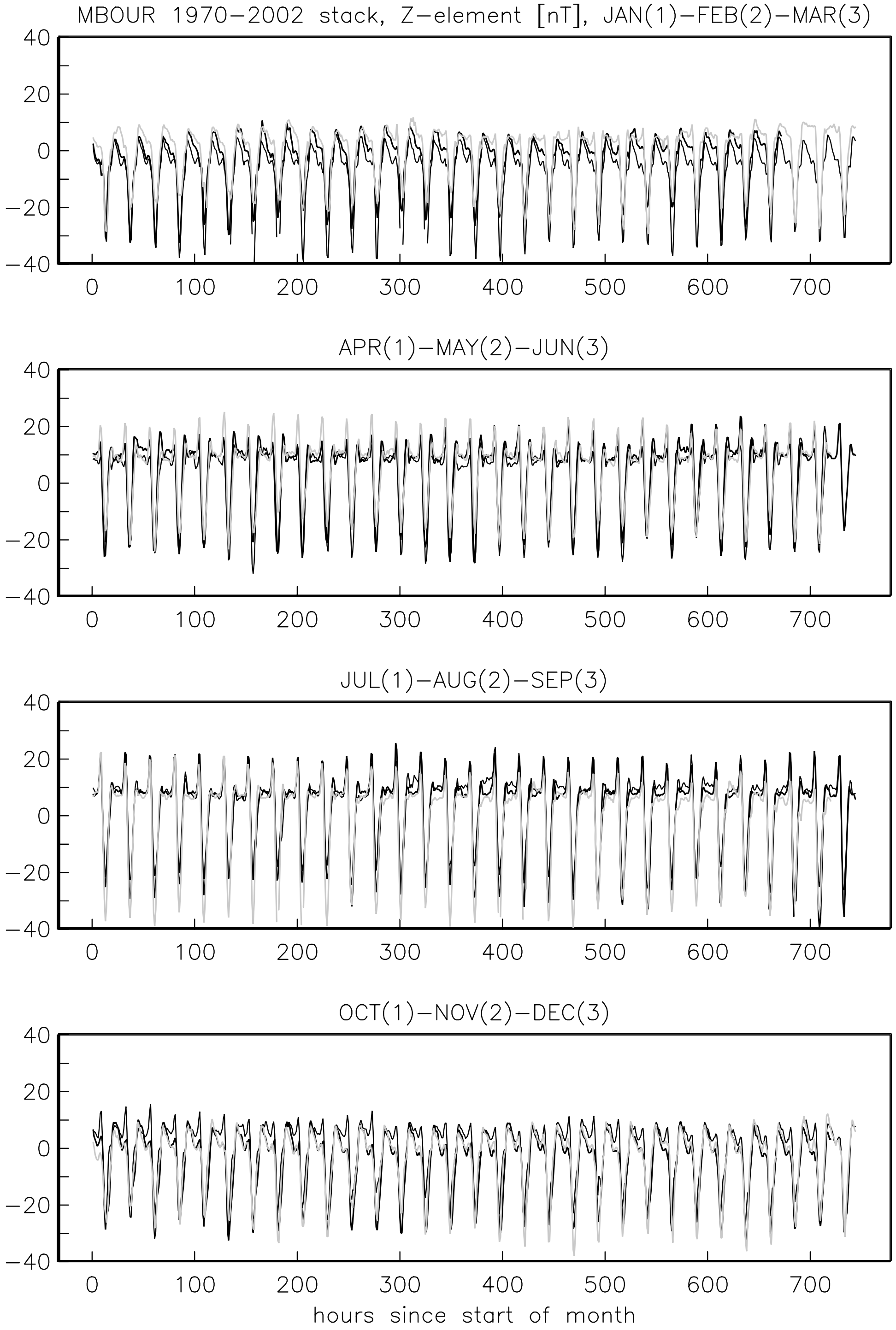

Figure 11b. A continuous 1-year-long times series of hourly geomagnetic *Z* element values [nT] obtained by stacking zero-mean detrended time series from individual years, as recorded at Mbour Observatory between 1970 and 2002.

solar daily variations for a 15-year stack (as analyzed in this paper) would require the continuous acquisition of 60 (i.e., 45 additional) years worth of data. This is a great illustration of the law of diminishing returns. It is also a testimony to the diligent efforts of past and present generations of geomagneticians who have ensured the existence and availability of long-term, high-quality, continuous observatory data for our present and others' future use.

[34] Traditional *Sq* induction studies analyze short, disjoint segments of geomagnetic observatory data in the frequency domain using arbitrary criteria to identify suitably quiet days. Our local time stacking procedure produces instead a 1-year-long continuous *Sq* signal that reflects the long-term average of the regular geomagnetic *X*, *Y*, *Z* daily variations at a given observatory. The stacked *Sq* signals provide a robust estimate of the average primary and

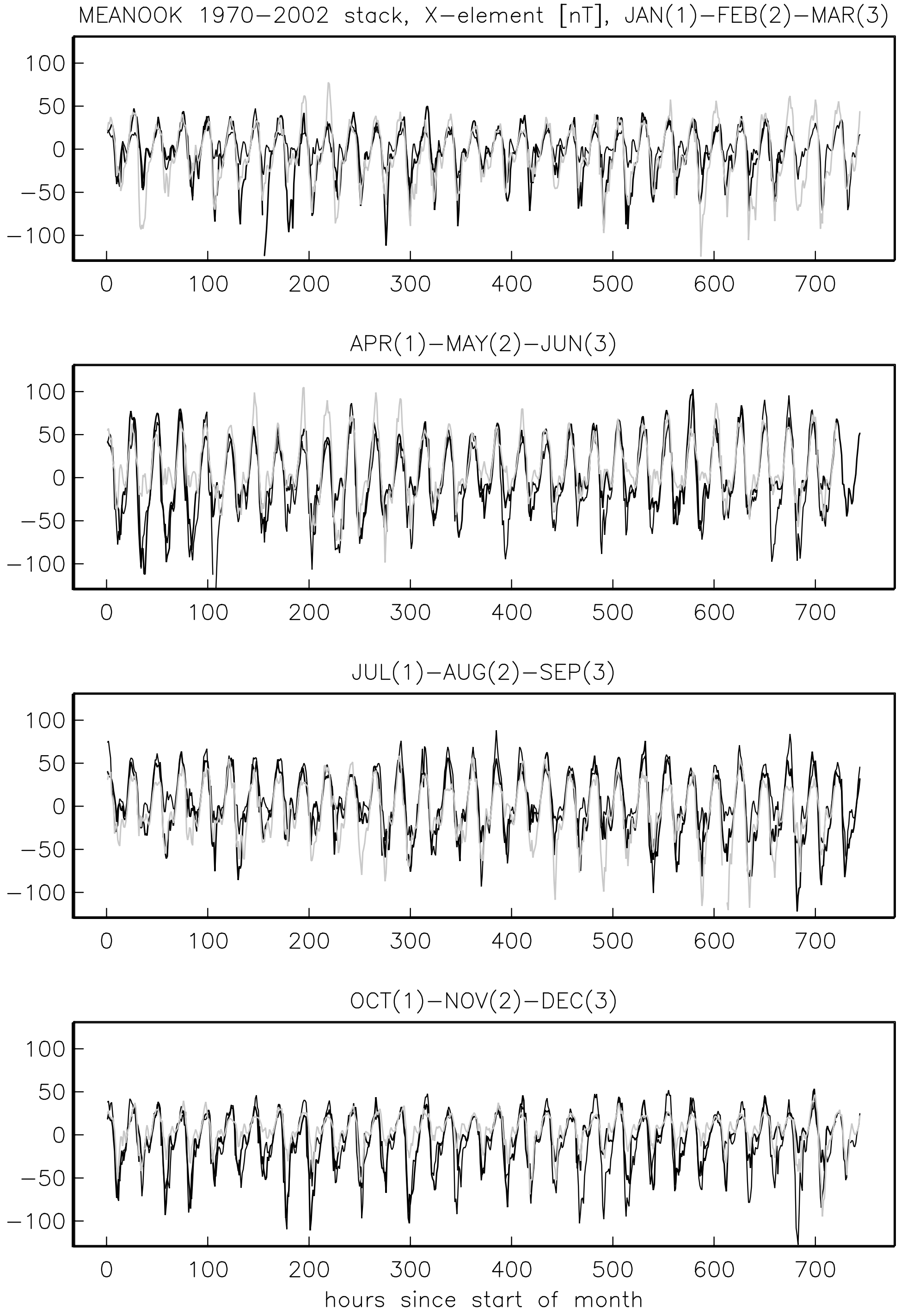

Figure 11c. a. A continuous 1-year-long times series of hourly geomagnetic *Z* element values [nT] obtained by stacking zero-mean detrended time series from individual years, as recorded at Boulder Observatory between 1970 and 2002. Labels 1, 2, and 3 in parentheses are as in Figure 8. The time series is displayed month-by-month for the convenience of display. Figure 11b. A continuous 1-year-long times series of hourly geomagnetic *Z* element values [nT] obtained by stacking zero-mean detrended time series from individual years, as recorded at Mbour Observatory between 1970 and 2002. Figure 11c. A continuous 1-year-long times series of hourly geomagnetic *X* element values [nT] obtained by stacking zero-mean detrended time series from individual years, as recorded at Meanook Observatory between 1970 and 2002.

induced components, with episodic and irregular contributions largely removed. Local time stacked *Sq* signals from multiple observatories could be used to develop reliable regional-scale and possibly global-scale time domain forward modeling and inversion of the induced component in terms of an underlying 3-D mantle conductivity model [*Hamano*, 2002; *Velimsky and Martinec*, 2005].

[35] We note that the seasonal variation persists in the local time stacked *Sq* signals. The *Sq* current vortices shift positions according to season which implies that electromagnetic induction in the Earth shall sample somewhat different subsurface regions in the mantle according to the season. The seasonal variation can be naturally accommodated in time domain modeling of *Sq* induction in the heterogeneous Earth using the local time stacked signals.

[36] Global maps of the lithospheric magnetic field based on satellite-borne measurements now achieve spherical harmonic degree 65–90 in spatial resolution. The greatest uncertainty in constructing the lithospheric maps is properly accounting for the contribution of external time-varying fields and their induced counterparts. The CM4 comprehensive model [*Sabaka et al.*, 2004] approach coestimates the parameters of a simplified external and induced ionospheric field model. The MF4 model [*Maus et al.*, 2006] uses nighttime data only to avoid the magnetic field of the *Sq* current system. We suggest that multiyear local time stacked *Sq* signals from multiple observatories could be used for greatly improved characterization of the *Sq* signals in global-scale lithospheric field modeling.

6. Conclusion

[37] A long-term, local time stack of hourly *X*, *Y* and *Z* elements recorded at a geomagnetic observatory attenuates irregular signals and also magnetic fields that are caused by current systems which are not of solar-daily periodicity, including episodic geomagnetic storm events. The resultant stacked time series is dominated by the regular solar daily variation, with few if any gaps, and can be used for improved *Sq* induction studies and comprehensive geomagnetic field modeling. The local time stacking is also advantageous in that quiet and active days do not need to be identified. This is important due to the difficulty in assigning a meaningful quiet/active threshold value. The induced *Sq* signal should stack coherently in local time; however, detailed 3-D forward modeling of induction in the heterogeneous solid Earth is required to quantitatively relate the day-to-day variability of the *Sq* current vortex strength with the irregular induced *Sq* signal. While it is still not possible to isolate the actual transient signal of the external source from geomagnetic observatory data, the local time stacking procedure advocated here removes much of the confounding day-to-day variability in the combined external plus induced signal.

[38] **Acknowledgments.** I thank Jakub Velimsky and an anonymous reviewer for helpful suggestions. The data used in this study were downloaded from http://spidr.ngdc.noaa.gov using the Space Physics Interactive Data Resource (SPIDR) provided by the U.S. National Geophysical Data Center.

References

Campbell, W. H. (1989), The regular geomagnetic-field variations during solar quiet conditions, in *Geomagnetism*, vol. 3, edited by J. A. Jacobs, pp. 385–460, Elsevier, New York.

Floyd, L., J. Newmark, J. Cook, L. Herring, and D. McMullin (2005), Solar EUV and UV spectral irradiances and solar indices, *J. Atmos. Sol. Terr. Phys.*, *67*, 3–15.

Hamano, Y. (2002), A new time-domain approach to the electromagnetic induction problem in a three-dimensional heterogeneous Earth, *Geophys. J. Int.*, *150*, 753–769.

Kuvshinov, A. V., D. B. Avdeev, and O. V. Pankratov (1999), Global induction by *Sq* and *Dst* sources in the presence of oceans: Bimodal solutions for non-uniform spherical surface shells above radially symmetric earth models in comparison to observations, *Geophys. J. Int.*, *137*, 630–650.

Langel, R. A., and W. J. Hinze (1998), *The Magnetic Field of the Earth's Lithosphere: The Satellite Perspective*, Cambridge Univ. Press, New York.

Malin, S. R. C., and S. Chapman (1970), The determination of lunar daily geophysical variations by the Chapman-Miller method, *Geophys. J. R. Astron. Soc.*, *19*, 15–35.

Maus, S., M. Rother, K. Hemant, C. Stolle, H. Luhr, A. Kuvshinov, and N. Olsem (2006), Earth's lithospheric magnetic field determined to spherical harmonic degree 90 from CHAMP satellite measurements, *Geophys. J. Int.*, *164*, 319–330.

Sabaka, T. J., N. Olsen, and R. A. Langel (2002), A comprehensive model of the quiet-time, near-Earth magnetic field: Phase 3, *Geophys. J. Int.*, *151*, 32–68.

Sabaka, T. J., N. Olsen, and M. E. Purucker (2004), Extending comprehensive models of the Earth's magnetic field with Oersted and CHAMP data, *Geophys. J. Int.*, *159*, 521–547.

Schmucker, U. (1999), A spherical harmonic analysis of solar daily variations in the years 1964–1965: Response estimates and source fields for global induction - I. Methods, *Geophys. J. Int.*, *136*, 439–454.

Velimsky, J., and Z. Martinec (2005), Time-domain, spherical harmonic-finite element approach to transient three-dimensional geomagnetic induction in a spherical heterogeneous Earth, *Geophys. J. Int.*, *161*, 81–101.

Volland, H. (1984), *Atmospheric Electrodynamics*, Springer, New York.

Woods, T. N., F. G. Eparvier, S. M. Bailey, P. C. Chamberlin, J. Lean, G. J. Rottman, S. C. Solomon, W. K. Tobiska, and D. L. Woodraska (2005), Solar EUV Experiment (SEE): Mission overview and first results, *J. Geophys. Res.*, *110*, A01312, doi:10.1029/2004JA010765.

Xu, W., and Y. Kamide (2004), Decomposition of daily geomagnetic variations by using method of natural orthogonal component, *J. Geophys. Res.*, *109*, A05218, doi:10.1029/2003JA010216.

M. E. Everett, Department of Geology and Geophysics, Texas A&M University, College Station, TX 77845, USA. (everett@geo.tamu.edu)