# 6 Results & Discussion

## 6.1 Changes in amplitude

Over the period 3rd–6th May 2009, there were two occasions on which the pendulum amplitude dropped significantly, for no apparent reason. This gives the opportunity to test the relationship derived in Section 4.2 between going and amplitude. The upper part of Figure 6.1 shows the time histories of amplitude and going, while the lower part shows going plotted against amplitude; it is clear that there is a link between them. The dashed line corresponds to the result of Section 4.2, that $dG/dA = -583\,\text{ms}\,\text{day}^{-1}/\text{mrad}$. The match between this and the data seems extremely good.

Another example is shown in Figure 6.2. On this occasion (in the early hours of the 15th April 2009), the clock had not been wound and when the weights reached the bottom of their descent, the clock stopped. In this case, the slope of −583 ms/day/mrad appears to hold initially, but as the pendulum amplitude decays further, going increases faster than predicted.

What might cause this? One potential problem is that for large changes in amplitude,

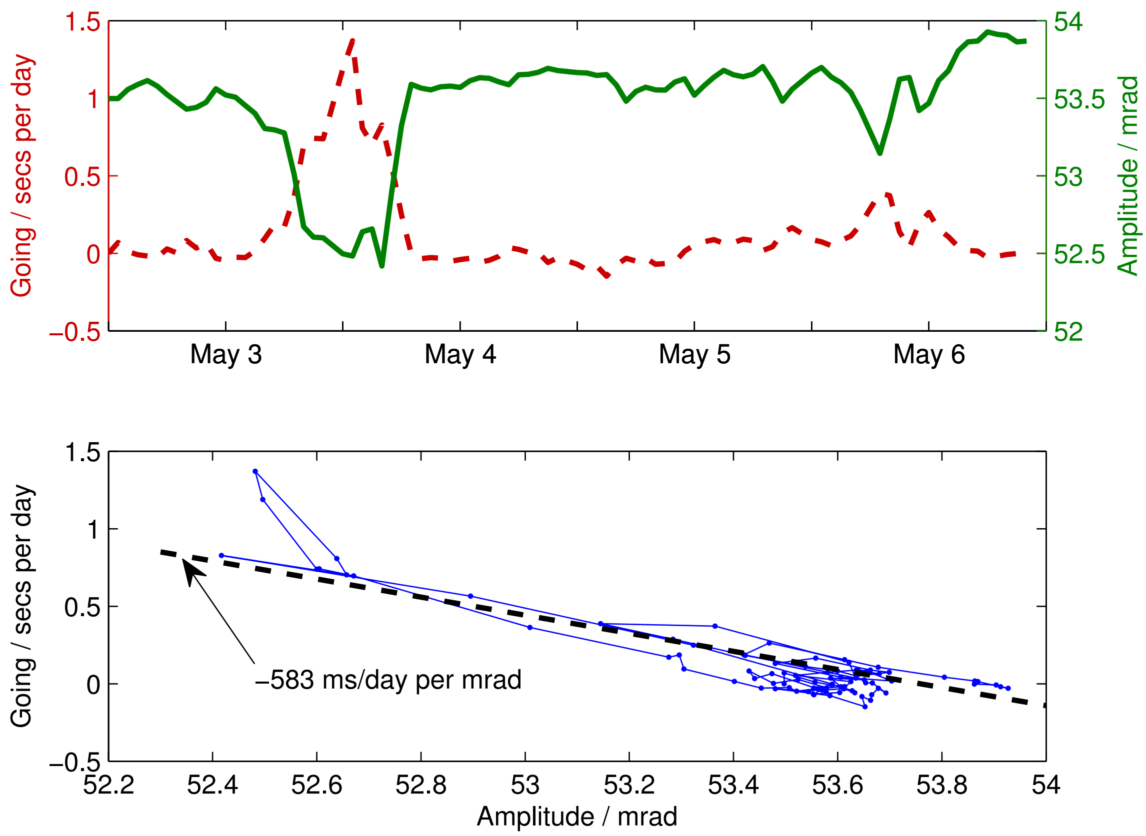


FIGURE 6.1: Going (dashed) & amplitude (solid). [3–6 May 2009, averaged hourly]

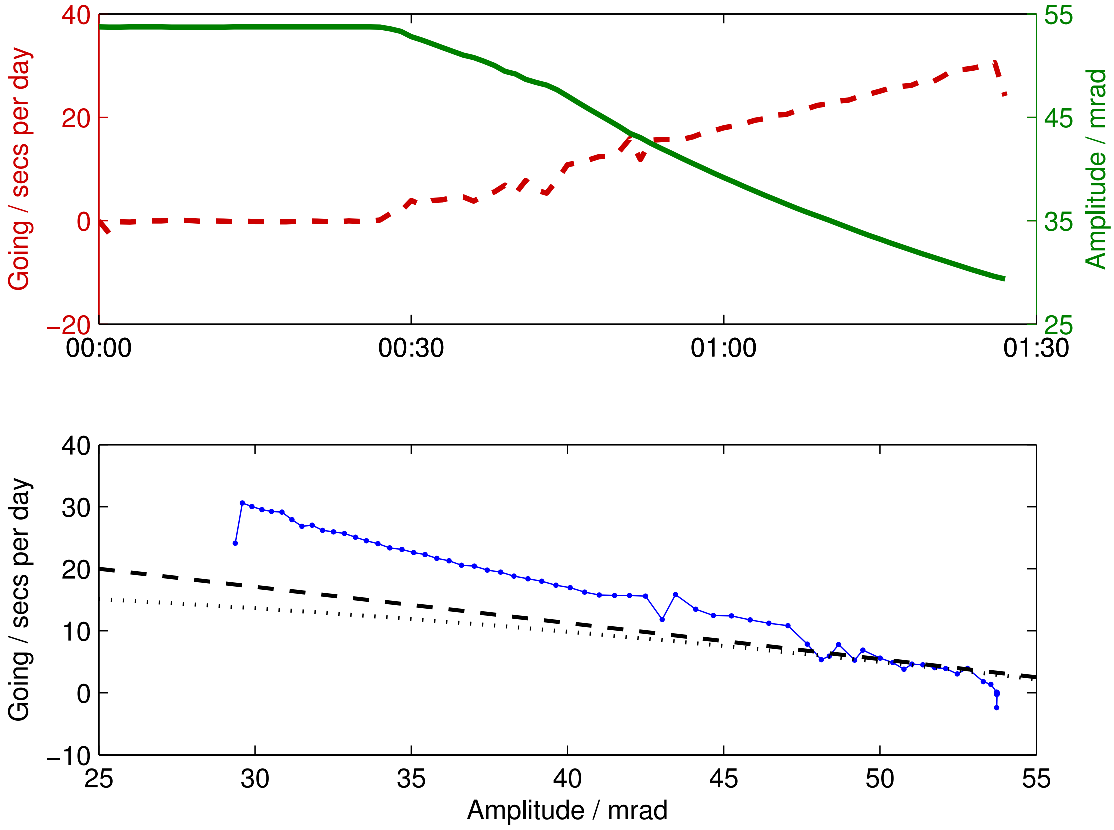


FIGURE 6.2: Going (dashed) & amplitude (solid). [15 April 2009, averaged over 1 minute]

the linear variation used above will no longer hold. Rather than a straight line, we need to plot the curve given by

$$G = \text{const} - \frac{A^2}{16}$$

This is shown in Figure 6.2 by the dotted curve: this improvement does not explain the discrepancy.

Another possibility is that the decay is being disrupted by variations in the weight tension, as the weights settle onto the bottom of their shaft. It would be interesting to repeat this analysis when the clock has been purposefully stopped and the weights cannot influence the pendulum. In any case, there is another effect at work.

Figure 6.3 shows a third example. Here, over the course of 7 days, there seem to be two distinct 'blobs' in which the going-amplitude law is followed, but something else has happened to shift between them. This might indicate a new effect with a *positive* slope of going against amplitude.

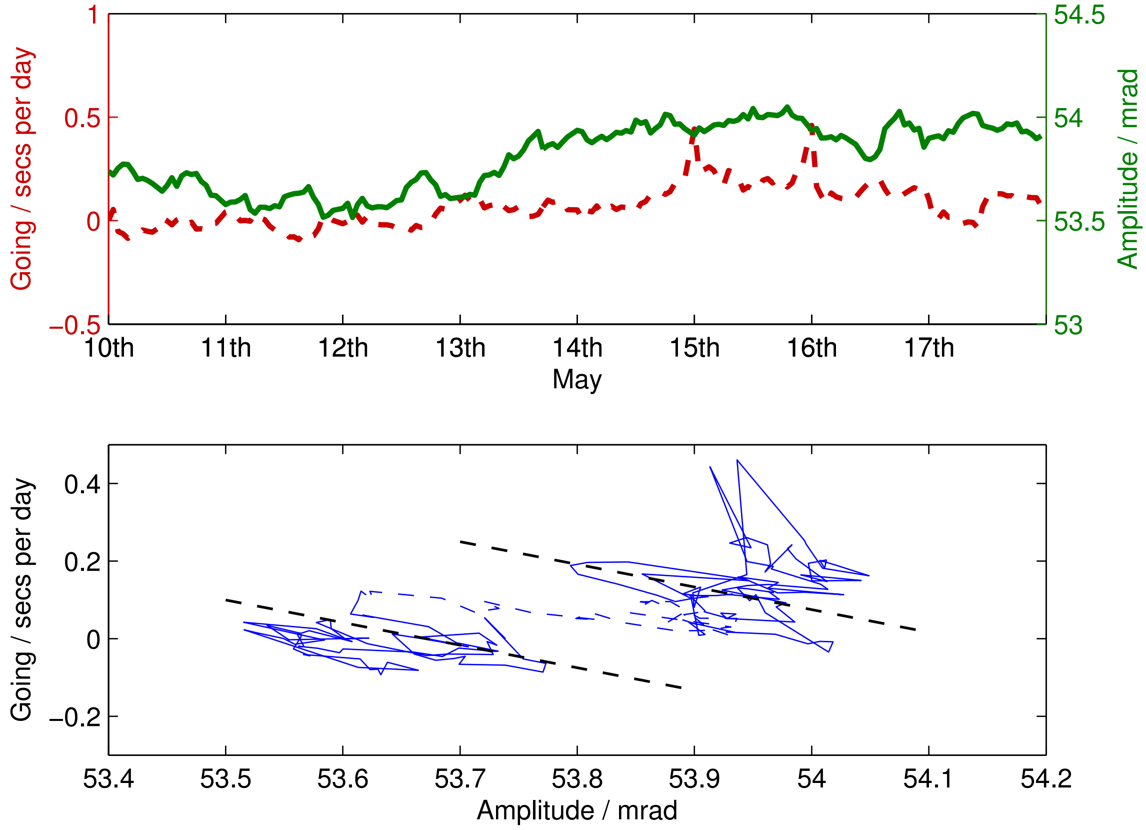


FIGURE 6.3: Going (dashed) & amplitude (solid). [10–17 May 2009, averaged hourly]

## 6.2 Changes in air density

As discussed in Section 4.7.1, pressure is a good proxy for air density, and is used in this example; Figure 6.4 shows the correlation between density, pressure, humidity and temperature to justify this. Figure 6.5 shows the variation of pressure and amplitude over 27 days in April & May 2009. As before, the upper part shows the time histories, and the lower part shows amplitude plotted against pressure.

The theoretical line of slope $dA/dp = -0.018$ mrad / hPa is drawn, and the agreement with the data is quite good. Note that there are two outliers, which correspond to the unusual drop in amplitude observed on the 3rd & 4th May and discussed in Section 6.1.

Overall we expect going to decrease with increasing air density (from the combined effects of drag, buoyancy and added mass) at $-2300\,\mathrm{ms\,day^{-1}/kg\,m^{-3}}$. The going over the same period as above is shown in Figure 6.6. There seem to be two periods where the going—density relationship is similar to predictions, separated by the large drop in amplitude on the 3rd & 4th May, although the gradient is closer to $-6000$ (dotted line) than $-2300$ (dashed line). As there are three effects contributing here it is difficult to know which prediction is wrong.

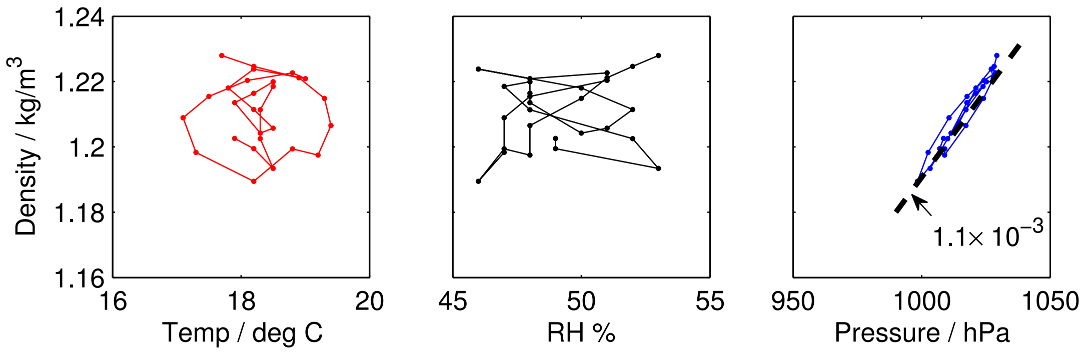


FIGURE 6.4: Density against air temperature, humidity and pressure. Pressure is the dominant influence. [20 April–17 May 2009, averaged daily].

## 6.3 Temperature & drift

Figure 6.7 shows the relationship between drift and temperature. The best-fit value is about −150 ms / degree, which is rather more than the value of −40 found in Section 4.5. This difference is unsurprising, given the many assumptions made about heat capacity, internal surface heat resistance and internal dimensions of the pendulum in order to find the value of −40.

With the predicted time constant of about 1.5 hours, there should be changes in drift due to short-term variations in temperature as well as the longer term ones just considered. Figure 6.8 shows the same period as Figure 6.7, but at a sample rate of once per hour rather than once per day. The same overall correlation is visible, but the diurnal temperature swings do not seem to have the expected effect on the drift. This suggests that the time constant is actually somewhat longer than 1.5 hours: either the thermal mass of the pendulum layers or the thermal resistance between them is larger than estimated.

## 6.4 Changes in pendulum length

Step changes in the length of the pendulum are not usually expected in a clock, apart from the temperature compensation effects discussed above. However, there was one occasion when this may have happened. The clock was not wound when it should have been, and it stopped in the early hours of 15 April 2009 (Figure 6.9, left). When it was restarted, the going had dropped to −23.5 s/day (Figure 6.9, right). This could have been due to the pendulum knocking into the wall and somehow making the bob weight fall slightly, as it was pushed to restart it. There are scratches on the IR sensor fitting to support this suggestion, but it is just a theory.

In any case, the change in going caused by a change in length is

$$\Delta G = \frac{-\Delta T}{T} = \frac{-\Delta L}{2L}$$

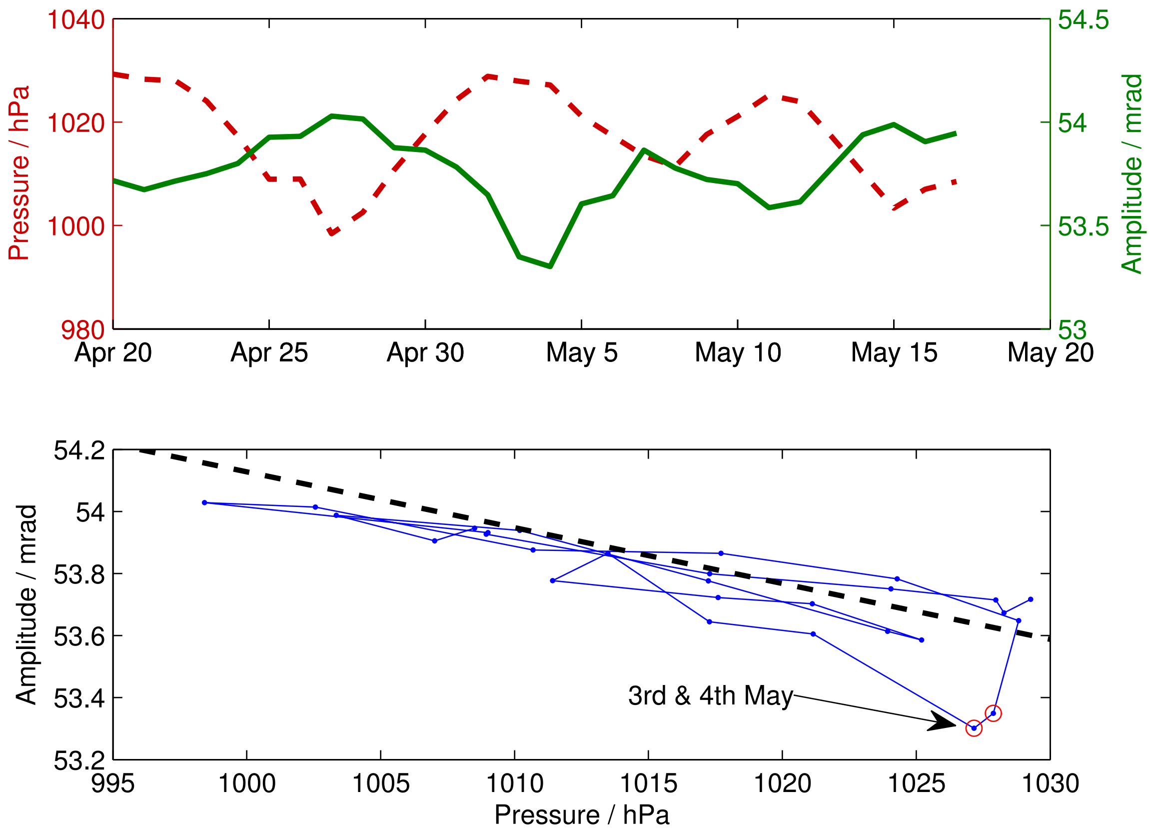


FIGURE 6.5: Amplitude (solid) & air pressure (dashed). [20 April–17 May 2009, averaged daily]. The points labelled "3rd & 4th May" are at unusually low amplitude, see Figure 6.1.

so this change in going would require a increase in length of 1.2 mm (given that the length of the pendulum is 2.2 m).

The going in Figure 6.9 returns to normal with the addition of lots of washers, which can be seen in the photo in Figure 4.2.

## 6.5 Tidal variations

The theory of extracting the very small tidal variations from everything else that is going on was discussed in Section 5, with the conclusion that at least 45 days of data would be required, probably more. Unfortunately currently only about 30 days of uninterrupted data are available; nonetheless it has been analysed and is shown in Figure 6.10. Here, the spectrum of the going has been found, both at the original sample interval of 3 seconds, and also calculated over one-hour intervals (only the hourly going is shown in the time domain; the noise in the 3-second going would swamp the plot). The spectra are shown below, for both the 3 second and hourly data. A Hann window of length of 5 or 10 'tidal lunar days' (i.e. period between the Moon passing overhead on successive occasions, slightly more than a solar day) was used to try and match the periodicy of the signal.

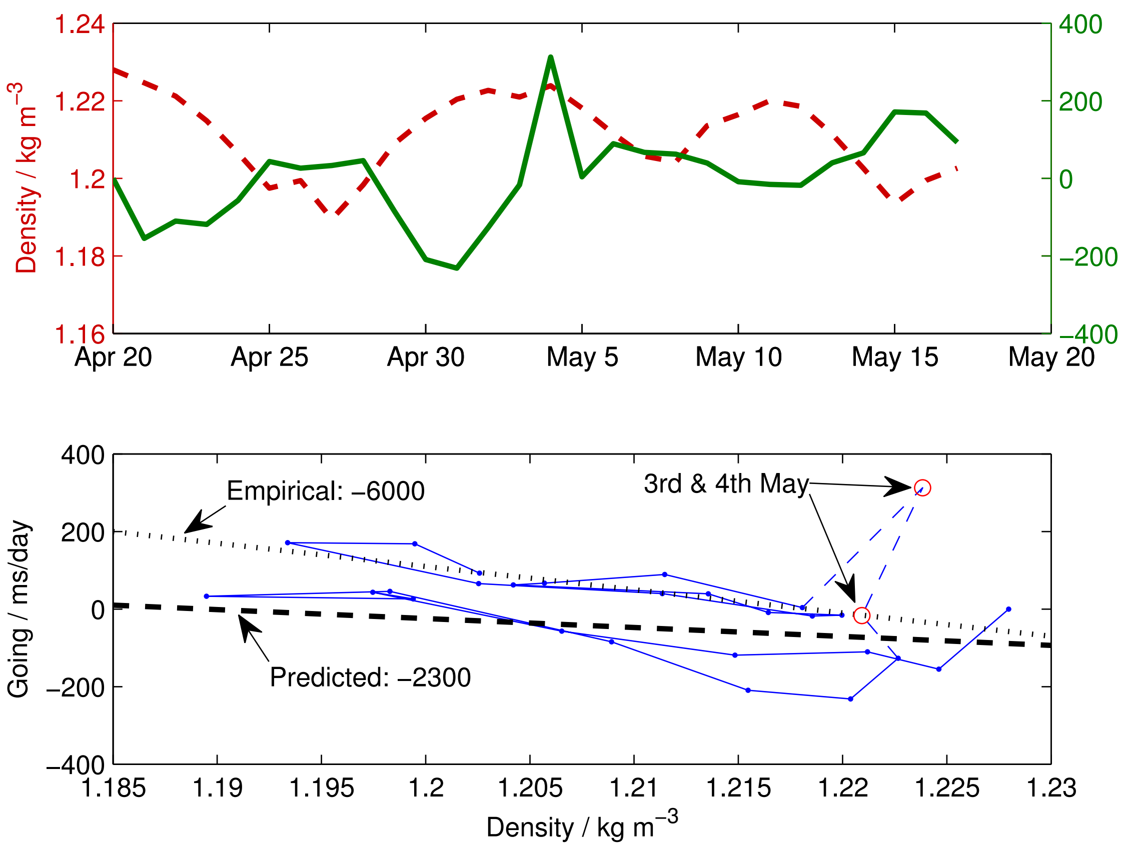


FIGURE 6.6: Going (solid) & air density (dashed). [20 April–17 May 2009, averaged daily]. As above the points labelled "3rd & 4th May" are outliers.

No tidal variation is visible; although there might seem to be a small peak at 2 cycles per day, this is still close to the noise level and in any case does not appear when the 10 day window is used. There still seems to be quite a lot of spectral leakage raising the spectrum at low frequencies, which could perhaps be reduced by clever use of other spectral analysis techniques. Hopefully also once a longer complete data record is available, better results will be possible.

It may also be possible to improve the going data by removing unwanted variations. For example, changes in amplitude have a large effect on going, but since the amplitude is known at every point in theory this variation could be subtracted, leaving a cleaner going signal.

## 6.6 Unexplained results

### 6.6.1 Step changes in going

Figure 6.11 shows an occasion on which the going changed quite significantly (about 150 ms / day) for no obvious reason. The other recorded quantities are also shown, and there

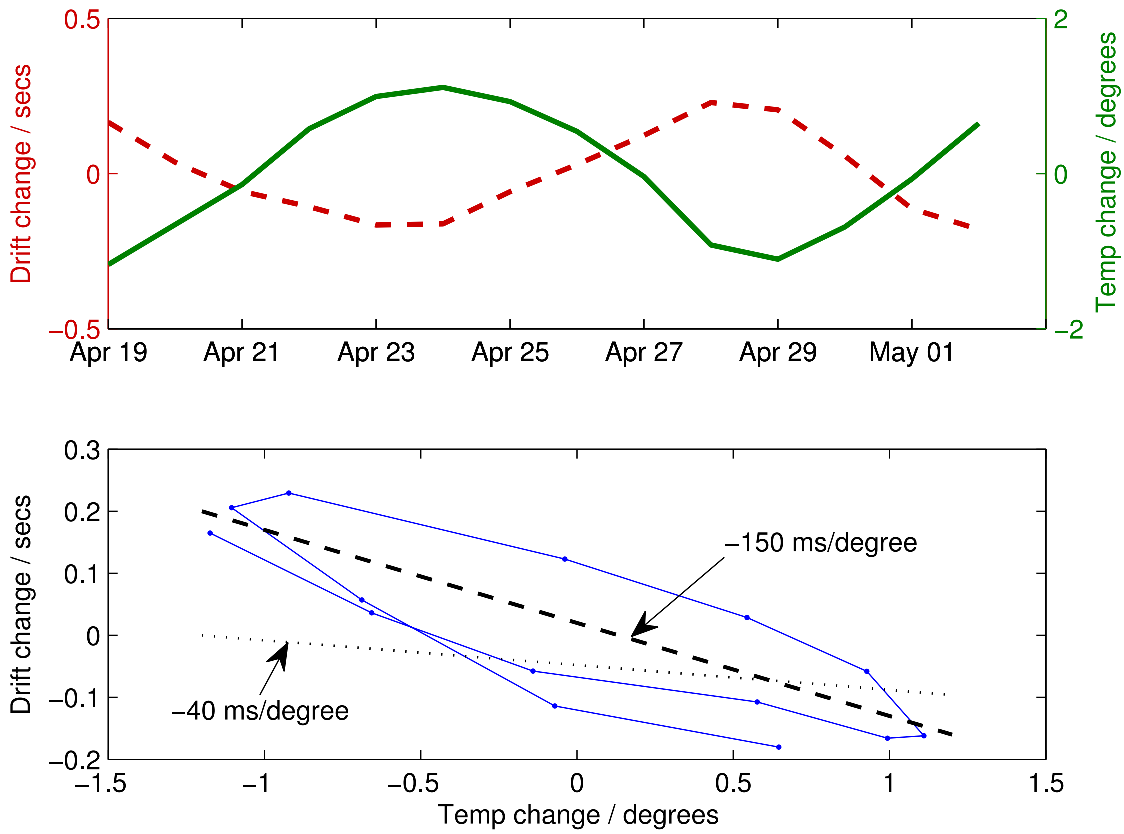


FIGURE 6.7: Drift (dashed) & temperature (solid). [19 April–2 May 2009, averaged daily].

seem to be no changes in them which might have caused it.

One theory is that, since the biggest change occurred roughly at midnight, the clock striking the hour may have prompted the change. Indeed, looking closely at the data around midnight, the going does seems to drop immediately after midnight, although the accuracy in going is quite low at short time scales so it is somewhat vague. A possible mechanism for this is the air currents created during the bells striking, which come from the vanes fitted to the bell-ringing wheels to regulate the speed of striking.

The vertical drag mechanism described in Section 4.6.4 might play a part here. Perhaps the striking of the bells could have reversed the direction of flow through the pendulum chamber, if there was little initial preference for either direction. An air flow sensor would make an interesting addition to the monitoring equipment.

### 6.6.2 Sudden drop in amplitude

Although the event shown in Figure 6.1 proves very nicely the going-amplitude relationship, there is no explanation in the other data for the sudden large drop in amplitude itself. Perhaps the falling weight snagged on something; this could have reduced the tension for a while, until the weight had descended further and freed itself.

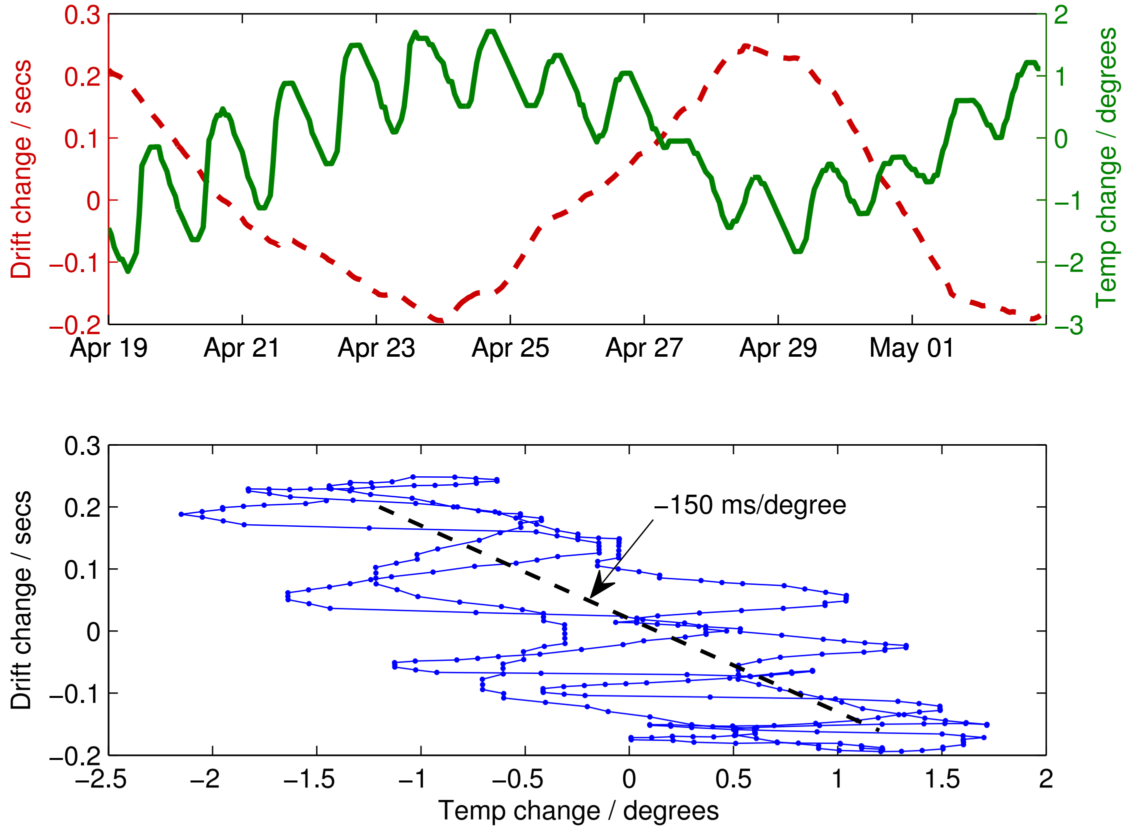


FIGURE 6.8: Drift (dashed) & temperature (solid). [19 April–2 May 2009, averaged hourly].

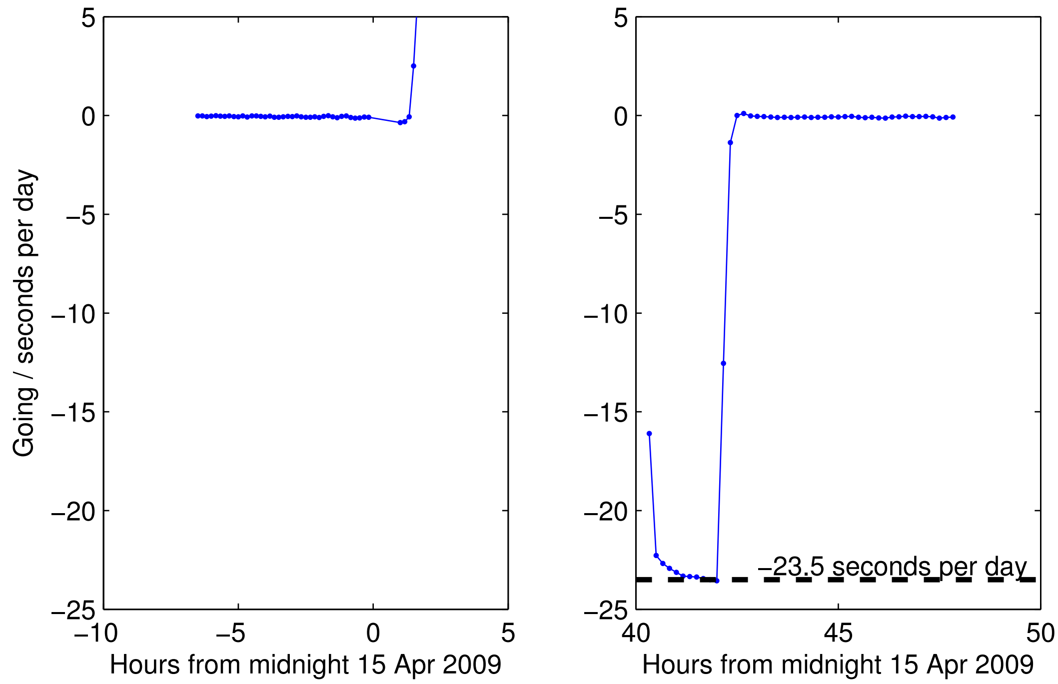


FIGURE 6.9: An accidental change in pendulum length? [14–16 April 2009, averaged over 10 minutes].

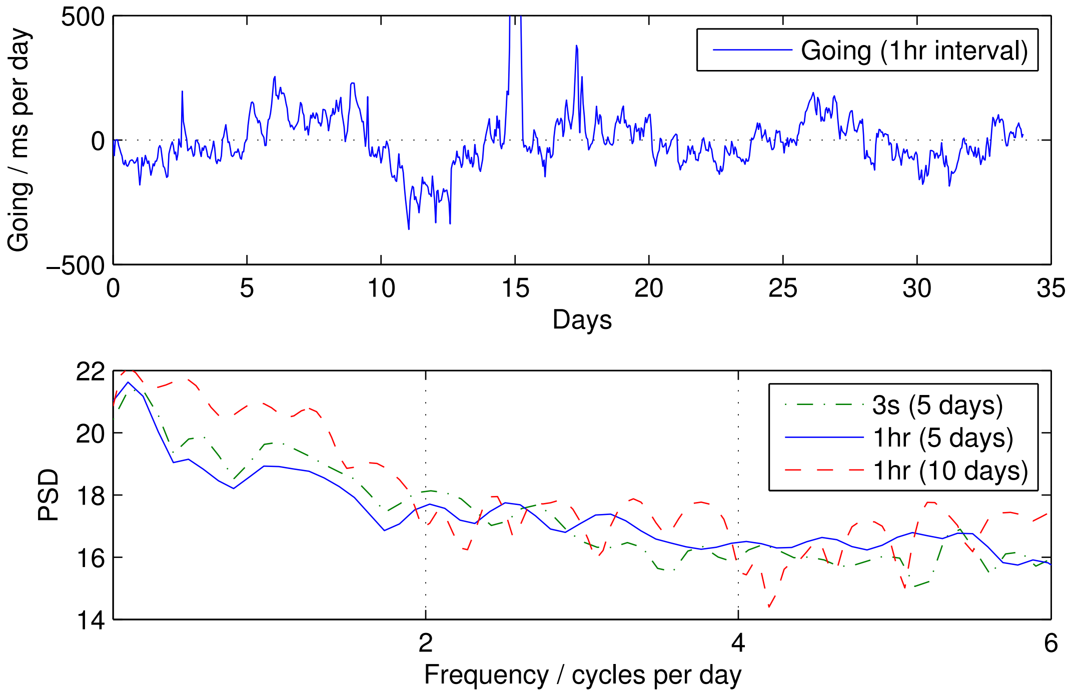


FIGURE 6.10: Spectral analysis: looking for the tidal variation in going. [19 April–22 May].

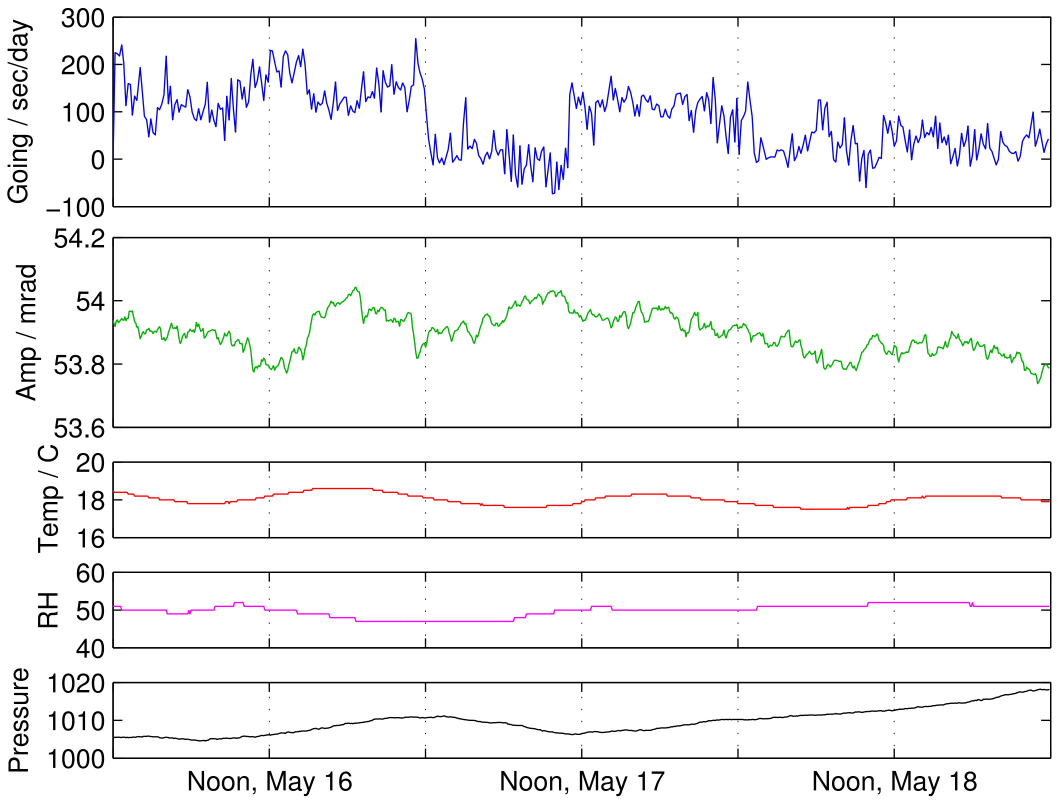


FIGURE 6.11: Unexplained changes in going. [16–18 May 2009]