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# Tree-stem diameter fluctuates with the lunar tides and perhaps with geomagnetic activity

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**Abstract** Our initial objective has been to examine the suggestion of Zürcher et al. (Nature 392:665–666, 1998) that the naturally occurring variations in stem diameter of two experimental trees of *Picea alba* were related to near-simultaneous variations in the lunisolar tidal acceleration. The relationship was positive: Lunar peaks were roughly synchronous with stem diameter peaks. To extend the investigation of this putative relationship, additional data on stem diameter variations from six other tree species were gathered from published literature. Sixteen sets of data were analysed retrospectively using graphical representations as well as cosinor analysis, statistical cross-correlation and cross-spectral analysis, together with estimated values of the lunisolar tidal acceleration corresponding to the sites, dates and times of collection of the biological data. Positive relationships were revealed between the daily variations of stem diameter and the variations of the lunisolar tidal acceleration. Although this relationship could be mediated

by a 24.8-h lunar rhythm, the presence of a solar rhythm of 24.0 h could not be ruled out. Studies of transpiration in two of the observed trees indicated that although this variable was not linked to stem diameter variation, it might also be subject to lunisolar gravitational regulation. In three cases, the geomagnetic Thule index showed a weak but reciprocal relationship with stem diameter variation, as well as a positive relationship with the lunisolar tidal force. In conclusion, it seems that lunar gravity alone could influence stem diameter variation and that, under certain circumstances, additional regulation may come from the geomagnetic flux.

**Keywords** *Abies alba* · *Juglans regia* · Lunisolar tidal acceleration · *Picea abies* · *Pseudotsuga menziesii* · Stem diameter variation · Thule index · *Tilia cordata* · Transpiration · Trees

## Abbreviations

CD	Coefficient of determination
$\delta D$	Stem diameter variation
$\delta g$	Lunisolar tidal acceleration (vertical component)
Th	Thule index
$T_s$	Rate of transpiration

## Introduction

Twelve years ago, Zürcher et al. (1998) reported a ‘strong correlation’ (their term) between the natural, rhythmic variation of stem diameter ( $\delta D$ ) of two trees of *Picea abies* (Norway spruce), as measured by high-resolution extensometry, and the timing and strength of the vertical component of the lunisolar tidal acceleration ( $\delta g$ )—a partial

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and indirect measure of the continually varying lunar gravitational force experienced everywhere on Earth as a consequence of the relative positions of Sun, Moon and Earth. Similar correlations were also mentioned in relation to stem-diameter variations of alder (*Alnus* sp.) trees (Zürcher et al. 1998). The two experimental spruce trees were grown in darkness within a controlled environment cabinet. The displayed variations in stem diameter (dilatation rhythms) were therefore considered to have been independent of entraining influences from fluctuations of lighting, temperature and humidity. Moreover, because the trees' stomata were said to be closed (Zürcher et al. 1998) and also because stems of trees from which the crown leaves had been removed showed similar diameter variations (Cantiani and Sorbetti Guerri 1989), an effect of transpiration on  $\delta D$  was ruled out. Instead of transpirational water movement serving as a source of stem diameter variations, a rhythmic and reversible flow of solutes between the symplasm of living cells and the apoplasm, including the cell walls, was proposed (Zürcher et al. 1998). More recent work has supported this opinion (Daudet et al. 2005), and anatomical studies of sapwood (Zweifel et al. 2000; Scholz et al. 2008) have indicated the cells of the developing secondary tissue, which could be involved in the dilatation rhythm of tree stems. It should, however, be pointed out that the relationship between lunar gravity and stem diameter proposed by Zürcher et al. (1998) could not be confirmed by Vesala et al. (2000) working with trees of *Pinus sylvestris* raised in Finland. Unfortunately, this report is not without its problems: Besides incorrectly stating the duration of the lunar period, these authors base their negative conclusion solely (apparently) on results gained from Fourier analysis of xylem diameter variation.

In view of the mentioned difference of opinion regarding a possible link between  $\delta D$  and the estimated lunisolar tidal acceleration  $\delta g$  prevailing during the period when stem diameters were measured, the present article renews examination of this proposed relationship. Data for  $\delta D$  originally recorded by Cantiani (1978), Cantiani and Sorbetti Guerri (1989) and Cantiani et al. (1994) have been used. Cyclical-rhythmic relationships can be rigorously investigated by making use of cosinor rhythmometry (Nelson et al. 1979) and other statistical procedures accepted by chronobiologists for the analyses of biological rhythms. Chronometric-statistical methods can evaluate, for example, the time delay(s) between one cycle (that pertaining to a presumed dependent biological variable, say) and a second cycle (such as that due to an independent geophysical variable). Precision can thus be given to the evaluation of interrelationships, which show indications of partial synchrony. The publications of Cantiani and his colleagues contain not only details of  $\delta D$ , as measured by sensitive extensometry, in a number of species of both hard- and softwood trees, but also simultaneous records of

transpiration (Cantiani and Sorbetti Guerri 1989), a process which may be relevant to the daily variation in stem diameter. Although these data were gathered many years ago, they are still valid for examining their relationships with the lunisolar tidal accelerations  $\delta g$  prevailing at the time and place of biological data collection.

Besides their well-known responses to gravity, living organisms are also responsive to external magnetoelectric fields—the second force in the cosmos after gravitation (Brown 1969; Żurbicki 1973; Galland and Pazur 2005; Zhou and Uesaka 2006; Ahmad et al. 2007). Therefore, in addition to  $\delta g$ , the effects of two other cosmic variables known to contribute to the Earthly geomagnetic flux (Maeda 1968) were introduced into our analysis of tree-stem diameter variation. These are the 'Thule index' (Th) and the 'Disturbance Storm Time index' (Ds) (Akasofu 1982). We asked of the time series of biological data gathered from the mentioned tree species, whether these two variables showed any relationships with the rhythms of  $\delta D$  or of transpiration.

Finally, we wish to remark upon the approach we have taken in examining the putative relationship between lunisolar gravity and tree-stem diameter variation. The present sets of data relating to  $\delta D$  and transpiration were originally collected by Cantiani (1978) and Cantiani and Sorbetti Guerri (1989) in their study of rhythmic stem diameter variation. In fact, the observations of Cantiani had led him cautiously to propose that the gravitational force of both Sun and Moon affected some of the tree-growth rhythms he had studied (Cantiani 1978). While Cantiani realised that this hypothesis was 'alquanto fantascientifica', he did call for rigorous experimentation upon the matter, a step towards which was taken by Zürcher et al. (1998). Visual inspection of these last-mentioned authors' data for  $\delta D$  and  $\delta g$  (the erroneous interchange of negative and positive signs for  $\delta g$  in their publication needs to be looked upon as a simple mistake) suggested—after our careful reconsideration—a positive relationship between  $\delta D$  and  $\delta g$  (Zürcher et al. 1998). However, one example, taken from 3 days of data recording, is not sufficient to allow conclusions about a general relationship, especially since the pattern of  $\delta g$  continually changes across the period of a lunar month. Unless longer term observations are conducted expressly to examine lunar/tree relationships, the best that can be done is to examine this putative relationship with the aid of a series of 'snapshots' of data gathered on different dates. While one snapshot showing one positive relationship is interesting (as in the case of results from Zürcher et al. 1998), numerous 'snapshots', gathered on various dates and over various lengths of time are of greater merit, and if they all show similar relationships between lunar gravity and stem diameter, as we present here [and which we had found also in a previous,

cognate study of lunar gravity and nastic leaf movements (Barlow 2007; Barlow et al. 2008)], then the possibility of a Moon and tree relationship begins to demand serious attention.

## Materials and methods

### Biological variables

The main concern is to examine the variation in stem diameter ( $\delta D$ , mm) of soft- and hardwood trees in relation to the lunisolar tidal acceleration  $\delta g$ . Data sets S1–S16 contain time-series records of  $\delta D$  and  $\delta g$ , and where appropriate, values of Th and Ds also, which were collected on a number of different dates (Table 1). The values of  $\delta D$  were originally gathered by Cantiani (1978) and Cantiani and Sorbetti Guerri (1989). In two cases, measurements of transpiration rate ( $T_s$ ,  $\text{g min}^{-1}$ ) were also made. Details relevant to the present data and their sources are given below.

### Stem diameter variations

Variations in stem diameter  $\delta D$  were recorded by extensometry from seven different temperate tree species growing in two different localities (Cantiani 1978; Cantiani and Sorbetti Guerri 1989). One set of observations was made on trees growing naturally in a forest at Vallombrosa, Italy ( $43^\circ 44' \text{ N}$ ,  $11^\circ 34' \text{ E}$ ; altitude, 950 m). A second set was gathered from trees grown within a controlled growth cabinet environment in Firenze, Italy ( $43^\circ 47' \text{ N}$ ,  $11^\circ 16' \text{ E}$ ; altitude, 36 m). Details of both types of growth conditions,

as well as the extensometric method, are described by Cantiani (1978), Cantiani and Sorbetti Guerri (1989) and Meluzzi and Sorbetti Guerri (1989).

*Forest-grown trees* Data sets S1 and S2 relate to a mature specimen (19.6 m tall) of *Tilia cordata* growing in Vallombrosa. Time series of  $\delta D$  were gathered via extensometer channel 7 (for S1) and channel 9 (for S2) placed at two different locations (7.5–13 m above ground level) upon the stem of the tree. Data collections took place on 19–23 September 1976. The values of  $\delta D$  in the time series were extracted for analysis from Fig. 6 of Cantiani (1978).

Data set S3 pertains to the already mentioned tree of *T. cordata*. Time series of  $\delta D$  were gathered via extensometer channel 9, between 24 June and 3 July, 1977. Data set S4 includes records from extensometer channel 11 placed 20 m above ground level on the main stem of a tree (32.5 m tall) of *Liriodendron tulipifera*. The recordings were on the same dates as for S3 of *Tilia*. Both sets of original data appear in Fig. 7 of Cantiani (1978).

Data sets S5 and S6 contain time series of  $\delta D$  for two isolated, vertically positioned, segments cut on 21 March 1977 from a living branch of Douglas fir, *Pseudotsuga menziesii*, that was 39 m tall. Both segments showed a rhythm of stem dilatation over a 10-day recording period, which commenced on 24 June 1977, 3 months after the segments were cut. Records for S5 were obtained from extensometer channel 5 placed on the bark of one of the segments, whereas those for S6 were from channel 6 located below the bark, in contact with living secondary tissue. Simultaneously, recordings of  $\delta D$  for data set S7 were taken, via extensometer channel 2 at a location on the

**Table 1** Summary of data sets S1–S16 containing time series of stem diameter variations ( $\delta D$ ) and transpiration rates ( $T_s$ ) originally recorded on the dates give by M Cantiani and colleagues from various hardwood and softwood tree species at two locations in Italy

Variable	Data set	Tree species	Location	Date of recording	Number of days
$\delta D$	S1, S2	<i>Tilia cordata</i>	Vallombrosa	19–23/09/1977	5
$\delta D$	S3	<i>Tilia cordata</i>	Vallombrosa	24/06–03/07/1977	10
$\delta D$	S4	<i>Liriodendron tulipifera</i>	Vallombrosa	24/06–02/07/1977	9
$\delta D$	S5, S6, S7	<i>Pseudotsuga menziesii</i>	Vallombrosa	23/06–02/07/1977	9
$\delta D$	S8, S9	<i>Pseudotsuga menziesii</i>	Vallombrosa	19–23/09/1976	5
$\delta D$	S10	<i>Picea abies</i>	Firenze	9–11/07/1988	2 1/2
$\delta D$	S11	<i>Picea abies</i>	Firenze	13–16/07/1988	2 1/2
$\delta D$	S12	<i>Picea abies</i>	Firenze	17–20/07/1988	4
$\delta D$	S13	<i>Abies alba</i>	Firenze	27–28/02/1988	2
$\delta D$	S14	<i>Juglans regia</i>	Firenze	24–26/03/1991	3
$\delta D$	S15	<i>Mespilus germanica</i>	Firenze	09–10/10/1989	2
$\delta D$	S16	<i>Mespilus germanica</i>	Firenze	21–24/10/1989	4
$T_s$	S10	<i>Picea abies</i>	Firenze	10–11/07/1988	2
$T_s$	S13	<i>Abies alba</i>	Firenze	27–29/02/1988	3

The data sets also include variations of the lunisolar tidal acceleration  $\delta g$  at the locations and dates indicated.

stem (17 m above ground level) next to where the two mentioned segments had been cut. All three time series of  $\delta D$  were extracted from Fig. 11 in Cantiani (1978). These same time series appear in Fig. 3 of Cantiani et al. (1994).

Cantiani (1978) recorded  $\delta D$  from a root (26 cm in diameter) of *P. menziesii*. Data sets S8 and S9 contain, respectively, time series of  $\delta D$  from this root and from the stem to which the root was linked. Recordings were made via extensometer channels 4 (root) and 1 (stem) on 19–23 September 1976. The results for these two data sets were extracted from Fig. 4 of Cantiani (1978). The same data appear in Fig. 2 of Cantiani et al. (1994).

*Trees in a growth cabinet* A laboratory growth cabinet located in Firenze was used by Cantiani and Sorbetti Guerri (1989) to test whether lighting conditions and transpiration affected stem diameter variation.

Three different time series of  $\delta D$  for a stem of a 9-year-old (1 m tall) Norway spruce tree (*P. abies*),<sup>1</sup> referred to as ‘tree no. 2’, are included in data sets S10–S12 and were recorded on three occasions during July 1988. On the first two occasions (9–12 July, and 13–16 July, respectively), tree no. 2 was grown first in 12-h light/12-h dark conditions and then was placed in continuous light. Values of  $\delta D$  for the corresponding data sets S10 and S11 were extracted from Figs. II-4 and II-5, respectively, of Cantiani and Sorbetti Guerri (1989). On the third occasion (17–20 July), the tree was placed in darkness. The respective  $\delta D$  values assembled for data set S12 were extracted from Fig. II-6 in Cantiani and Sorbetti Guerri (1989) [The same graph of  $\delta D$  for this tree, tree no. 2, is presented as Fig. 1a in the publication of Zürcher et al. (1998), as well as appearing in Fig. 9 of Cantiani et al. (1994)].

Data set S13 contains a time series of  $\delta D$  values from a stem of a 10-year-old white fir (*Abies alba*) grown in 12-h light/12-h dark conditions. The measurements were gathered on 27–29 February 1988 and were extracted from Fig. I-2 of Cantiani and Sorbetti Guerri (1989). The same measurements also feature in Fig. 1 in Cantiani et al. (1994).

Data for  $\delta D$  of a stem of *Juglans regia* growing in ‘conditions de photopériode normale’ were extracted from Fig. 7 of Cantiani et al. (1994) and placed in data set S14. The dates of the extensometer recordings were 24–26 March 1991.

Data sets S15 and S16 contain time series of  $\delta D$  from a stem of a 6-year-old tree of *Mespilus germanica*. In the first

case (S15), the tree was grown in darkness; in the second case (S16), the same tree had been placed in a 12-h light/12-h dark regime. The respective time series of  $\delta D$  were extracted from Figs. VII-2 and VII-1 of Cantiani and Sorbetti Guerri (1989)—the last-mentioned figure also features as Fig. 10 in Cantiani et al. (1994). The dates on which the data for S15 and S16 were recorded were 9–10 October 1989 and 21–24 October 1989, respectively.

#### Variations in transpiration rate

A time series of transpiration rates  $T_s$  from *P. abies* on 10–11 July 1988 is contained in data set S11. The same tree (tree no. 2) had simultaneously supplied the already-mentioned values of  $\delta D$ . Two other records of  $T_s$  for *P. abies* are contained in the already-mentioned data sets S10 and S12. All these time series were extracted from Figs II-1, II-2 and II-3 in Cantiani and Sorbetti Guerri (1989).

Data set S13 also includes a time series for  $T_s$  in *A. alba* gathered on 27–29 February 1988, simultaneously with the data for  $\delta D$ . The data were extracted from Fig. I-1 of Cantiani and Sorbetti Guerri (1989). The same data for  $T_s$  appear in Fig. 5 in Cantiani et al. (1994).

Transpiration rates were measured from the loss of weight, over time, of the trees and their containers, taking care that it was only the tree, not the soil, from which water was lost (Cantiani and Sorbetti Guerri 1989).

#### Geophysical variables

##### Lunisolar tidal acceleration

Variations in the vertical component of the lunisolar tidal acceleration  $\delta g$  were estimated according to programmes routinely used by us (see also Barlow et al. 2008). The horizontal component of  $\delta g$  also varies, but the effect on the tidal acceleration is negligible. The computations are based on gravimetric formulae prepared by Longman (1959). Data inputs for the estimation of  $\delta g$  relevant to the present study were the latitude, longitude and altitude above sea level of the already-mentioned locations of the experimental trees, as well as the calendar dates (Table 1) for which the  $\delta g$  values were required. The computation of  $\delta g$  produced time series, which used the local times at which recordings of  $\delta D$  and  $T_s$  were made.

To put the lunisolar tidal  $\delta g$  values into perspective, it should be recalled that the gravimetric unit for  $\delta g$  is the micro-Galileo and that  $9.81 \times 10^8 \mu\text{Gal}$  ( $9.81 \text{ m/s}^2$ ) are equivalent to 1 G unit of Earthly gravity.

Tidal theory has been thoroughly described (Bartels 1957; Tomaschek 1957; Melchior 1983). However, in order to explain the ‘meaning’ of  $\delta g$  more precisely,

<sup>1</sup> In the publications of Cantiani and Sorbetti Guerri (1989) and of Cantiani et al. (1994), the Latin name of Norway spruce [‘abete rosso’ (It.) or ‘l’épicéa’ (Fr.)] is given as *Picea excelsa* Link., whereas it is given as *Picea abies* Karst. in the publication of Zürcher et al. (1998). Clearly, the same individual tree is being referred to in each case. The name *Picea abies* (L.) Karsten is retained here.



we offer the following remarks. The lunisolar tidal acceleration results from the fact that the Earth is not only a single mass point but co-exists with Sun and Moon. The Earth is an elastic body and, in response to the relative positions of Sun and Moon, it exhibits elastic deformations, with maximal elevations reaching some tens of centimetres. Gravitational acceleration continually varies at points on the Earth's surface due to these deformations. The result is a residual (tidal) acceleration,  $\delta g$ . A 3-mm vertical elevation at a given location on the Earth's surface, as a result of the joint action of the masses of the Sun and Moon, is equal to 1  $\mu\text{Gal}$ , and this value is subtracted from the local Earthly 1 G gravitational acceleration of  $9.81 \times 10^8 \mu\text{Gal}$ . Thus, the values of  $\delta g$ , while actually relating to the local values of Earthly gravity, stand proxy for the lunisolar gravitational force that is bearing upon the Earth at the given times, dates and places. Cyclical variation in the relative distances between Sun, Moon and Earth over time (say, 1 year) has a very small effect on  $\delta g$ .

The basic wave of  $\delta g$  has a period of 12 h, and two maxima and two minima appear during the day. In relation to the Sun, the vertical component (and only this component is considered here) of  $\delta g$  reaches its maxima (positive) at noon and midnight and its minima at sunrise and sunset. With respect to the Moon, there is an analogous arrangement: The basic period is equal to the half of a lunar day, i.e. 12.44 h, and the amplitude is twice the amplitude of the solar wave. On days with a new and full moon, maxima of both waves nearly coincide, and the resulting tidal wave is particularly high (the sum of both waves), whereas in the first and last quarter, maxima of one wave coincide with minima of the other wave and the resulting wave is lower. It is the relative positions of Sun and Moon that therefore govern the values of  $\delta g$ , the contribution of the Sun to the gravitational 'pull' on the Earth being about 46% that of the Moon. In relation to the Earth's 1 G gravitational constant, those of Sun and Moon are 27.9 and 0.16 G, respectively. However, distance from Earth affects their gravitational 'pull': Relative to distance of the Moon, the Sun is 389 times further from the Earth.

Besides the vertical component of the tidal acceleration (here denoted as  $\delta g$ ), there is also a horizontal component. Its value moves within the same limits as the vertical component but is shifted in phase and is delayed after the vertical component by  $\pi/2$ . This component influences the direction of a vertical line, the maximal deviation being 0.0182 s of an arc. This deviation is variable and exhibits the same periods as  $\delta g$ , also in accordance with the relative positions of

the Sun and the Moon with respect to the Earth. In the present paper, we deal only with the vertical component of  $\delta g$ , as did [Zürcher et al. \(1998\)](#) and [Vesala et al. \(2000\)](#). Due to its periods being similar to  $\delta g$ , the use of the horizontal component (or the deviation from the vertical) does not any bring new, independent information.

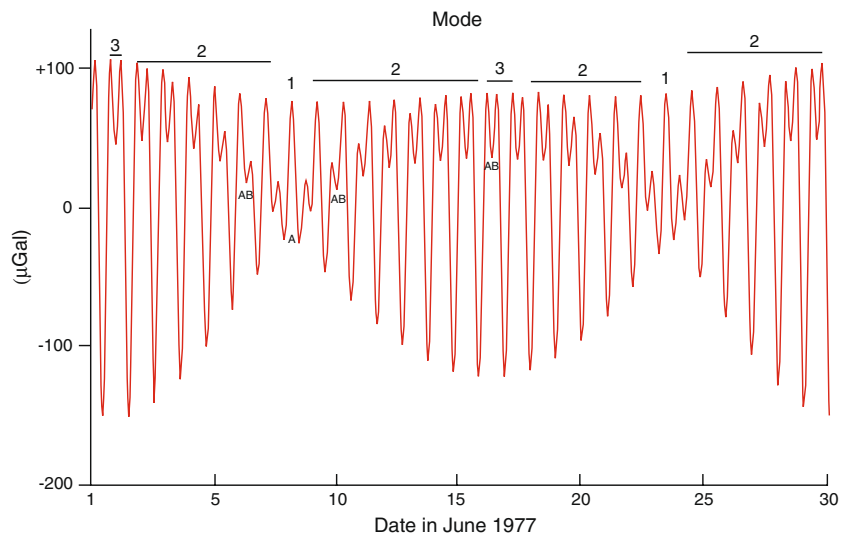
The distances Earth-to-Sun as well as Earth-to-Moon vary with time due to the elliptical orbits of the Earth and of the Moon. These variations influence the amplitudes of the tidal acceleration, but when compared with the results arising in the case of circular orbits, the differences are very small. Moreover, these variations have long periods (1 year for the Sun, and one anomalistic month of 27.55 days for the Moon tides). Therefore, these variations cannot express themselves during short intervals during which the tree diameters were presently investigated.

This ideal model applies only for the equinox accidentally coinciding with the new or full moon, i.e. both bodies move in the equatorial plane. In general, the diurnal waves are not symmetric, and the actual lunar tidal waves are a combination of the 12:44-h and the 24.88-h waves with amplitudes which change rapidly with time. The whole tidal wave is then a combination of four waves, contributed by both Sun and Moon, with different and variable amplitudes. The wave-like variations of  $\delta g$  for one of the months (June 1977) coinciding with one observation period (in Vallombrosa, Italy) during the present investigations of  $\delta D$  are shown in Fig. 1. On other dates, slightly different patterns of  $\delta g$  are present.

The atmosphere of the Earth also exhibits variations due to tidal effects, with periods similar to those for the solid Earth. These variations are reflected in small variations of the air pressure observed on the Earth's surface, the biggest difference between maximal and minimal atmospheric pressures reaching 0.1 hPa ([Volland 1988](#)). This takes place on the equator, during the full and new moon. In meteorology, atmospheric pressure is presented with an accuracy of 0.1 hPa. Thus, although the described tidal effect on air pressure is not negligible, it is relatively small. It is possible that this meteorological variable could affect rates of transpiration and, perhaps, even the amplitude of stem diameter variation.

With reference to the computed maximal (peak) values of  $\delta g$ , three modes repeat during the lunar month shown in Fig. 1, one mode giving way to another during this period. On any given day, one of the following modes may be encountered: mode 1, a single peak or maximum of  $\delta g$  (A in Fig. 1); mode 2, an unequal pair A,B of peaks (A appearing first, followed by B, or vice versa); and 3, a

**Fig. 1** Pattern of variation of  $\delta g$  ( $\mu\text{Gal}$ ) across the month of June 1977, estimated for Vallombrosa, Italy, whence records of  $\delta D$  from trees were obtained. Three modes (1, 2, 3) of  $\delta g$  peaks are indicated. They are useful with reference to the “Results and discussion” and figures presented in the text

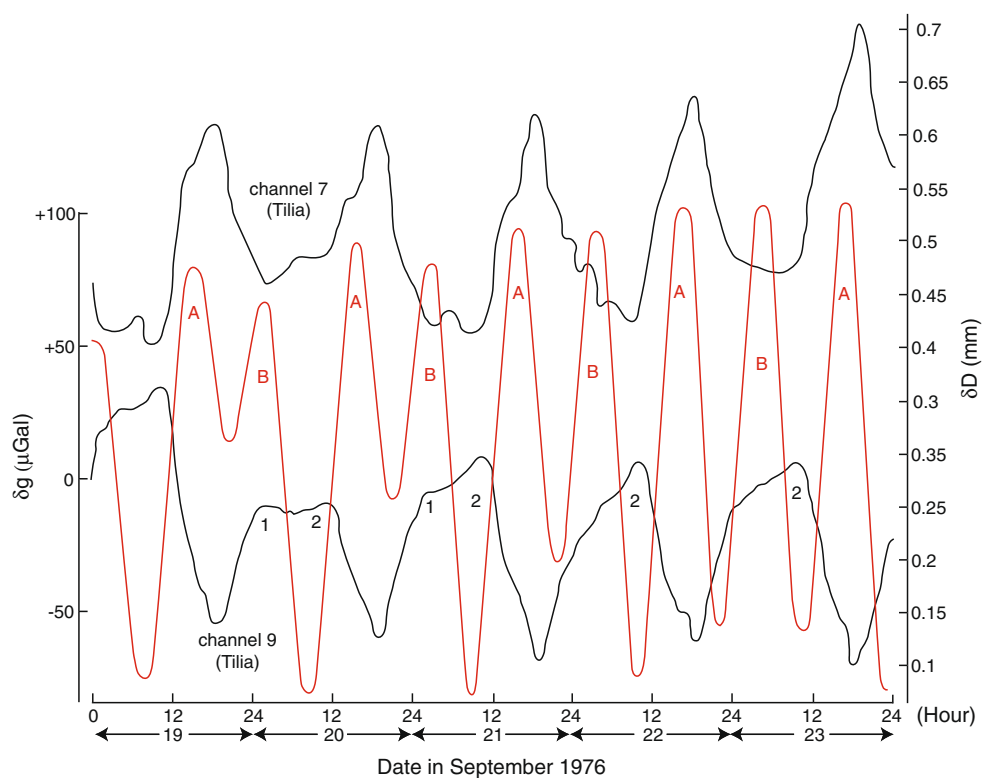


pair of peaks of equal magnitude. These three modes serve as ‘highlights’ in the visual inspection of a changing pattern of  $\delta g$  values (Figs. 2, 3, 4, 5, 6, 7, 8, 9 and 10). For the horizontal component of tidal variation, very similar (though not identical) modes would be obtained, only shifted in phase. This quantity will not, therefore, be treated separately.

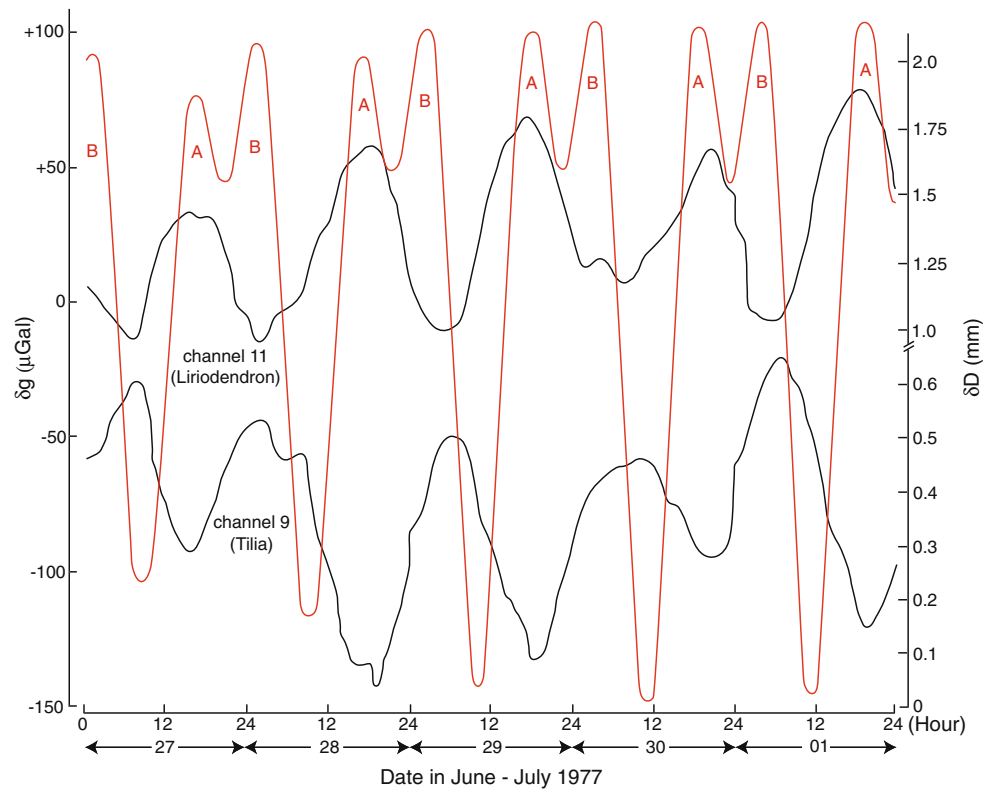
The pattern of  $\delta D$  can also show paired peaks, numbered 1 and 2 in the graphs which follow. They are analogues of the paired A,B peaks of  $\delta g$ . The nub of the present investigation of the tree-stem dilatation rhythm in relation to lunar tide is, in fact, whether  $\delta g$  is closely tracked by  $\delta D$ ,

an event which may imply some sort of ‘causal’ relationship. Therefore, a further question is whether or not the temporal patterns, or time series, of  $\delta D$  and  $\delta g$  are in phase or out of phase, and, if the latter, how many hours delay is there between the respective peaks and troughs of  $\delta D$  and  $\delta g$ , and could such delays arise purely by chance? A related question is whether the regular ‘splitting’ of the peaks and troughs in the time series of  $\delta g$  (Fig. 1) disturbs the establishment of a regular rhythm of  $\delta D$  or, indeed, of any of those biological processes which have a tendency to follow either a 24.0-h solar day or a 24.8-h lunar day (Palmer 2000).

**Fig. 2** Tree stem diameter variation  $\delta D$  (black lines) during September 1976 recorded via extensometer channels 7 and 9 located at different heights on a tree of *Tilia cordata*. Contemporaneous variations of  $\delta g$  (red lines) are also shown. In the case of  $\delta g$ , pairs of peaks, A and B, are present during the observation period. Likewise, there are indications of a changing relative prominence of paired peaks 1 and 2 in the time series of  $\delta D$  from channel 9. Note that  $\delta D$  peaks 1 and 2 from the two different extensometer channels associate with different A and B peaks of  $\delta g$ . Dates and times of day are shown in the two horizontal axes both here and in other figures



**Fig. 3** Time series of  $\delta D$  and  $\delta g$  similar to those shown in Fig. 2. Extensometer channel 9 was located on a tree of *Tilia cordata*; channel 11 was located on a tree of *Liriodendron tulipifera*. Recordings were made during June to July 1977

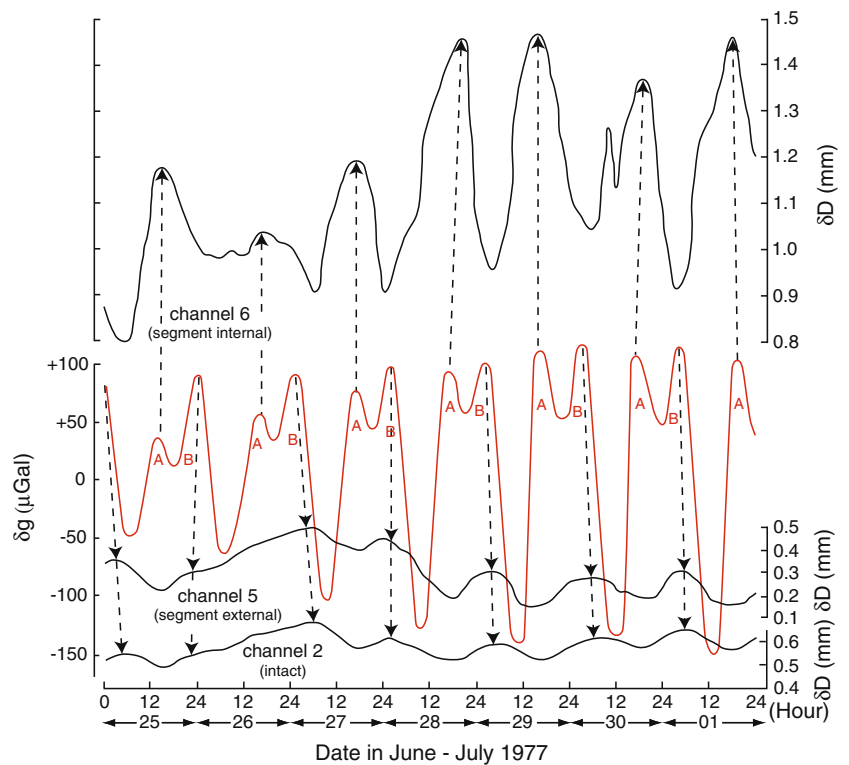


*Geomagnetic variables*

With respect to geomagnetic activity, two types of variables were examined. The first is the Geomagnetic Polar Cap

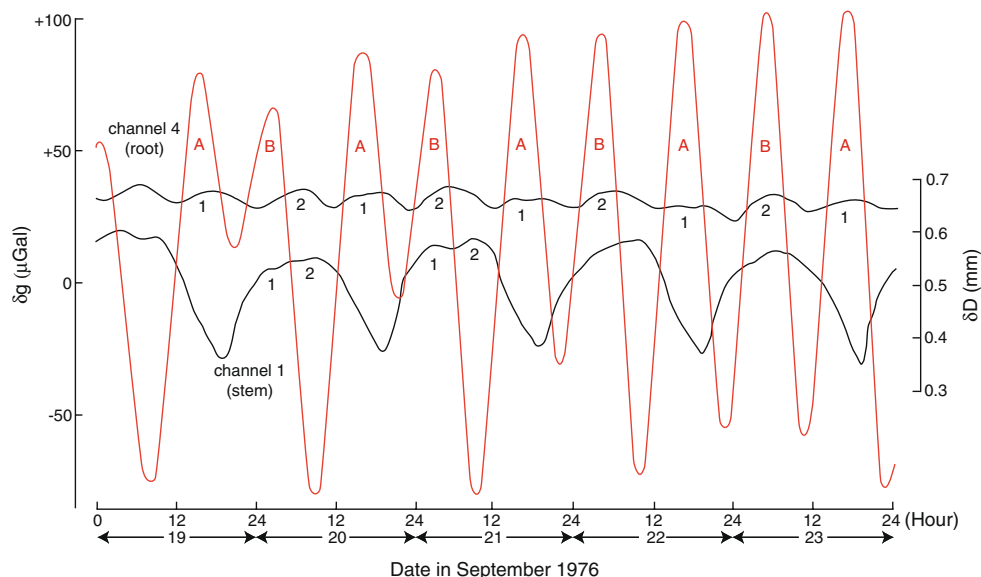
Index, called here the Thule Index (Th, no units), which is based on an idea by Troshichev et al. (1979) (see also Maeda 1968). Th represents the magnetic activity, at the polar cap, generated by parameters of the solar wind, such

**Fig. 4** Time series of  $\delta D$  from cut branch segments of *Pseudotsuga menziesii* during June to July 1977, together with the contemporaneous record of  $\delta g$  (red line). Channel 2 recorded from an intact portion of stem, whereas channels 5 and 6 were located, respectively, on the surface of the bark and at the level of the cambium on a branch segment cut from the tree 3 months earlier. Peaks of  $\delta D$  coincide (see vertical arrows with broken shafts) with either an A peak (see channel 6) or a B peak (see channels 2 and 5) of  $\delta g$





**Fig. 5** Time series of  $\delta D$  from a root and a stem of *Pseudotsuga menziesii* via extensometer channels 4 and 1, respectively. Contemporaneous records of  $\delta g$  are also shown (red line). Note that peaks and troughs of  $\delta D$  are more frequent in the root than in the stem



as its velocity and the southward and azimuthal components ( $B_z$  and  $B_y$ , respectively) of its interplanetary magnetic field. The Thule index, because of its universality, stands proxy for the geomagnetic activities which apply at the two sites (Vallombrosa and Firenze) of the present biological investigations.

The second geomagnetic variable is the Disturbance Storm Time index Dst (called here Ds, units of nanotesla, nT) derived from hourly scalings of low-latitude horizontal magnetic variation. This index represents the effect of the globally symmetrical westward-flowing, high-altitude equatorial ring current related to large magnetic storms (Mayaud 1980; O'Brien and McPherron 2002). Positive and negative values of Ds indicate, respectively, either an enhancement or a weakening of the Earth's magnetic field. Geomagnetic disturbances included in Ds are minute in comparison with the Earth's main magnetic field (some hundreds of nanotesla compared with 50,000 nT of the main field). Nevertheless, they may influence organisms in which electric currents are active.

Values of Th and Ds are available at the following websites: [ftp://ftp.ngdc.noaa.gov/STP/SOLAR\\_DATA/RELATED\\_INDICES/PC\\_INDEX/THULE](ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/RELATED_INDICES/PC_INDEX/THULE) (for Th) and [ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC\\_DATA/INDICES/](ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/) and also [http://wdc.kugi.kyoto-u.ac.jp/dst\\_final/index.html](http://wdc.kugi.kyoto-u.ac.jp/dst_final/index.html) (for Ds). From these records, time series of Th and Ds were extracted for the same periods over which biological observations were made.

#### Data analysis

##### Visual inspection

Visual inspection of plotted data was used for assessing relationships between biological and geophysical variables,

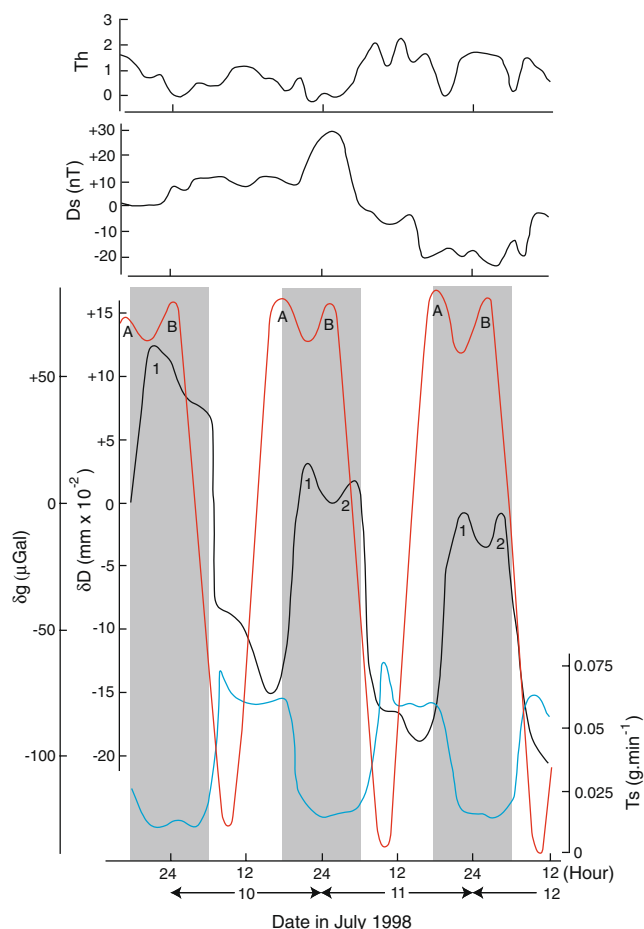
as performed in a related context (Barlow 2007; Klein 2007; Barlow et al. 2008). 'Highlights' in the time series of each variable, especially those of  $\delta D$  and  $\delta g$ , were usually related to the timings of particular maximum or minimum values (peaks or troughs), or to the times at which these values show the greatest rates of change (e.g. rapid fall or rise from a respective peak or trough). Each highlight represents a 'nuance' in the time-series data which may not immediately be captured by statistical analysis. For example, the sinusoids derived by cosinor analysis are the smoothed paths through the peaks and troughs of the data points produced by the fitting procedure. Each highlight might therefore be justifiably considered separately in relation to  $\delta g$ .

The time between the occurrence of a peak of  $\delta D$  (generally  $Y$ , the dependent response, e.g. a biological variable) and of  $\delta g$  (generally  $X$ , the independent, explanatory, e.g. a cosmogeophysical variable) is a measure of the lag  $L$  between  $X$  and  $Y$ , or between  $Y$  and  $X$ . A positive value of  $L$  denotes a delay of  $Y$  after  $X$  ( $L_{XY}$ ), and a negative value denotes delay of  $X$  after  $Y$  ( $L_{YX}$ ). A positive  $L_{XY}$  corresponds with a negative  $L_{YX}$ , the latter being equal to  $L_{XY}$  minus the period length. Accordingly,  $L_{XY} - L_{YX} = \text{period length}$ .

##### Statistical procedures

Data from complete 24-h solar days (commencing at 0:00 h) were used for statistical analysis. However, in the case of data set S12, because of the special interest concerning the values of  $\delta D$  from tree no. 2 of *P. abies* in relation to  $\delta g$  (see Introduction and also Zürcher et al. 1998), the data from the whole 75-h time series were incorporated into the analyses.

**Cosinor analysis** Univariate cosinor analysis (Bingham et al. 1982) was used to assess the presence of linear or



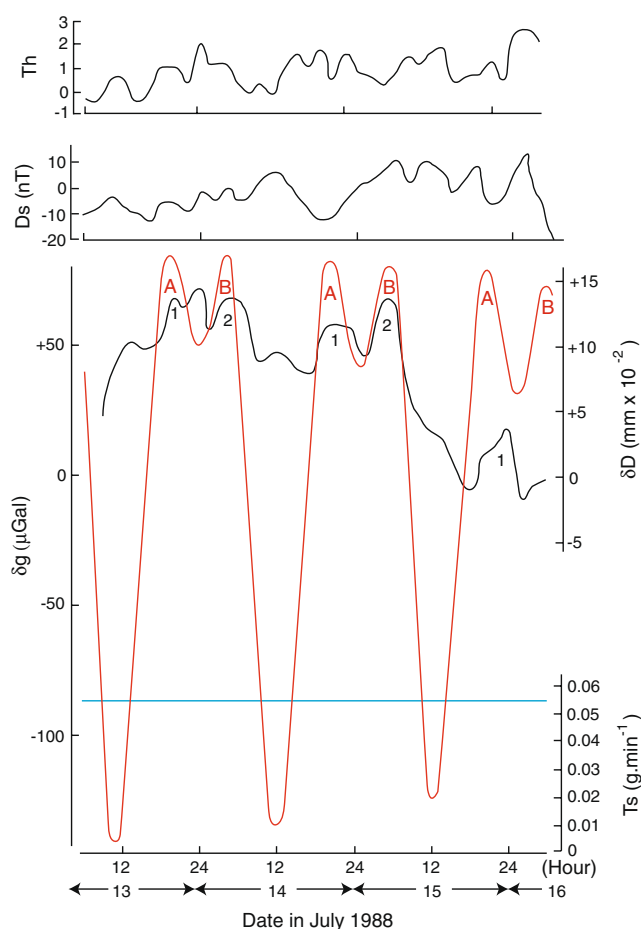
**Fig. 6** Tree no. 2 of *Picea abies* was growing in a cabinet where there was a 12-h light/12-h dark cycle (dark periods are stippled). There was diurnal variation of  $T_s$ . Values of  $\delta D$  (black lines) and transpiration  $T_s$  (blue lines), and of  $\delta g$  (red lines), were recorded during July 1988. In each case, pairs of maximal peaks A,B of  $\delta g$  are nearly coincident with paired peaks 1,2 of  $\delta D$ . Contemporaneous values for the Thule (Th) and the Disturbance Storm Time (Ds) indices are shown in the upper panels

parabolic trends for  $x$  and  $y$  values versus time  $t$ , as well as periodicities (circadian 24.0 h, or circalunidian 24.8 h, with their harmonics up to the tenth) within the time series of both biological and cosmogeophysical data. The method utilises least squares to fit a (co)sine wave [(co)sinusoid] regression to the values under consideration (Nelson et al. 1979). The 95% confidence intervals of the amplitude and acrophase (time of peaking), as well as the 95% confidence (for means) and 95% tolerance (for individual observations) corridors for the total approximating function, were estimated and entered into the graphed data.

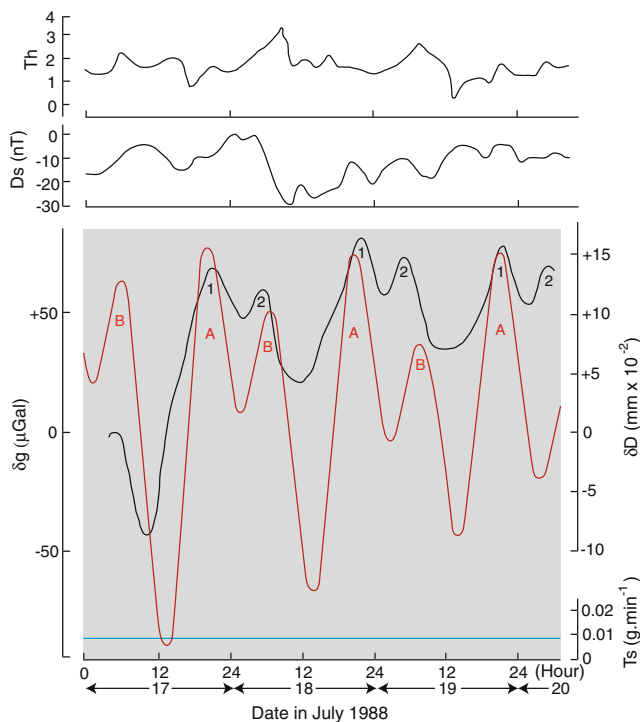
In the simplified cosinor evaluation, single peaks of  $\delta g$  during, say, one lunar day, as in mode 1 (Fig. 1), were treated as single sinusoids. When there were pairs of peaks (A and B) of  $\delta g$  during a lunar day, as in modes 2 and 3 (Fig. 1), the two peaks of the A,B pair were smoothed and treated as

though they were parts of a single sinusoid. Pairs of peaks 1 and 2 in the time series of  $\delta D$  were considered similarly.

**Cross-correlation** The cross-correlation method of Bartlett (1953) describes the linear regression between  $x$  and  $y$  expressed by the common correlation coefficient  $r_{x,y}$  (on the ordinate) as a function of a lag  $L$  (on the abscissa). The point estimate of  $r_{x,y}$  is accompanied by its 95% confidence corridor. Non-overlapping of the zero value of  $r_{x,y}$ , represented on the horizontal axis, means either a significant positive or a negative stochastic dependence of  $y$  upon  $x$  for the given lag. The decisive information is whether the 24 h-cycling of  $r_{x,y}$  versus  $L$  is significant. If so, it will testify that both variables are mutually resonating—in the sense of a coherence, perhaps as part of “a universal synchronisation of natural cyclic processes...based on a composite system of universal causal interactions” (Vasil’eva, 1998). These multidimensional actions can work immediately or with a delay: formally, with a lag  $L_{xy}$  or  $L_{yx}$ , where only the former



**Fig. 7** Tree no. 2 of *Picea abies* was now grown in continuous light.  $T_s$  was constant at approximately  $0.055 \text{ g H}_2\text{O min}^{-1}$ . Details of other measurements are as mentioned in the legend to Fig. 6



**Fig. 8** Tree no. 2 of *Picea abies* was growing in darkness (indicated by the stippling of the whole panel).  $T_s$  was at a minimal level of approximately  $0.01 \text{ g H}_2\text{O min}^{-1}$ . Details of other measurements are as mentioned in the legend to Fig. 6

will be considered as physiologically meaningful. A direct causal effect, e.g. gravity  $\rightarrow$  tree, with or without a delay, is not excluded, however.

**Coherence** A coherence indicates the presence of cycling with the same period lengths but with various phase shifts

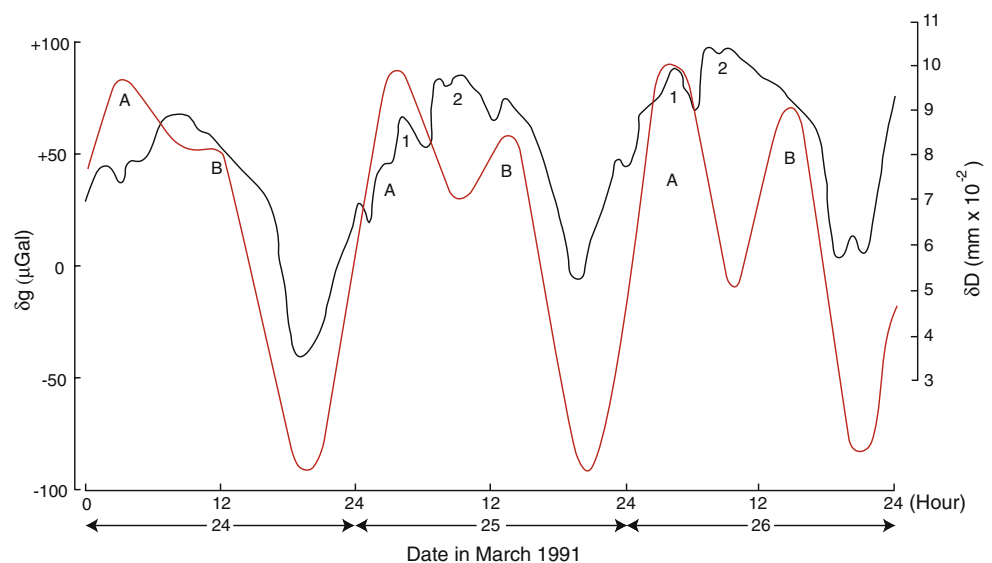
in the data sets. Coherence between two or more variables was searched for by means of cross-spectral analysis (Hannan 1970). Ordinary coherence relates to two variables ( $x, y$ ), whereas multiple coherence evaluates the existence of coherence between one target variable ( $y$ ) and other variables ( $x, w, z, \dots$ ). Partial coherence relates to that between two variables ( $x, y$ ) after excluding the confounding influence of other variables ( $w, z, \dots$ ).

#### Meaningful relationships derived from statistical analyses

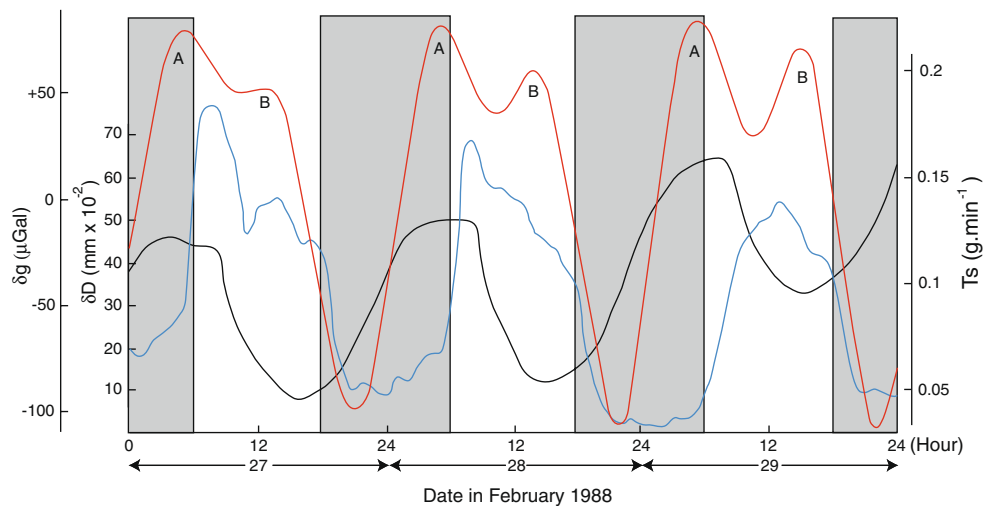
The objective of the above statistical tests was to reveal meaningful relationships between two or more data time series. Significant statistical correlations between biological and geophysical variables do not necessarily imply causation; however, where the two time-series have particularly complex patterns that run in parallel (e.g. Lang 1972), such a supposition might have some justification.

The most important statistical parameters in the present analyses are the significant period lengths, the values of the correlation coefficient  $r$ , the durations of the lags  $L$ , and the coefficients of partial coherence. The present time series of biological data extend over 2–10 days. The longer the time series the more favourable the possibility of discovering temporal trends in, say, the values of  $L$ . The usage of confidence intervals in cosinor and cross-correlation analyses yields a statistical uncertainty not only for the values of  $x, y$  or  $r$  but also for the timing in the cosinor and for the  $L$  estimates in cross-correlation. For example, a confidence interval for  $L$  of 3 h may well cover the zero value.

**Fig. 9** Time series of  $\delta D$  (black line) recorded from a stem of *Juglans regia* during March 1991 and the contemporaneous variations of  $\delta g$  (red line)



**Fig. 10** Time series of  $\delta g$  (red line) and the simultaneously recorded  $\delta D$  (black line) and transpiration rate  $T_s$  (blue line) from a stem of *Abies alba* during February 1988. This tree was grown in a 12-h light/12-h dark cycle (dark periods are stippled)



## Results and discussion

### Variation in stem diameters and lunisolar tidal acceleration

Results are presented in connection with the hypothesis that a valid, and perhaps causal, relationship exists between  $\delta D$  and  $\delta g$ . Supporting evidence is based on graphical representations (Figs. 2, 3, 4, 5, 6, 7, 8, 9 and 10) of these two variables and also upon quantitative and statistical evaluations of the original numerical data. Both perspectives are discussed below.

#### *Trees at an open-air site: results from Vallombrosa*

Time series of  $\delta D$  recorded during September 1976 from a stem of *T. cordata*, as well as the corresponding lunisolar tidal values  $\delta g$ , are shown in Fig. 2. Values of  $\delta D$  obtained via extensometer channel 7 reveal that peaks of  $\delta D$  approximately coincide with the first peak A of each A,B pair of peaks of  $\delta g$ . This pattern, however, is not exactly replicated in results gained simultaneously from extensometer channel 9, positioned lower down the same stem. On 20 September, peak 1 of  $\delta D$  is associated with peak B of the paired A,B peaks of  $\delta g$ . Later, on 21–23 September, the shoulder (1) of  $\delta D$  values is showing a decline and peak 2 of  $\delta D$  appears to have ‘back-tracked’ and to associate more closely with the B peak of the paired A,B peaks of  $\delta g$  (Fig. 2). Thus, the peaks of  $\delta D$  from the two channels 7 and 9 developed at different times; they coincided with different peaks (A and B) of  $\delta g$ , and perhaps showed indications of changing their association with one or other of the  $\delta g$  peaks.

The record of  $\delta D$  via extensometer channel 9 from *T. cordata* on 27 June to 1 July 1977 (Fig. 3) is similar to the pattern of  $\delta D$  during September 1976 (cf. channel 9 in Fig. 2). The single peaks of  $\delta D$  follow the second peak B of each of the paired A,B peaks of  $\delta g$ . However, the

simultaneously recorded single peaks of  $\delta D$  obtained from a nearby tree of *L. tulipifera*, via extensometer channel 11, are associated with the A peaks of the A,B pair of peaks of  $\delta g$ .

From these results (shown in Figs. 2 and 3), it is evident that different locations on the same tree, or at locations on two nearby trees, can display different temporal patterns of  $\delta D$ . Other data (not shown here) also displayed this feature (see Cantiani 1978). Thus, at one location, the pattern of  $\delta D$  is not necessarily synchronous with respect to the pattern of  $\delta D$  at another location: This is because one location on a stem may respond to the A peak of the A,B pair of  $\delta g$  peaks, whereas another location may respond to the B peak.

Results from *P. menziesii* (Fig. 4) not only show features similar to those displayed by *Tilia* but also demonstrate another remarkable property. As noted by Cantiani (1978), segments of a branch cut from a tree continued to show daily variations of  $\delta D$  for as long as the cambium remained alive, which may be for 6 months or more. In one such case (Fig. 4), the peaks of  $\delta D$  (from extensometer channels 5 and 6) coincided with one or other of the paired peaks of  $\delta g$ . Extensometer channel 6, located against the secondary xylem (i.e. below the bark), recorded peaks of  $\delta D$  which coincided with the A peaks of the paired A,B peaks of  $\delta g$ . Readings from channel 5 located on the surface of the bark showed peaks of  $\delta D$  coinciding with the B peaks of  $\delta g$ . A set of ‘control’ data recorded from channel 2 on the stem from which the branch segments had been cut showed the same rhythm of  $\delta D$  as did the excised branch portions at channel 5 (Fig. 4). A second cut segment showed the same pattern of variation of  $\delta D$  as did the one already mentioned (data not shown, but see Cantiani 1978).

A root of *P. menziesii* was studied during September 1976. Variations of  $\delta D$  were generally in near-synchrony with the rhythm of  $\delta D$  displayed in the stem to which the root was attached (Fig. 5). However, whereas extensometer channel 4 located on the root recorded ten peaks of  $\delta D$

during the 5-day recording period, channel 1 located on the stem recorded five peaks of  $\delta D$  during the same period. For the root, every first peak of  $\delta D$  (peak 1) coincided with an A peak of the A,B pair of  $\delta g$  peaks. The other, alternate peaks of  $\delta D$  (peak 2) coincided (at least on 20–23 September 1976) with the B peaks of  $\delta g$  (Fig. 5).

The peaks of  $\delta D$  in the stem recorded by channel 1 are broad and each may be a double peak (1,2). The first (1) of the paired stem peaks of  $\delta D$  coincided with the B peak of the A,B pair of peaks of  $\delta g$  (Fig. 5).

It is not clear why the root should be more sensitive to  $\delta g$  than the shoot (i.e. more peaks of  $\delta D$  developed in a given time and did so apparently in response to each peak of  $\delta g$ ). The same patterns of  $\delta D$  in this root and this shoot were expressed in the following year, between 19 and 26 April 1977 (data not shown, but see Cantiani 1978, Fig. 3). Judging by the markedly different amplitudes of  $\delta D$  in the root (variation of about 0.25 mm per cycle) and shoot (variations of 2.5 mm) (Fig. 5), the respective wavelengths of  $\delta D$  may be related to the thickness of the bark tissue (thinner in the case of root, thicker in the case of the stem).

#### *Trees in a growth cabinet: results from Firenze*

Data concerning  $\delta D$  were obtained from *Pinus abies* by Cantiani and Sorbetti Guerri (1989). Observations made on 9–12 July 1988 were the first of three experiments into the effect of transpiration on  $\delta D$ , though discussion of this transpirational aspect will be deferred until later in this section. A tree referred to as tree no. 2 (another tree of *P. abies*, tree no. 1, was found to give similar results) was grown in 12-h light/12-h dark conditions. Paired peaks (1,2) of  $\delta D$  can be discerned about 4 h after the corresponding paired peaks A,B of  $\delta g$  (Fig. 6). In a second experiment, during the period 12–19 July, when tree nos. 1 and 2 were now growing in continuous light, the pattern of  $\delta g$  had not altered substantially, but now there was closer correspondence between the paired peaks of both  $\delta D$  and  $\delta g$  (Fig. 7).

The third experiment took place on 17–20 July 1988. Tree no. 2 of *P. abies* was now grown in continuous darkness (Fig. 8). The data recorded for  $\delta D$  are particularly important because they were presented by Zürcher et al. (1998) in connection with these authors' suggestion of a link between  $\delta D$  and the lunisolar tidal acceleration  $\delta g$ . The darkened growth cabinet was used in order to minimise (but not abolish) the possible effect of transpiration upon  $\delta D$ . The results (Fig. 8) show not only how the paired A,B peaks of  $\delta g$  had developed from the time some days earlier when the experiment commenced (cf. Figs. 6 and 7) but also reveal that during the 75-h recording period, three relatively 'strong' first peaks (1) of  $\delta D$  developed in approximate coincidence with three correspondingly 'strong' A peaks of  $\delta g$  (Fig. 8). On the two whole days of

18–19 July, two alternate peaks (2) of  $\delta D$  developed shortly before the second, 'weak' B peak of  $\delta g$  (Fig. 8).

Given the good coincidence between peaks of  $\delta D$  and  $\delta g$  in mid-July 1988 (Fig. 7), it can only be conjectured how the slight mismatch of the peaks arose at the later dates shown in Fig. 8. Nevertheless, it can be seen that the time between each successive A and B peaks in a pair of such peaks of  $\delta g$  lengthened over the observation period during July. It may be that the biological system had been continually attempting to develop a rhythm of its own (a solar rhythm, say, or one developed in response to the earlier light/dark regime) and that this was continually being challenged by the ever-changing lunar rhythm. In addition, any dilatation rhythm initiated in the tree stem (to follow a lunar rhythm, say) might require some time to adjust to the changing pattern of  $\delta g$ . Complete coincidence of the  $\delta D$  and  $\delta g$  rhythms may occur only rarely. The two rhythms are usually out of phase due to the changing lunar rhythm and the inertia in the dilatation rhythm. Hence, as observed in the quantitation of such results (Table 2), the corresponding time delays between  $\delta D$  and  $\delta g$  lead mostly to positive and also to a few negative values of  $L$ .

Concluding these visual assessments are results which confirm the apparently consistent positive relationship between  $\delta D$  and  $\delta g$ . They were obtained from the hardwood species, *J. regia* and *M. germanica*. In the case of data from *J. regia*, the graph of  $\delta g$  (Fig. 9) shows the evolution of the maximal values during the 3 days of observation during March 1991. It can only be conjectured as to how the development of  $\delta g$  at earlier dates influenced the illustrated pattern of  $\delta D$  (Fig. 9). However, on 25–26 March, there are hints of an apparent splitting of the  $\delta D$  maxima into two peaks, 1 and 2 (Fig. 9), a split which coincides with the splitting of the maximum of  $\delta g$  into two peaks A and B.

Results from *M. germanica* were more complicated than in any other species analysed. When the *Mespilus* tree was grown in a 12-h light/12-h dark regime the pattern of  $\delta D$  values revealed broad double (1,2) peaks (data not shown) that coincided with the A and B peaks of  $\delta g$ . Later, when the same tree was transferred to darkness, a third daily peak (3) of  $\delta D$  was evident (data not shown). Two of the three peaks of  $\delta D$  values coincided with maximal  $\delta g$  values. Values of the time-delay  $L$  were easily obtained (Table 2).

#### Geophysical variables and stem diameter variations

A preliminary assessment of the relationship between two geomagnetic variables—Thule index  $Th$  and Disturbance Storm Time index  $D_s$ —and  $\delta D$  was made in connection with the data collected from *P. abies* (Figs. 6, 7 and 8), *A. alba* and *J. regia*. In the case of *P. abies*, visual inspection of the graphs in Figs. 6, 7 and 8 indicates



**Table 2** Times delays ( $L_v$ , h) between peaks of  $\delta g$  and  $\delta D$  for various species of softwood and hardwood trees

Species	Species	Date of recording	$\delta g$ peak (A or B); $\delta D$ peak (1 or 2)	No. of $\delta D$ peaks considered	$L_v$	Figures
<i>Tilia cordata</i>	S1; channel 7	19–23/09/1976	A	5	+3, +3, +2, +1, +1	2
<i>T. cordata</i>	S2; channel 9	20–23/09/1976	B; 1	4	0, 0, 0, –	2
<i>T. cordata</i>	S2; channel 9	20–23/09/1976	B; 1,2 (smoothed)	4	+5, +5, +5, +2	2
<i>T. cordata</i>	S3; channel 9	25/06–02/07/ 1977	B	8	+8, –, +7, +1, +3, +7, +3, +3	3
<i>Liriodendron tulipifera</i>	S4; channel 11	25/06–02/07/ 1977	A	9	+7,+3,+7,+1, +1, –1, +2, 0, 0	3
<i>Pseudotsuga menziesii</i>	S6; channel 6	24/06–02/07/ 1977	A	9	+4.5, 0, 0, +1.5, +3, 0, +1.5, 0, 0	4
<i>P. menziesii</i>	S5; channel 5	24/06–02/07/ 1977	B	9	+3, 0, +1.5, 0, 0,+1.5, +1.5, 0, 0	4
<i>P. menziesii</i>	S7; channel 2	24/06–02/07/ 1977	B	9	+4.5, 0, +4.5, 0, +1.5, +1.5, 0, +1.5, +1.5	4
<i>P. menziesii</i>	S8; channel 4	19–23/09/1976	A; 1	5	+3, +2, +1, +1, +1	5
<i>P. menziesii</i>	S8; channel 4	19–23/09/1976	B; 2	5	–, +6, +2, +2, +1	5
<i>P. menziesii</i>	S9; channel 1	19–23/09/1976	B; 1 and 2 (smoothed)	5	+5, +6, +4, +4, +1	5
<i>P. abies</i>	S10	09–12/07/1988	A; 1	3	+4, +4, +5	6
<i>P. abies</i>	S10	09–12/07/1988	B; 2	3	–, +4, +2	6
<i>P. abies</i>	S10	09–12/07/1988	A,B; 1,2 (both peaks smoothed)	3	–, +4, +4	6
<i>P. abies</i>	S11	13–16/07/1988	A; 1	3	+1, +1, +2	7
<i>P. abies</i>	S11	13–16/07/1988	B; 2	3	+1, 0, –	7
<i>Picea abies</i>	S12	17–20/07/1988	A; 1	3	+3, +1, 0	8
<i>P. abies</i>	S12	17–20/07/1988	B; 2	3	–1, –3, –	8
<i>Abies alba</i>	S13	27–29/02/1988	A	3	0, 0, +2	10
<i>Juglans regia</i>	S14	24–26/03/1991	A, B; 1,2 (both peaks smoothed)	3	+4, +3, 0	9
<i>Mespilus germanica</i>	S15	10–12/10/1989	A/2	3	–3, –2, –	Not shown
<i>M. germanica</i>	S15	10–12/10/1989	B/1	3	+2, +2, +1	Not shown
<i>M. germanica</i>	S16	21–24/10/1989	A/3	4	0, 0, 0, 0	Not shown

Where there were clear peaks of the respective variables, the estimates of  $L_v$  are printed in the temporal sequence in which they developed. A positive value of  $L_v$  means that a peak of  $\delta g$  occurred in advance of a peak of  $\delta D$ ; a negative value indicates the converse. A zero value of  $L_v$  indicates coincidence of peaks of both  $\delta g$  and  $\delta D$ . A blank value (–) for  $L_v$  indicates that no value could be obtained due to absence of an evident peak. The column ‘Figures’ indicates the figure in the text which illustrates the peaks from which  $L_v$  values were estimated. However, sometimes, for reasons of space, not all peaks can be illustrated (see Figs. 3 and 4). These unseen peaks have, nevertheless, provided estimates of  $L_v$ ; these values are printed in italic type. Estimates of  $L_v$  are also given for *Mespilus germanica* even though its results are not illustrated with figures in the text.

possible correspondences between Th and  $\delta g$  and, hence, between Th and  $\delta D$ . However, the index Ds had, apparently, a different rhythm to that of Th. The changing pattern of Ds therefore appears to be independent of, and unlikely to be positively correlated with, any pattern which applies to either  $\delta g$ ,  $\delta D$  or Th.

Given the respective short and long wavelengths of  $\delta D$  for root and stem of *P. menziesii* (Fig. 5), a record of Th was taken in case this parameter could in some way underlie the greater sensitivity of roots to  $\delta g$  compared to the stem: i.e. Th may sensitise the root tissue to variations of  $\delta g$ . In this case, however, the time series of Th did not seem support this notion (data not shown).

#### Transpiration rates and stem diameter variations

It is necessary to provide some explanation not only for the rhythm of  $\delta D$  but also for its apparent relationship with lunar gravity. To this end, transpiration rates  $T_s$  in two species of conifer, *P. abies* and *A. alba*, were examined [as was done originally by Cantiani and Sorbetti Guerri (1989)], using these authors’ data, to assess whether  $T_s$  could be a candidate determinant of  $\delta D$ : in particular, whether the daily rise and fall in the values of  $\delta D$  were preceded, or were coincident, with increases and decreases of  $T_s$ . This topic evidently requires an in-depth examination of both the internal and external factors, which may be

involved. Nevertheless, we venture the following preliminary observations.

The graphs presented in Figs. 7 and 8 indicate that, in *P. abies*, stem diameter variations are independent of variations of  $T_s$ : in the two cases illustrated,  $T_s$  was held at two different constant rates by either light or dark growth conditions, yet the stem continued to show variations of diameter. Therefore, at present, the sole candidate determinant of  $\delta D$  is  $\delta g$ .

There is, nevertheless, a superficially attractive reciprocal relationship between  $T_s$  and  $\delta D$  (Figs. 6 and 10). However, the alternating light and dark periods used in the experiments with *P. abies* and *A. alba* may have led to a relationship between  $\delta D$ ,  $T_s$  and  $\delta g$  that was different to that expressed when constant light or dark regimes were used. Given that there are three variables,  $T_s$ ,  $\delta D$  and  $\delta g$ , and irrespective of the lighting regime employed, the results in Figs. 6 and 10 imply two possibilities with respect to  $\delta D$ : that  $T_s$  is a determinant of  $\delta D$  or that  $\delta D$  is a determinant of  $T_s$ ; in each case,  $\delta g$  is a co-determinator of  $\delta D$ . The use of the alternating 12-h light/12-h dark regime might help to resolve this problem, but only if the light or dark phases could be shown to influence one of the variables, say  $T_s$ , independently of the other, say  $\delta D$ . Figure 6 shows that, as would be expected,  $T_s$  increased rapidly to reach a maximum value (quantitatively similar to the value achieved in continual light, cf. Fig. 7) shortly after the onset of the light period. Later,  $T_s$  declined upon the onset of darkness. However, the question is whether there were additional or independent influences that could regulate  $T_s$ . It is notable that, in the two whole days of observation, the decline of  $T_s$  coincided with the attainment of the A peak of the paired A,B peaks of  $\delta g$ . Likewise, the onset of the rapid increases of  $T_s$  coincided with rapid decreases in  $\delta g$  from its B peak (Fig. 6).

The observations from *A. alba*, where a 12-h light/12-h dark regime was also employed, confirm the possible interrelationships between the three variables,  $T_s$ ,  $\delta D$  and  $\delta g$ , as described above for *P. abies*.  $T_s$  increased most steeply when the light period commenced (Fig. 10), but this increase also coincided with a fall from the A peak of  $\delta g$ .  $T_s$  declined rapidly when the light period terminated, but this decline coincided with the decline of  $\delta g$  from their B peak maxima. Although not mentioned earlier, it can be seen in Fig. 10—as we have come to expect—that successive maxima of  $\delta D$  coincide with successive peak values of  $\delta g$ , in this case with the A peak of the A,B pairs of peaks.

In both *P. abies* and *A. alba*, it is noteworthy that there was a slow increase of  $T_s$  during the dark period, before the light period commenced (Figs. 6 and 10). In both cases, the increases coincided with the increase in  $\delta g$  values. Although the rapid increase in  $T_s$  was surely triggered by the onset of light, nevertheless, in both species of trees, the increases in  $T_s$  also coincided with rapid downturns of  $\delta g$ .

For *Abies*, the relevant downturns were those of the A peaks of  $\delta g$ , whereas for *Picea*, it was those of the B peaks. It may be a coincidence that the transitions between light and darkness in both these experiments occurred at the time of a peak of  $\delta g$  values.

#### Quantitative evaluations

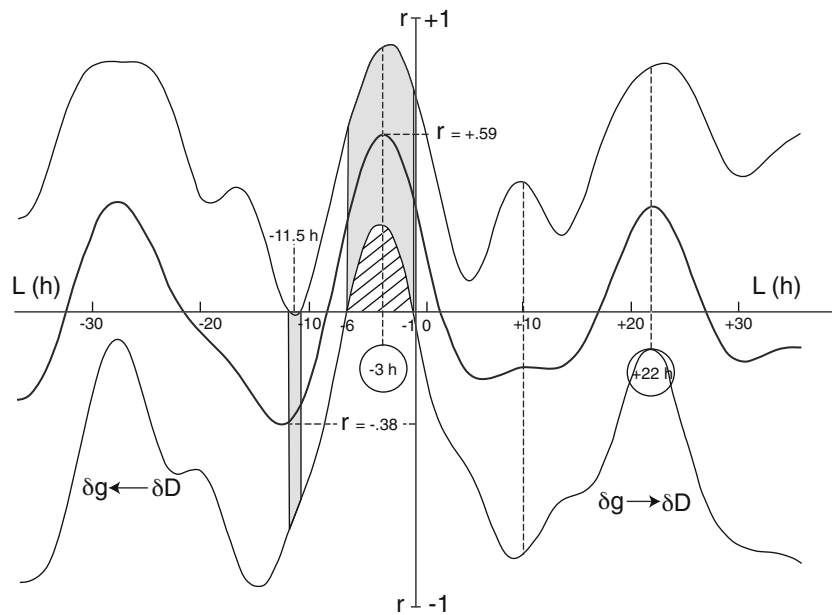
##### *Stem diameter variations in relation to lunisolar tidal acceleration*

*Visual inspection* Time series of  $\delta D$  (Figs. 2, 3, 4, 5, 6, 7, 8, 9 and 10) nearly always demonstrated that each peak of  $\delta D$  followed a peak of  $\delta g$  after a short time delay. These delays ( $\delta D$  after  $\delta g$ ), as judged from visual inspection, are indicated as positive values of  $L$  in Table 2 (here denoted by  $L_v$ ). Values of 0, +1 and +2 h are quite characteristic of the delay between  $\delta g$  and the following  $\delta D$ . Had the delays been more random, rather than putatively being related to the timing of the peak of  $\delta g$ , then they would have shown values between 5 and 12 h, these being the half-period between pairs of peaks A,B and major single peaks.

In a few cases,  $L_v$  had a negative value (Table 2) due to a peak of  $\delta D$  preceding the nearest peak of  $\delta g$ . The negative values, however, may indicate variation in the putative response of  $\delta D$  to  $\delta g$ . Presumably, there is some inertia in the biological system regulating stem diameter; hence,  $-L_v$  values should not necessarily be taken as evidence of a biological event anticipating a geophysical event (Khabarova 2004). As suggested above, such anticipation may arise as a consequence of the particular structure of biological rhythms vis à vis lunar rhythms.

*Statistical evaluation* The principal statistical assessments were made with respect to the relationships between  $\delta D$  and  $\delta g$  and between  $\delta D$  and Th. Searches were also made for coherences within the time series of  $\delta D$  and  $\delta g$ . In the case of the dark-grown tree no. 2 of *P. abies*, cross-correlation indicated that the possible effective delay of  $\delta D$  after  $\delta g$  was 22 h (Fig. 11). This result is similar to that revealed by visual inspection (Table 2). The plot of the parabolic regression between  $\delta D$  and  $\delta g$ , with the  $-3$  h adjustment due to the value of  $L$ , is shown in Fig. 12. In the case of *A. alba*, the delay for the positive relationship of  $\delta D$  with  $\delta g$  had a similar value.

Regressions and cross-correlations relating  $\delta D$  with Th indicated significant relationships (Figs. 12 and 13). Using data set S11 relating to *P. abies* and the relevant time-delay-adjusted values of Th and of  $\delta g$ , the following regression equations were obtained (see Fig. 12):  $\delta D = 9.7 + 0.09\delta g - 0.001\delta g^2$  ( $P < 0.001$ ) and  $\delta D = 13.0 - 1.84Th - 0.975Th^2$  ( $P < 0.001$ ). Using data



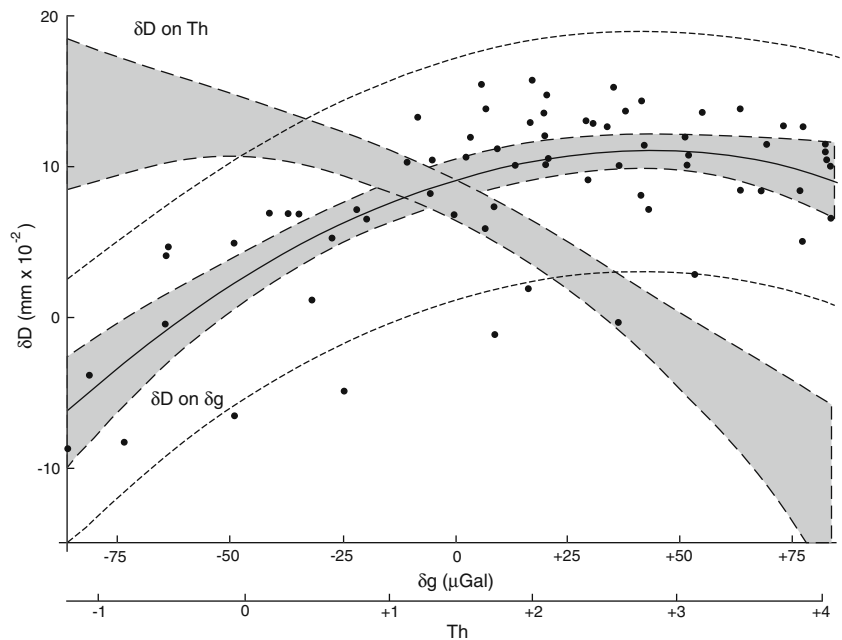
**Fig. 11** Cross-correlation between  $\delta g$  (independent variable) and  $\delta D$  (dependent variable) using data set S12 from *Picea abies* (cf. Fig. 8). Vertical axis shows the correlation coefficient,  $r$ ; horizontal axis shows the time delay  $L$  between the two fitted sinusoids corresponding to  $\delta g$  and  $\delta D$ . Positive  $L$  values for a time delay of  $\delta D$  after  $\delta g$  (denoted as  $\delta g \rightarrow \delta D$  in the graph) belong to the right-hand horizontal semi-axis, whereas negative  $L$  values for the opposite delay of  $\delta D$  advanced before  $\delta g$  ( $\delta g \leftarrow \delta D$ ) belong to the left-hand semi-axis. For

the peaks,  $L_{xy} = L_{\delta g \rightarrow \delta D} = +22$  h,  $L_{yx} = L(\delta g \leftarrow \delta D) = 3$  h, both together constituting the period length of 25 h. In addition to the point estimates of  $r$  for separate values of  $L$  (bold solid line), a 95% confidence corridor for  $r$  is also given (upper and lower thinner lines). Significant departures of the  $r$  value from 0 are indicated by shading and stippling in the area between the horizontal axis and the confidence corridor. The direction of time-shifting is marked by the arrow, the head of the arrow pointing to the delayed variable

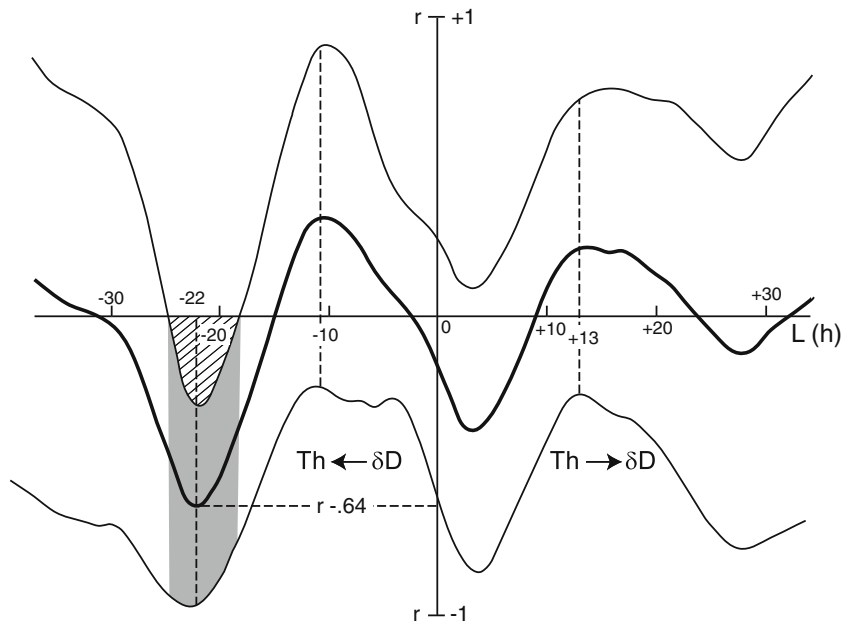
set S13 relating to *A. alba*, the corresponding regression equations were as follows:  $\delta D = 39.3 - 0.21\delta g (P < 0.001)$  and  $\delta D = 56.9 - 24.94.Th (P < 0.001)$ . If  $\delta g$  influences the values of  $Th$ , then a putative direct influence of  $Th$  on  $\delta D$  is unlikely. However, in consideration of the results

from assessments of coherence (see following paragraph), it would be premature to rule out a geomagnetic influence from  $Th$  using arguments based on regression analysis. A graphical summary of the relationships between  $\delta D$ ,  $\delta g$  and  $Th$ , as they apply to *P. abies*, is given in Fig. 14.

**Fig. 12** Parabolic dependences of  $\delta D$  upon  $Th$  and  $\delta D$  upon  $\delta g$  are shown in relation to data set S12 from *Picea abies* (cf. Fig. 8). The limits of the 95% confidence corridors for both relationships are indicated by the stippled areas. The values used for  $\delta D$ ,  $\delta g$  and  $Th$  are those which had been derived from the respective delays in relation to  $\delta D$  (cf. Figs. 11 and 13). The regression equations are given in the text. The delay of  $\delta g$  after  $\delta D$  is 3 h for the peak of the correlation coefficient and that of  $Th$  after  $\delta D$  is 22 h for the trough



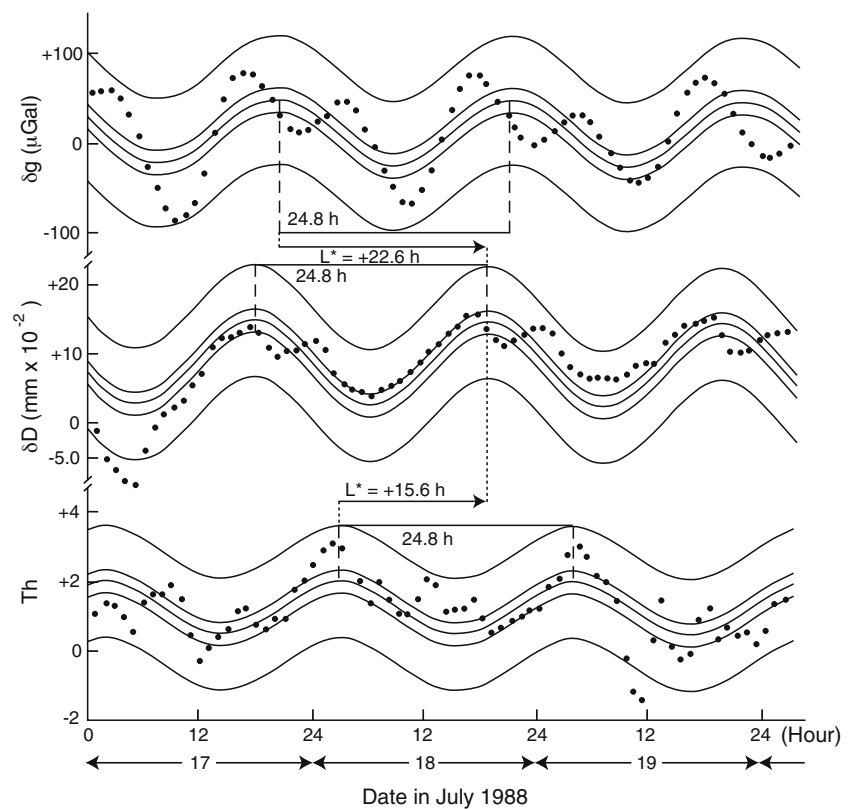
**Fig. 13** Cross-correlation similar to that shown in Fig. 11 but dealing with the relation between  $\delta D$  and  $Th$ . The data for these geophysical variables coincide with data pertaining to the biological variables from data set S12 for *P. abies* (cf. Fig. 8). The conventions for interpreting the correlogram are as in the legend for Fig. 11. Note that the log value of  $L=+13$  h of  $\delta D$  after  $Th$  may also extend to  $L=+15$  h or more, and thus accommodate the value of  $L^*=+15.6$  h indicated in Fig. 14, which was evaluated by cosinor analysis



It would be difficult, if not impossible, to test which relationship is more in accord with the time series of  $\delta D$ , a 24.0-h solar rhythm or a 24.8-h lunar rhythm. With regard to the hypothesis that, in the data gained from *P. abies*, a solar rhythm regulates the changes in  $\delta D$ , the corresponding coefficient of determination (CD, i.e. the square of the correlation coefficient, which tells of the proportion of the

total variance in the data explained by the regression) is 0.905. However, if the hypothesis is that a lunar rhythm is the determinant, then the estimated CD is 0.917. Likewise, data from *A. alba* reveal the CDs in relation to  $\delta D$  to be 0.989 (solar) and 0.984 (lunar). These analyses speak for an almost statistically indistinguishable participation of Sun and Moon in the regulation of  $\delta D$ , where *A. alba* is

**Fig. 14** Simplified cosinor analyses of data relevant to *Picea abies* gathered during mid-July 1988 (cf. Fig. 8). The data relate to  $\delta g$ ,  $\delta D$  and  $Th$ . Time delays ( $L^*$ ) between successive peaks are indicated (cf. Figs. 11 and 13). Note that the double peaks of  $\delta g$  and  $\delta D$  (cf. Fig. 8) have been smoothed as single sinusoids, thereby removing some of the nuanced ‘highlights’ of these variables. The original data for  $\delta D$  (circle) relate to tree no. 2 of *P. abies* and have been presented by Cantiani and Sorbetti Guerri (1989) and by Zürcher et al. (1998). Circalunidian (24.8 h) cycling with its harmonics is evident for each variable. The broken vertical lines mark the limits of a 24.8-h lunar ‘day’. The 95% confidence corridors (narrow bands) and 95% tolerance corridors (broad bands) around the respective regressions are shown



concerned, whereas for *P. abies* there is indication of a slight predominance of an effect from the Moon on  $\delta D$ .

The two data sets S11 and S13 were searched for coherence using ordinary, multiple and partial cross-spectral analyses to obtain the respective coefficients from separate period lengths. A test of data (S11) from *P. abies* showed that ordinary coherence between  $\delta g$  and  $\delta D$  was significant for the periods under 3 h and over 9 h; multiple coherence was significant between  $\delta D$  with Th, on the one hand, and between  $\delta g$  with Th, on the other hand, for the periods under 2 h and over 21 h; partial coherence between  $\delta g$  and  $\delta D$  after exclusion of Th was non-significant, but between  $\delta D$  and Th, excluding  $\delta g$ , it was significant for the periods 3.6–3.8 and 12.8 h. These findings speak in favour of mutual links between the actions of macrocosmic forces (lunisolar gravity and Thule index) in the regulation of tree stem diameter variation. In fact, variations in Th which coincided with the  $\delta D$  values gathered from *J. regia* (Fig. 9) also showed some small positive correlation (data not shown). Clearly, a much larger study is needed to establish (or deny) these relationships, but nevertheless, these preliminary assessments indicate that there is a statistical methodology capable of revealing hitherto unlooked-for interrelationships.

#### *Lunisolar tidal acceleration in relation to geomagnetic activity*

Although relationships between different geophysical variables are beyond the scope of the present paper, they should, nevertheless, be briefly mentioned because they bear on the possibility that Th and  $\delta g$  together may affect  $\delta D$ .

In view of the possibility that Earthly and lunar gravity can influence the geomagnetic flux (Maeda 1968), three time series S12, S13 and S14 were examined to see if any relationships were apparent between the numerical data for Th and  $\delta g$  contained therein. These variables showed plausible correlative interrelationships (CD=0.905 and CD=0.962) in two of the three time series (from S12 and S13). However, relationships between Th and  $\delta D$  were found to be weak (CD=0.57, approximate) in all three cases.

### General discussion

In general, there were many close correspondences between peaks and troughs of  $\delta D$  and  $\delta g$ , as well as significant statistical correlations between the respective time series of these variables. In some cases,  $\delta D$  peak 1 (say) visibly tracked  $\delta g$  peak A; in other cases, it was  $\delta g$  peak B that was tracked by  $\delta D$  (Figs. 2 and 3). This feature may explain why some simultaneously obtained records of  $\delta D$  were not in synchrony with each other, even though they concerned parts of the same tree or related to two neighbouring trees

(*Liriodendron* and *Tilia*, Fig. 3). This means that care must be taken when analysing and discussing these types of data. Moreover, some caution needs to be exercised in pursuing relationships with the A and B peaks of  $\delta g$  until the full picture of lunisolar gravity can be obtained by estimating also its horizontal component. An implication of the observation of asynchrony of  $\delta D$  within or between trees is that the changing modes of  $\delta g$  are closely tracked and responded to by whatever internal biological system regulates  $\delta D$  in the stems and roots. Comparisons of the delay between  $\delta g$  and  $\delta D$ , as assessed by visual and statistical evaluations, indicate some differences between them. This is largely because the statistical approach, at least as used here, amalgamates paired peaks of  $\delta g$  and  $\delta D$  into single peaks. The maximal values of each peak in a pair obviously will influence the fitting of sinusoids. The visual approach, however, retains the important nuances in the plotted data.

Regarding the biological regulator of  $\delta D$  and the transduction and integration of lunisolar gravity  $\delta g$ , nothing is yet known of the thresholds of perception (Volkman and Tewinkel 1996; Barlow and Powers 2005) of this particular geophysical variable. All observed peaks and troughs of  $\delta g$  were accompanied by analogous peaks and troughs of  $\delta D$ . It may be that, in the cases of the tree species studied, sufficient variation of  $\delta g$  was experienced to produce corresponding variations in  $\delta D$ . The height from the ground of the recording point on the tree stem was one factor, which influenced the amplitude of  $\delta D$  (Cantiani and Sorbetti Guerri 1989) but, as already indicated, this may be attributed to the thickness of the bark according to its age.

Ideally, correlations between  $\delta g$ ,  $\delta D$  and Ts should be sought throughout a complete lunar month, thus accommodating the changing relationships brought about by the changing modes of  $\delta g$ . Softwood conifers seem ideal to test such relationships since they transpire and show rhythmic variations in  $\delta D$  throughout the year. Remarkably, their branches and trunks exhibit this rhythm even when removed from the living tree and cut into segments (Fig. 4). This finding alone is sufficient to dispel the notion of a relationship between transpiration and  $\delta D$ , and the same conclusion is reached from observation on trees that have been defoliated or their crowns removed: the dilatation rhythm of  $\delta D$  persists (Cantiani and Sorbetti Guerri 1989). Nevertheless, some workers (Vesala et al. 2000; Sevanto et al. 2003) persist with the view that water potential and transpiration underlie stem diameter variation. The above-mentioned observations do not accord with such a notion. Moreover, it is difficult to see how the published data of Sevanto et al. (2003) support their view in any convincing way: Their data for  $\delta D$  from two species of trees put alongside the corresponding transpiration data do not indicate any particularly logical relationship—and, unfortunately, the authors omit from the graphs the rather



crucial sign (+ or -) for the  $\delta D$  values (see their Figs. 1 and 2).

The pattern of peaks and troughs of lunisolar  $\delta g$  may act as a timekeeper capable of regulating cyclical effects on plant functioning induced by solar rhythms. The timekeeper continually brings a solar-driven rhythm back into line with a lunar rhythm. This could account for the difficulty, or impossibility, of unambiguously attributing variation of  $\delta D$  to either Sun or Moon because influences from both are at work continually and simultaneously (Brown 1976). Sometimes, independent receptors for the Sun and Moon effects on biological rhythms have been proposed (Webb and Brown 1959). Even though geomagnetic forces are weak and poorly understood in relation to life, they evoke clear responses in relation to biological processes (Brown 1976). A general conclusion derived from consideration of  $\delta D$ - $\delta g$  interrelations might be summed up in the words of Burr (1945): "It is, therefore, not at all impossible that the lunar cycle produces, in some as yet undiscovered way, tides in the tree. Moreover,...since growth in trees is in part a matter of hydration, it may eventually turn out that the effect of the lunar cycle...is as direct as on the [marine] tidal level."

Variations in Thule index often did not appear to accord with either changes in lunar gravity or the biological events studied, though they did so weakly in three cases (see Figs. 6, 13 and 14). However, it should not be forgotten that putative influences from lunar gravity could be products of a nexus of cosmic influences (Brown 1964; Vasil'eva 1998), reflecting an earlier view of Tchijevsky who pointed out<sup>2</sup> that apparently chaotic biological/geophysical relationships might become explicable when much more is known about cosmic cycles (Tchijevsky 1940). While such cycles often take months or years to complete (Breus et al. 1995), in the present cases, the responses of trees to  $\delta g$  were rapid, being accomplished within a few hours (Table 2).

The possible practical importance of these studies should be considered. Zürcher (1999) and Zürcher et al. (2010), as well as commercial companies such as 'Tonewood' (2009) have referred to traditional forestry experiences which indicate that valuable technical properties of wood are subject to variation according to the synodic phase of the Moon during which trees are felled. The present findings indicate that, for practical purposes, relating  $\delta g$  to stem diameter variation might provide a basis for optimising the times of night and day for the felling of trees in relation to subsequent utilisation of their wood.

<sup>2</sup> "Ainsi les contours chaotiques de tel out el phénomène dans ses forms dynamiques subissent quand on change de point de vue, une transformation. Il se révèle comme un mouvement harmonieux qu'on peut figurer par une série d'oscillations sinusoidales soumis dans le temps aux oscillations des forces invisibles de l'énergie cosmique ou solaire." (Tchijevsky 1940, p224).

Equally important is our hope that, by exposing these relationships between  $\delta g$  and  $\delta D$ , more discussion may be raised, and hopefully, new and properly controlled experiments can be devised, perhaps on a worldwide basis, in order to capture the continual shift of lunar tidal accelerations. If confirmatory of a relationship between trees and lunar gravity, then new theories of this linkage must be sought, as Dorda (2004) has already attempted, and then experimentally pursued.

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**Conflict of interest** The authors declare that they have no conflict of interest.

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