GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L08203, doi:10.1029/2006GL028764, 2007

Suggestive correlations between the brightness of Neptune, solar variability, and Earth's temperature

H. B. Hammel[1] and G. W. Lockwood[2]

Received 14 November 2006; revised 16 January 2007; accepted 15 March 2007; published 19 April 2007.

[1] Long-term photometric measurements of Neptune show variations of brightness over half a century. Seasonal change in Neptune's atmosphere may partially explain a general rise in the long-term light curve, but cannot explain its detailed variations. This leads us to consider the possibility of solar-driven changes, *i.e.*, changes incurred by innate solar variability perhaps coupled with changing seasonal insolation. Although correlations between Neptune's brightness and Earth's temperature anomaly—and between Neptune and two models of solar variability—are visually compelling, at this time they are not statistically significant due to the limited degrees of freedom of the various time series. Nevertheless, the striking similarity of the temporal patterns of variation should not be ignored simply because of low formal statistical significance. If changing brightnesses and temperatures of two different planets are correlated, then some planetary climate changes may be due to variations in the solar system environment. **Citation:** Hammel, H. B., and G. W. Lockwood (2007), Suggestive correlations between the brightness of Neptune, solar variability, and Earth's temperature, *Geophys. Res. Lett.*, *34*, L08203, doi:10.1029/2006GL028764.

1. Introduction

[2] The visible reflectivity of the giant planet Neptune varies on decadal timescales [*Lockwood and Jerzykiewicz*, 2006 (hereinafter referred to as LJ06); *Hammel and Lockwood*, 2007 (hereinafter referred to as HL07)]. The underlying cause of the variations is not understood. The long timescales involved pose a particular challenge: a single trip around the Sun for this planet requires 164.8 terrestrial years. To make a meaningful assessment of seasonal variability, a consistent data set must exist over many decades. Fortunately, several such data sets exist.

[3] One long-term (1950–2006) set of Neptune observations is visible-wavelength photometry from Lowell Observatory at 551 nm (Strömgren y; Johnson V transformed to y) and 472 nm (Strömgren b; Johnson B transformed to b). These data (Figures 1a and 1b) were corrected to a heliocentric opposition distance of 30.071 AU and geocentric distance of 29.071 AU [*Lockwood and Thompson*, 2002; LJ06]. Variations in brightness due to changes in the apparent area of Neptune's oblate disk as a function of its year are negligible at 0.5% (smaller than the triangles in Figure 1). Other sources of error (including corrections for differential extinction in the Earth's atmosphere and for uncertainties of comparison star magnitudes) sum in quadrature to less than 1% (LJ06).

[4] Beginning in the mid 1980s, a steady rise in brightness dominated the lightcurves (Figures 1a and 1b). In a different long-term data set, Neptune's mid-infrared ethane emission rose steadily over the past two decades (Figure 1c) modeled as an increase in Neptune's globally-integrated stratospheric temperature [*Hammel et al.*, 2006]. Figure 1 also includes physical ephemeris data for Neptune over the past decades. Because Neptune's rotation axis is tilted 29° with respect to its orbit, the sub-solar latitude (where the Sun is directly overhead on the planet) varies over the course of the planet's year; it reached southern summer solstice in 2005 (Figure 1d). Heliocentric distance reached a maximum in the early 1960s (Figure 1e, which pertains specifically to insolation at Neptune since the planet's apparent brightness already has been adjusted to a fixed distance).

2. Neptune's Long-Term Disk-Integrated Variability

[5] *Sromovsky et al.* [2003] interpreted Neptune's brightening since the mid 1980s as evidence for a lagged seasonal response to variations induced by Neptune's changing sub-solar latitude as a function of its year; their model is shown as a dotted line in Figure 1a. However, as is seen in Figure 1 and discussed in detail by LJ06 and HL07, the pre-1970 photometry is inconsistent with this particular seasonal interpretation. We therefore seek an alternative to the published simple model of Neptune's long-term secular brightening, in particular an explanation that includes the data between 1950 and 1966.

[6] Although seasonal changes in the viewing angle (sub-solar latitude; Figure 1d) could be responsible for some of the brightening trend, there must be an additional influence because Neptune continued to brighten steadily as it reached southern summer solstice in 2005. Likewise, for recent decades an atmospheric effect driven by varying heliocentric distance (Figure 1e) is not ruled out *per se* (e.g., variability in atmospheric aerosol content caused by insolation changes), but the earliest decade of observation does not support such a supposition. Furthermore, both heliocentric distance and sub-solar latitude vary smoothly (Figures 1d and 1e), while Neptune's brightness does not (see data from 1960 through 1980 in Figures 1a and 1b). Additional factors, in Neptune's atmosphere or in the external solar system environment, must therefore be at work.

[7] We explored various solar-geophysical and terrestrial records in search of a pattern match to Neptune's variability. Figure 2 shows Neptune's b photometric lightcurve along

---

[1] Space Science Institute, Boulder, Colorado, USA.
[2] Lowell Observatory, Flagstaff, Arizona, USA.

0094-8276/07/2006GL028764$05.00

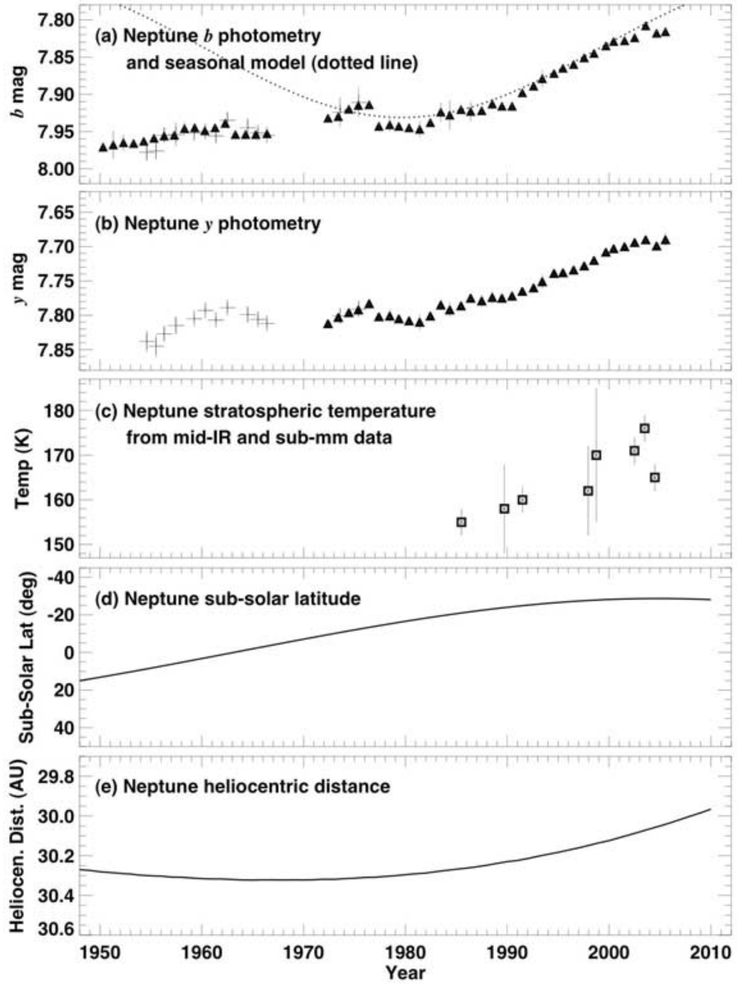

Figure 1. Long-term variations of Neptune. (a) Disk-integrated photometry of Neptune at Strömgren *b* (LJ06, HL07), along with the proposed seasonal model of *Sromovsky et al.* [2003] (dotted line). Solid triangles before 1970 are differential *B* magnitudes and plus signs are two-color *B* magnitudes; both were transformed to *b* magnitudes. Solid triangles after 1970 are *b* magnitudes. (b) Disk-integrated photometry of Neptune at Strömgren *y* (LJ06). Plus signs are two-color *V* magnitudes transformed to *y* magnitudes; solid triangles are *y* magnitudes. The brightnesses in Figures 1a and 1b have been adjusted to fixed distances from the Sun and Earth. (c) Neptune stratospheric temperature measurements from mid-infrared spectra in 1985, 1991, and 2002–2004 [*Hammel et al.*, 2006], and three independent assessments: a nominal model for 1989.72 based on Voyager observations as cited by *Marten et al.* [2005]; a 1997.95 value used by *Bézard et al.* [1999] to model Infrared Space Observatory data; and a 1998.75 value deduced from sub-mm CO observations by *Marten et al.* [2005]. Together, the data suggest a steady rise in temperature over the past two decades. (d) Neptune's sub-solar latitude. (e) Neptune's heliocentric distance. Data in Figures 1d and 1e are inverted (smaller values toward the top) to facilitate comparison with brightnesses in Figures 1a and 1b.

with other data that show similar temporal behavior. The three curves in Figure 2b illustrate different measurements of Earth's global mean temperature anomaly over many decades of observations with an 11-year boxcar smoothing applied to remove the effects of the solar cycle. We specifically exclude solar cycle variations in this paper because our previous work in this area has proved inconclusive (LJ06 and references therein). Smoothing is appropriate since we are discussing multi-decade changes. We also examined sinc smoothing, Gaussian smoothing, and smoothing optimized for time-series analysis with back- and fore-casting. These resulted in minor variations on the boxcar results, with amplitude comparable to (or less than) the variation seen in the different temperature records shown in Figure 2.

[8] An important caveat is that even for the well-studied Earth temperature variability, the steady rise in temperature since the mid 1970s is not fully understood, but has an anthropogenic component due in part or entirely to rising greenhouse gases, in combination with changes induced by sulfate and volcanic aerosols, and/or other forcing factors [e.g., *Mann et al.*, 1998; *Broccoli et al.*, 2003; *Stott*, 2003]. Total solar irradiance seems to be ruled out as a driving factor in temperature variations, although other components of solar output may still play a role [*Foukal et al.*, 2006].

[9] *Foukal* [2002] compared the Earth global temperature anomaly (Figure 2b) with an 11-year-smoothed total solar

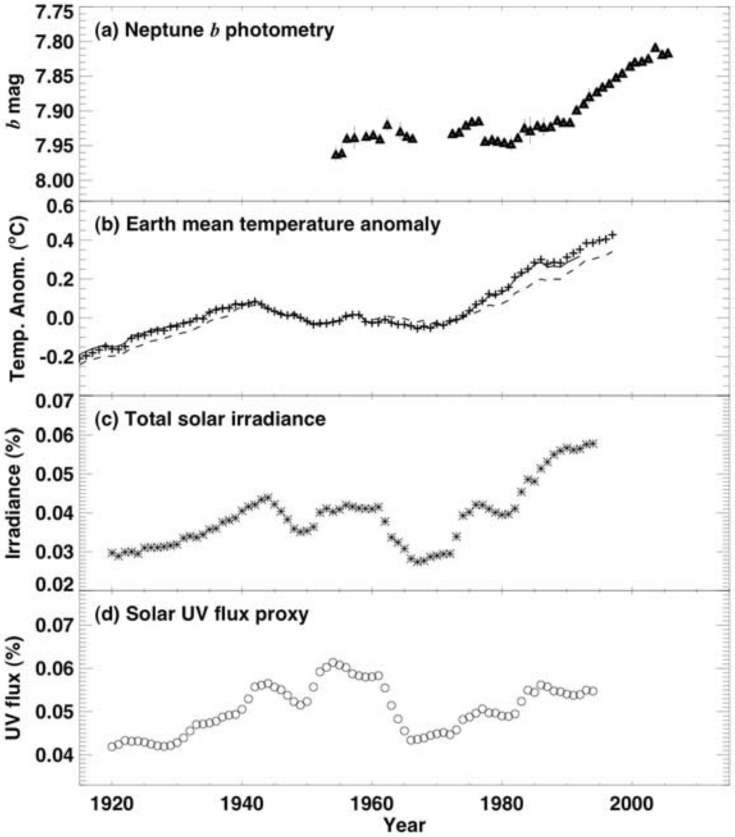

Figure 2. Neptune, Earth, and the Sun. (a) Disk-integrated visible photometry of Neptune (LJ06) as defined for Figure 1a. No temporal offset has been applied to the Neptune data here. (b) Measurements of Earth's "global mean temperature anomaly" (the anomaly is defined as the difference in °C between the yearly mean temperature and the mean of the period from 1951 to 1980). Three data sets are shown: plus signs are zonal-mean annual surface temperature anomaly [*Hansen et al.*, 1999, 2001], the solid line is global surface air temperature anomaly [*Hansen and Lebedeff*, 1987, 1988], and the dashed line is zonal-mean annual land-ocean temperature index [*Hansen et al.*, 2001]. (c) An empirical model of total solar irradiance (asterisks), S, from *Foukal* [2002], plotted as percent variation as a function of year. (d) Projected areas of bright magnetic plage elements (circles), A_{PN}, from *Foukal* [2002], which can be considered a proxy for solar UV flux, plotted as percent variation as a function of year. We limit our comparison with solar activity to the published data (through 1994) of *Foukal* [2002]. Although annual on-line Earth temperature records extend to the current year [*Hansen and Lebedeff*, 1988; *Hansen et al.*, 2001] (data available at http://data.giss.nasa.gov/gistemp/), we show 11-year-averaged values and thus do not include data after 1995.

irradiance model S (Figure 2c), finding a correlation coefficient of 0.91. The model utilizes both measured irradiances and projected areas of bright magnetic plage elements A_{PN} from which historic irradiance values were estimated [see *Foukal*, 2002]. Foukal found the correlation with estimated solar UV flux—which one might suspect as being a more relevant forcer of planetary conditions because of its large range of variability—was considerably less significant. (As discussed below, irradiance may be—indeed, is likely to be—a proxy for some other more relevant solar parameter.)

3. Statistical Assessment of Neptune's Variability

[10] We performed a similar statistical analysis, comparing Neptune's *b* brightness directly with the Earth's global mean temperature anomaly, the smoothed total solar irradiance S [*Foukal*, 2002], and Foukal's A_{PN} as a proxy for solar UV flux [*Foukal*, 2002]. We performed the analysis for a range of temporal offsets for Neptune, finding maximum correlation at −10 ± 5 years (i.e., Neptune variations lag the solar variability). Within this interval, the correlation coefficient of Neptune's blue brightness (Figure 2a) with the Earth global mean temperature anomaly (Figure 2c) is $|r| > 0.90$. (The actual correlation is negative because Neptune's brightness is expressed in magnitudes, which decrease as the planet brightens.) Perhaps it is not a coincidence that the radiative time constant of Neptune's stratosphere is of order a decade [*Conrath et al.*, 1990], but a full investigation of the atmospheric physics is beyond the scope of this paper.

[11] The Earth/solar-irradiance correlation coefficient of 0.91 of *Foukal* [2002] was based on 85 years of data (1915–1999). Sampling those data over a shorter interval (*i.e.*, similar to the Neptune data: 1950–1999), reduces r to 0.89. In other words, the Earth temperature values are as well correlated with solar irradiance ($r = 0.89$) as they

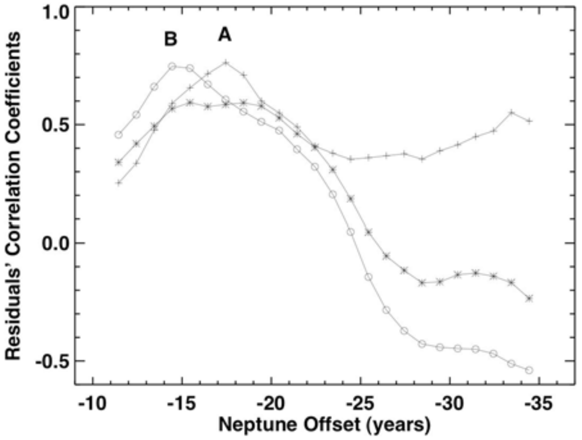

Figure 3. Correlation of residuals for long-term data sets. Correlation coefficients as a function of Neptune offset (in years) are shown between Neptune's brightness residuals ("residuals" are the difference of the data from the best-fit polynomial, where the polynomials are fit over the temporal intervals sampled by Neptune) compared with: solar irradiance residuals (asterisks); solar UV flux proxy (circles); and Earth temperature anomaly residuals (plus signs). Two peaks are marked: Case A at −17 years and Case B at −14 years. These cases (data, polynomial fits, and residuals) are shown in detail in Figure 4. Table 1 lists correlation coefficients.

are with Neptune's blue brightness (|r| > 0.90), assuming a 10-year lag of the Neptune values.

[12] Unfortunately, none of these correlations is statistically significant. The individual yearly measurements of Neptune (and Earth and the Sun, for that matter) do not represent statistically independent random measurements: in each case they are part of a time series characterized mainly by monotonic trends that lead naturally to high correlation. Although there are dozens of individual measurements, the serial correlation of the annual values leads to a very small number of degrees of freedom, with an associated huge reduction in formal significance. To determine if statistically-meaningful residual correlations exist, we examined the detailed structure superposed on the trends.

3.1. Correlations of De-Trended Residuals

[13] We fit each data set with a second-order polynomial function to remove trends and curvature (as discussed above, this trend on Neptune could be related to varying sub-solar latitude, insolation, or some other as-yet unidentified factor, perhaps in combination). We then computed the correlation of the de-trended data, lagging the Neptune data in one-year intervals from 0 to 69 years (the range over which we have complete data sets), and omitting yearly average data points in the solar/terrestrial data sets at times when there are no corresponding Neptune annual measurements. Figure 3 shows the resulting correlation coefficients as a function of lag.

[14] Neptune-Earth and Neptune-irradiance residual correlation curves show a positive correlation peak at −17 years ("A" in Figure 3), echoing the broad peak found in the original data sets. The Neptune-UV residual correlation curves also show a peak located at a slightly shorter lag of −14 years ("B" in Figure 3).

[15] Figure 4 shows the original data, the polynomial fits, and the temporally-offset residual plots for Cases A and B. Table 1 shows the correlation coefficients for the two cases. In Case A (Figure 4, top), the resemblance between the Neptune and Earth residuals is notable. For the residual correlations of the data subsets shown in Figure 4 (top), Earth's temperature is as well correlated with Neptune as it is with total solar irradiance (Table 1). When comparing Neptune with the Sun, we find a slightly higher correlation with UV flux than with irradiance. Similarly, in Case B—which identifies the maximum correlation between Neptune and UV flux—Neptune and Earth's temperature are better correlated than Neptune and solar irradiance (Figure 4, bottom; Table 1). We infer that irradiance is not the likely driver of changes in these planetary atmospheres; rather, UV flux or some other varying solar parameter is a more probable factor.

[16] *Foukal* [2002], in his discussion of Earth's temperature anomaly and its possible correlation with his solar irradiance values, noted that the empirical irradiances reproduced well the double maxima in Earth temperature anomaly data around 1942 and 1957; the Earth data also exhibited a steady rise beginning near 1968. Neptune's brightness, too, shows double maxima around 1962 and 1976, as well as a steady rise since the mid 1980s, which match well the Earth data when lagged.

3.2. Statistical Significance of De-Trended Correlations

[17] We now address the question of significance of the residuals' correlations (Table 1). Marked resemblance aside, we can assign these correlations a formal numerical statistical significance indicative of whether these correlations occur simply due to chance. The relevant factor is the number of degrees of freedom in these data sets, which, because of serial correlation in these time sequences, is a substantially smaller number than the number of discrete measurements or the number of annual means.

[18] We assume four degrees of freedom for the decades-long Neptune data set, based on the number of zero crossings in the residual plots in Figure 4. The Neptune-Earth correlation value |r| = 0.76 thus yields a probability $P \sim 0.2$, indicating a 20% probability of a chance correlation. Spurious correlations among low-frequency signals in natural phenomena are notoriously common, and we perhaps have encountered yet another example. Limited temporal coverage for Neptune precludes high statistical significance whether the illustrated phenomena are causally related or not. Furthermore, the Earth system is subject to various internal forcings as mentioned above (tropospheric sulfate content, volcanic activity, and multi-decadal climate variations). Low formal statistical significance does not mean the correlations we find are in fact spurious, only that we cannot demonstrate otherwise.

4. Discussion

[19] Overall, total solar irradiance has fluctuated over the past three solar cycles with an amplitude less than 0.1% [*Foukal et al.*, 2006]. Neptune's overall brightness variation over the past half century (Figure 1) is roughly 12% in

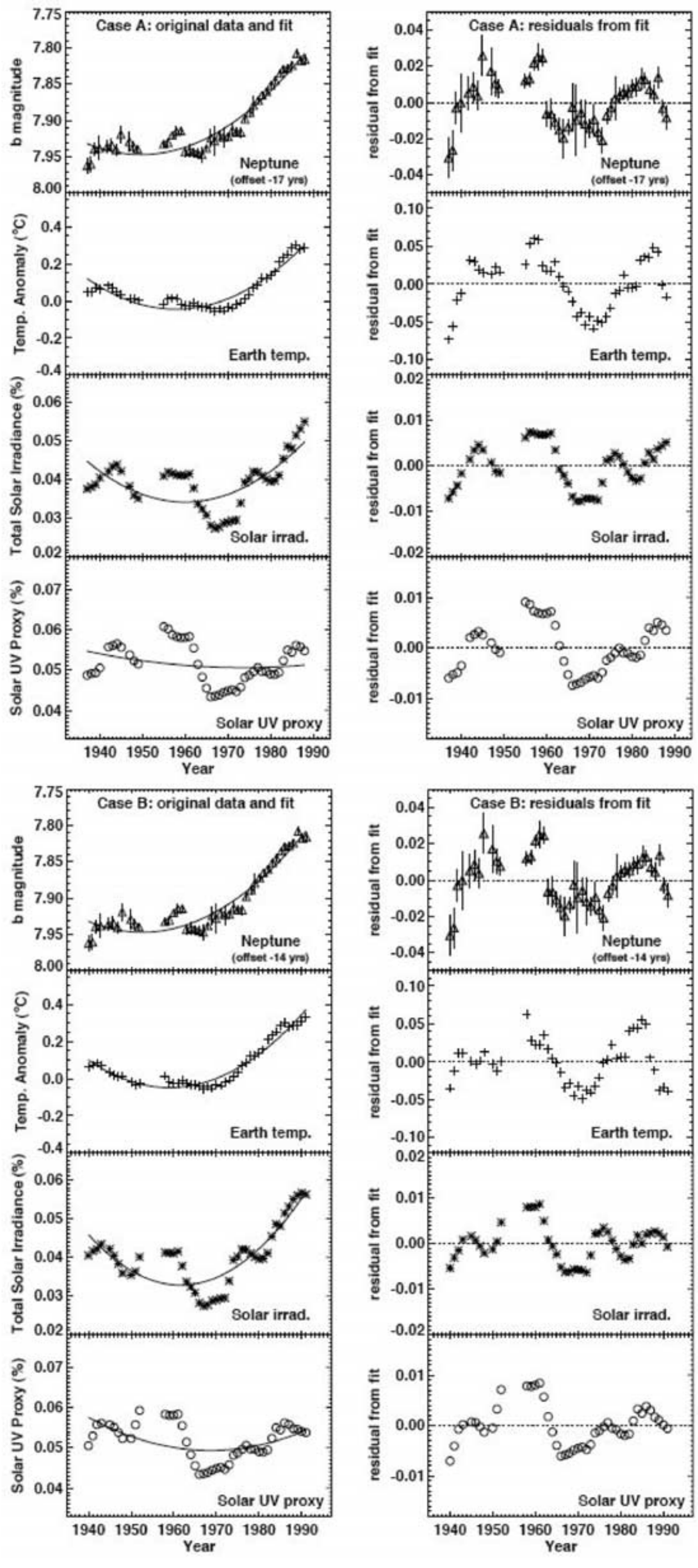

Figure 4. (top) Data and residuals used for Case A. These data were used to compute the "Case A" coefficient in Figure 3 (17-year offset). The left column shows, from top to bottom, the original data sets and their best-fit second-order polynomial for Neptune, Earth's temperature anomaly, total solar irradiance, and solar UV flux proxy; only these data—sub-samples selected to match the temporal sampling of the Neptune data—were used for the polynomial fits. The right column shows the residuals after the best-fit polynomial has been subtracted. (bottom) Data and residuals used for Case B. These data were used to compute the "Case B" coefficient in Figure 3 (14-year offset). Columns are defined as in Figure 4 (top). The apparent difference between the Earth and solar data sets shown here and in Figure 4 (top) is due to the sub-sampling.

Table 1. Correlation Coefficient Matrices[a]

	Earth Temperature Anomaly	Total Solar Irradiance	Solar UV Flux Proxy
	Case A: Neptune Offset = -17 *Years*		
Neptune	0.76	0.58	0.60
Earth Temperature Anomaly	—	0.76	0.82
Total Solar Irradiance	—	—	0.82
	Case B: Neptune Offset = -14 *Years*		
Neptune	0.59	0.56	0.74
Earth Temperature Anomaly	—	0.53	0.65
Total Solar Irradiance	—	—	0.65

[a] Each entry represents the absolute value of the correlation coefficient, r, for the cases labeled in Figure 3 and shown in Figure 4. Correlation coefficients for Earth-irradiance, Earth-UV, and irradiance-UV differ in Cases A and B because the values were computed for data subsets determined by the offset of Neptune (only correlations with Neptune are shown in Figure 3).

intensity (~0.12 magnitudes). If solar irradiance alone were the primary driver of Neptune's variations, then a large amplification would be needed, of order 120. This seems improbable given our current understanding.

[20] However, other components of the solar output might have an impact on the atmospheres of both Neptune and Earth (*e.g.*, ultraviolet flux, magnetic field strength, cosmic ray shielding). For example, some research indicates the Sun's total magnetic flux has increased by 40% over the past 30 years [*Lockwood et al.*, 1999], although others challenge this assertion [*Hildner et al.*, 2000]. As noted above, Neptune was better correlated with UV flux than irradiance. The other solar components have yet to be investigated in the context of this paper.

[21] Various mechanisms were advanced to explain the putative inverse correlation of Neptune's brightness with the 11-year solar cycle during the 1970s [*Lockwood and Thompson*, 1979, 1986, 1991], including darkening of stratospheric aerosols by increased UV flux [*Baines and Smith*, 1990] and solar modulation of galactic cosmic rays that could trigger ion-induced nucleation [*Moses et al.*, 1989]. (An attempt by *Roques et al.* [1994] to correlate Neptune stratospheric temperatures with the 11-year solar cycle was hampered by sparse occultation data.) Given the change in the nature of Neptune's brightness variations since those early investigations, some of these mechanisms may be worth revisiting. Furthermore, there could be as-yet-unknown positive feedback mechanisms within Neptune's atmosphere that amplify weak forcing.

[22] A complete examination of a driving mechanism for the long-term changes in the atmosphere of Neptune warrants further examination, in our opinion. Development of a detailed microphysical-photochemical-dynamical model is well beyond the scope of this paper. Our goal is to alert readers to the suggestive correlations we have described. If the correlations are robust, then we can predict Neptune's brightness in the coming years as discussed below.

5. Implications

[23] Observations during the next decade may provide a critical test of the hypothesis that Neptune's brightness changes are related to some component of solar variability. The seasonal model of *Sromovsky et al.* [2003] predicts a continued steady increase in brightness (Figure 1a). In contrast, a solar correlation with a 17-yr offset predicts that Neptune's brightness should remain flat for a few years and then begin rising again (cf. Figures 2b and 4, top: the inflection in Neptune's rising brightness starting in 2003 corresponds to the inflection seen near 1986 in the solar record). If Neptune's brightness is driven solely by changing sub-solar latitude, it should remain flat for a few years and then begin a slow decline (Figure 1d). The most recent data for 2004 and 2005 show that Neptune's brightness trend may indeed be flattening (Figures 1a and 1b); additional observations over the next several years may well distinguish between the two latter cases.

[24] One lesson from this study is that caution is advised for those looking at correlations of time series data. Simple correlation analyses can be misled by underlying trends, with the resulting coefficients not truly representative of the formal correlation. Examination of residuals from the trend may give a more appropriate measure of an existing correlation. Also, assignment of statistical significance to correlations must be treated with caution, even when correlations appear to be high. In time-series data, the number of discrete measurements may not be the correct number to use for degrees of freedom.

[25] In summary, if Neptune's atmosphere is indeed responding to some variation in solar activity in a manner similar to that of the Earth albeit with a temporal lag (Figure 4, top), then: (1) we predict a multi-year "flattening" (slope change) in the steady rise of Neptune's brightness for a few years, and a subsequent rise thereafter; and (2) Neptune may provide an independent (and extraterrestrial) locale for studies of solar effects on planetary atmospheres.

[26] **Acknowledgments.** HBH acknowledges support for this work from NASA grants NAG5-11961, NAG5-10451, and NNG06GI25G. The existence of long-term data sets from Lowell Observatory made this paper possible; recent observations were supported by NASA grant NNG04GO59GT. We thank J. Hansen and colleagues at the Goddard Institute for Space Studies for producing the Earth temperature data sets, and the Distributed Active Archive Center at the Goddard Space Flight Center for data formatting and distribution (sponsored by NASA's Mission to Planet Earth program). We acknowledge comments from anonymous referees on an earlier draft, as well as feedback from D. K. Lynch and P. V. Foukal.

References

Baines, K. H., and W. H. Smith (1990), The atmospheric structure and dynamical properties of Neptune derived from ground-based and IUE spectroscopy, *Icarus*, *85*, 65–108.

Bézard, B., P. N. Romani, H. Feuchtgruber, and T. Encrenaz (1999), Detection of the methyl radical on Neptune, *Astrophys. J.*, *515*, 868–872.

Broccoli, A. J., K. W. Dixon, T. L. Delworth, T. R. Knutson, R. J. Stouffer, and F. Zeng (2003), Twentieth-century temperature and precipitation trends in ensemble climate simulations including natural and anthropogenic forcing, *J. Geophys. Res.*, *108*(D24), 4798, doi:10.1029/2003JD003812.

Conrath, B. J., P. J. Gierasch, and S. S. Leroy (1990), Temperature and circulation in the stratosphere of the outer planets, *Icarus*, *83*, 255–281.

Foukal, P. (2002), A comparison of variable solar total and ultraviolet irradiance outputs in the 20th century, *Geophys. Res. Lett.*, *29*(23), 2089, doi:10.1029/2002GL015474.

Foukal, P., C. Fröhlich, H. Spruit, and T. M. L. Wigley (2006), Variations in solar luminosity and their effect on the Earth's climate, *Nature*, *443*, 161–166.

Hammel, H. B., and G. W. Lockwood (2007), Long-term atmospheric variability on Uranus and Neptune, *Icarus*, *186*, 291–301.

Hammel, H. B., D. K. Lynch, R. W. Russell, M. L. Sitko, L. S. Bernstein, and T. Hewagama (2006), Mid-infrared ethane emission on Neptune and Uranus, *Astrophys. J.*, *644*, 1326–1333.

Hansen, J., and S. Lebedeff (1987), Global trends of measured surface air temperature, *J. Geophys. Res.*, *92*, 13,345–13,372.

Hansen, J., and S. Lebedeff (1988), Global surface air temperatures: Update through 1987, *Geophys. Res. Lett.*, *15*, 323–326.

Hansen, J., R. Ruedy, J. Glascoe, and M. Sato (1999), GISS analysis of surface temperature change, *J. Geophys. Res.*, *104*, 30,997–31,022.

Hansen, J. E., R. Ruedy, M. Sato, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson, and T. Karl (2001), A closer look at United States and global surface temperature change, *J. Geophys. Res.*, *106*, 23,947–23,963.

Hildner, E., C. N. Arge, and V. J. Pizzo (2000), The solar magnetic field is not increasing, *Bull. Am. Astron. Soc.*, *32*, 835.

Lockwood, G. W., and M. Jerzykiewicz (2006), Photometric variability of Uranus and Neptune, 1950–2004: Implications for seasonal models, *Icarus*, *180*, 442–452.

Lockwood, G. W., and D. T. Thompson (1979), A relationship between solar activity and planetary albedos, *Nature*, *280*, 43–45.

Lockwood, G. W., and D. T. Thompson (1986), Long-term brightness variations of Neptune and the solar cycle modulation of its albedo, *Science*, *234*, 1543–1545.

Lockwood, G. W., and D. T. Thompson (1991), Solar cycle relationship clouded by Neptune's sustained brightness maximum, *Nature*, *349*, 593–594.

Lockwood, G. W., and D. T. Thompson (2002), Photometric variability of Neptune, 1972–2000, *Icarus*, *156*, 37–51.

Lockwood, M., R. Stamper, and M. N. Wild (1999), A doubling of the Sun's coronal magnetic field during the past 100 years, *Nature*, *399*, 427–429.

Mann, M. B., R. S. Bradley, and M. K. Hughes (1998), Global-scale temperature patterns and climate forcing over the past six centuries, *Nature*, *392*, 779–787.

Marten, A., H. E. Matthews, T. Owen, R. Moreno, Y. Hidayat, and Y. Biraud (2005), Improved constraints on Neptune's atmosphere from submillimetre-wavelength observations, *Astron. Astrophys.*, *429*, 1097–1105.

Moses, J. A., M. Allen, and Y. L. Yung (1989), Neptune's visual albedo variations over a solar cycle: A pre-Voyager look at ion-induced nucleation and cloud formation in Neptune's troposphere, *J. Geophys. Res.*, *16*, 1489–1492.

Roques, F., et al. (1994), Neptune's upper stratosphere, 1983–1990: Ground-based stellar occultation observations. part III: Temperature profiles, *Astron. Astrophys.*, *288*, 985–1011.

Sromovsky, L. A., P. M. Fry, S. S. Limaye, and K. H. Baines (2003), The nature of Neptune's increasing brightness: Evidence for a seasonal response, *Icarus*, *163*, 256–261.

Stott, P. A. (2003), Attribution of regional-scale temperature changes to anthropogenic and natural causes, *Geophys. Res. Lett.*, *30*(14), 1728, doi:10.1029/2003GL017324.

H. B. Hammel, Space Science Institute, 4750 Walnut Street, Suite 205, Boulder, CO 80303, USA. (hbh@alum.mit.edu)

G. W. Lockwood, Lowell Observatory, 1400 W. Mars Hill Road, Flagstaff, AZ 86001, USA.