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The shape of the *Sq* current system

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Abstract. Many years ago Mayaud (1965) suggested that a tilted, rather than symmetric, current system may be responsible for the form of daily magnetic variations near the focus of the current system. With arrays of magnetometer stations, both in Australia and in Europe, it is now demonstrated that such tilted systems do exist at certain times. At other times the magnetic variation near the focus is deformed by a previously reported extra morning current system which is apparently unconnected to the regular *Sq* system.

Keywords. Geomagnetism and paleomagnetism (Time variations, diurnal to secular) – Ionosphere (Electric fields and currents; Mid-latitude ionosphere)

1 Introduction

This work arises out of a seminal paper by Mayaud (1965) where he suggests that the form of the daily variation of the horizontal component of the earth's magnetic field H, in the region of the focus of the *Sq* current system, may indicate that the *Sq* current whorl is tilted or flattened. Generally this idea has been studied using data from a few observatories which form a chain in latitude across the focus position at a similar longitude. Often the assumption is then made that the *Sq* current whorl maintains its shape and latitude as it moves westward across the chain of observatories. Mayaud himself admits that some of the observations may be interpreted as a change in latitude of the focus during its westward progress. And we have been able to observe such a change (Stening et al, 2005a).

The availability of an array of observatories spread across the mainland of Australia during 1989–1990 (the so-called AWAGS array) has given the opportunity to follow the central part of the *Sq* current whorl as it changes its shape and position with time. We will seek to determine whether some observed H variations near the focus are really due to the shape of the current system or to some other factor.

Figure 1 reproduces the shape of the tilted current system along with the expected variations of H at the focus and just north and south of the focus. Mayaud calls this system T_h^m, meaning a *Tilted* system with the lines of current flow displaced *higher* in the *morning*. Mayaud's pictures represent a situation in the Northern Hemisphere while we will mainly be examining currents in the Southern Hemisphere.

An examination of Fig. 1 reveals several features which may point to a tilted current whorl:

1. Zero ΔH occurs when the magnetic field direction is exactly eastward or westward. The latitude where this happens is towards the south at places east of the focus and towards the north at places west of the focus.

2. The maximum of the ΔH curve occurs later in time as we go from north to south of the focus. This can be seen in the right hand diagram of Fig. 1. Similarly the time of minimum of ΔH occurs later in the south.

3. The time of zero crossing of the ΔH curve likewise becomes later as we go from north to south of the focus.

4. Similarly the eastward magnetic variation ΔY goes through zero later at latitudes south of the focus than north of the focus.

2 Some results

Figure 2 shows the X and Y magnetic variations on 2 June 1990 when the largest K_p value was 2. Figure 3 shows the current vectors on the same day at 4 h UT or about 14 h LT in Eastern Australia. The current function contours drawn are in fact derived from a spherical cap harmonic analysis of the data, following the method of Haines (1985) and Haines and

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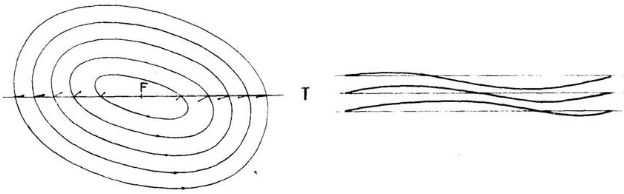

Fig. 1. Taken from Mayaud (1965), the flow lines for a tilted current system in the Northern Hemisphere are shown on the left with associated magnetic field directions given by arrows along a line passing through the focus F. On the right is a schematic of the daytime variation of the magnetic field H or X at a station just north of the focus, at the focus and just south of it.

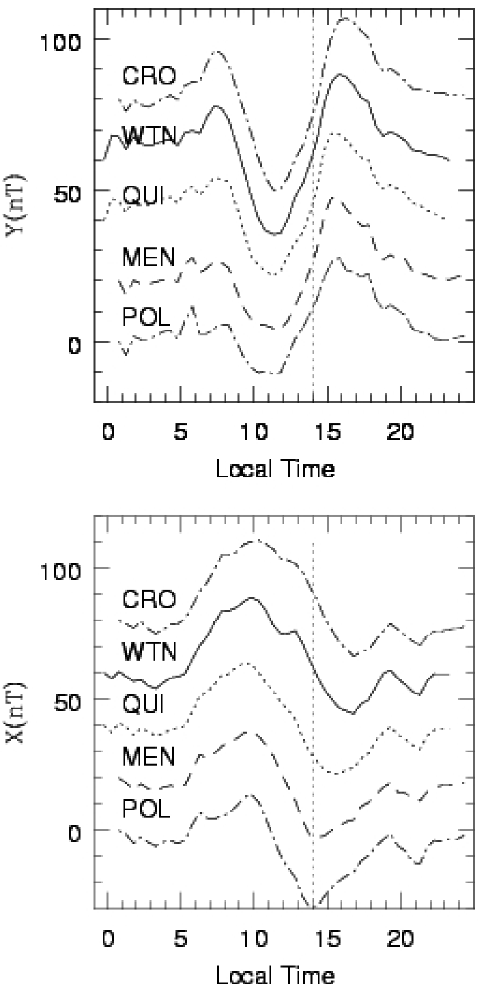

Fig. 2. Variation of the hourly means of the northward and eastward magnetic components, X and Y, at a chain of stations on the east side of Australia on 2 June 1990. See Fig. 3 for locations of stations. Each plot is adjusted to zero at midnight and the plots are displaced by 20 nT for easier viewing. The vertical dashed line indicates the time of passage of the focus.

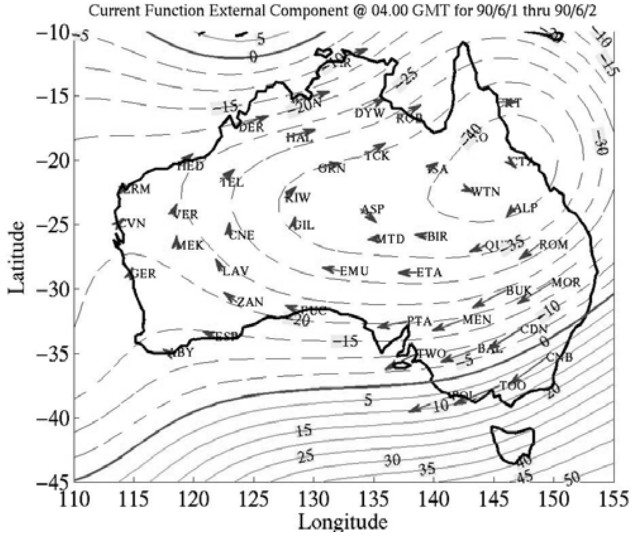

Fig. 3. Current systems at 4 h UT on 2 June 1990. The arrows are drawn by rotating the observed magnetic field directions clockwise through 90°. The contours have a spacing of 5 kA and are derived by spherical cap harmonic analysis.

Torta (1994), and using a cap with centre at 27.5 S, 132.5 E, with half-width 20° and spatial index k=5. The contours presented should represent the contributions from external currents only, not including the effects of currents induced below the earth's surface. An examination of the contours locates the focus of the current system between WTN and CTA while looking at the current arrows alone places it near 24 S, 138 E. Although a tilt cannot be clearly seen from this diagram (it is more "banana-shaped"), larger currents appear in the south-east of the continent. Furthermore the time of the minimum in X in Fig. 2 gets earlier as we go from the northern station (17 h at CRO and WTN) to the southern station (14 h at POL). The time of the minimum in Y does not vary appreciably.

In spite of these indicators of a tilted current system, the morning maxima at the southern stations like MEN and POL do not appear to be part of the *Sq* current whorl at all. These maxima were shown by Stening et al. (2005b) to be related to some other early morning eastward current flow. For the more northern stations this eastward flow blends in with the eastward currents from the *Sq* system, but the maximum in ΔX at stations equatorward of the focus, like CRO, occurs much earlier (10 h LT) than the local time of the focus, which is quite late on 2 June 1990 near 14 h LT.

Figure 4 shows the half hourly mean magnetic variations on 27 January 1990 from a chain of stations near 130° longitude. This example has been selected because there is a minimum in the morning and a midlatitude station near the focus like KIW shows both a minimum and a maximum. The time of the minimum in X varies from 7.5 h at WYN in the north to 10.5 h at EUC in the south. The times of the morning

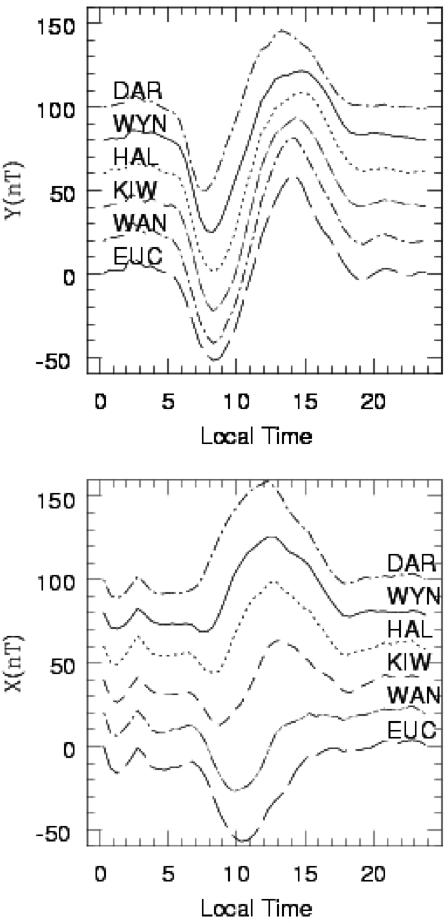

Fig. 4. Magnetic variations for 27 January 1990, plotted every half hour, as for Fig. 2.

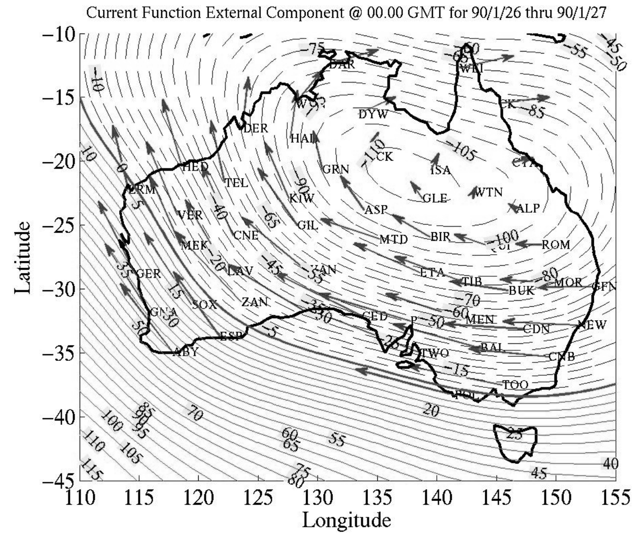

Fig. 5. Current systems at 0.8 h UT on 27 January 1990, as for Fig. 3.

minimum in Y, and also of the zero in Y, get later from north to south but with a difference of only about one hour. Figure 5 shows the current vectors on this day at 0.8 h UT or 9.5 h LT (the local time for the DAR-EUC chain). One can get some sense of a tilt from the contours in the diagram. This is confirmed by tracing the latitude at which the current reverses from west to east. Moving from east to west, this latitude is between ALP and WTN, 23°, then just south of TCK, 20°, to just south of DER, 18°. Taking these east and west points with a latitude difference of 5° (or 550 km) and an east-west difference of 2250 km, a rough calculation indicates a “tilt angle” for the current system of about 14°. The local time of the focus at this longitude coincides with the minimum in ΔX at the southernmost station, EUC, is near to the zero in ΔX at the midlatitude station KIW and is earlier than the maximum in ΔX at DAR.

Figure 6 shows magnetic variations from 8 April 1990. The differences in the time of the minimum in X are small, only about one hour. The differences in the times of minima in Y are similarly small.

Figure 7 shows the current vectors at 2.3 h UT or 11.8 h LT (local time for the CRO-POL chain) for the stations plotted in Fig. 6. While the computer generated contour lines do not emphasise the tilt of the current whorl, it can be demonstrated again by comparing latitudes at which the current reverses from west to east. This varies from a latitude of 32° between BUK and CDN to 17° between WYN and HAL, a difference of 15°. A rough calculation yields a tilt angle of 41°.

During daylight hours X at MEN has two minima and a maximum. Does this signal a current system like Mayaud’s F_h with current lines closer together on the poleward side of the focus than on the equatorward side? Or are we encountering another current system in the afternoon, analogous to that which we have mentioned in the morning?

Figure 8 shows a very clear double maximum in the X variation at WTN and neighbouring stations. However the morning maximum is clearly generated by the previously mentioned morning current system (Stening et al., 2005b) and is not related to the *Sq* current whorl. A series of contour plots for this day is shown in Fig. 9. At the earlier times the morning eastward current dominates in the west. As time progresses, the regular *Sq* current whorl moves in from the east and sits centrally at 3.8 h UT (12.8 h local time at 135° longitude). At this time both the contours and current arrows clearly show that the whorl is not tilted. At 4.8 h UT, although the contours suggest some tilt, other tests for tilt are not satisfied.

Figure 10 reinforces the interpretation of the morning maximum in X being due to a separate current system which causes the observed X variation amplitude to increase with increasing latitude around 8 h–9 h LT in contrast to the usual decrease of X with latitude. This is reflected in the variation of the vertical magnetic field component Z, which also goes

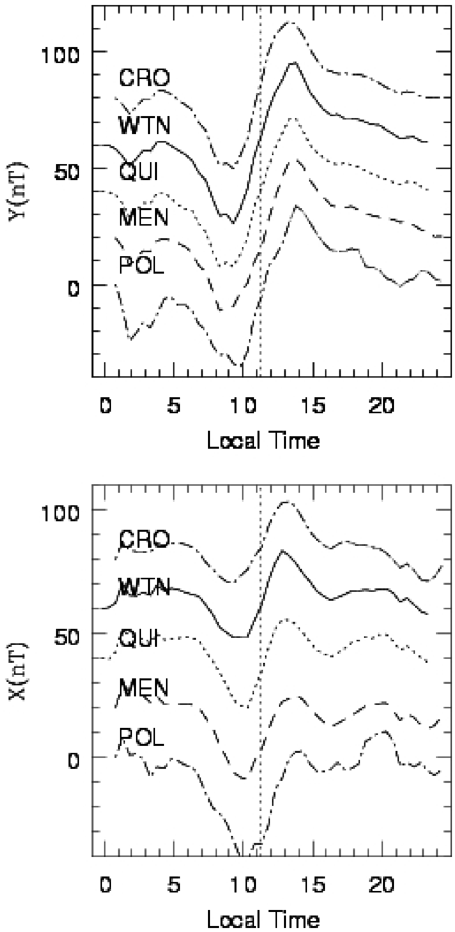

Fig. 6. Magnetic variations on 8 April 1990, plotted every half hour, as for Fig. 2.

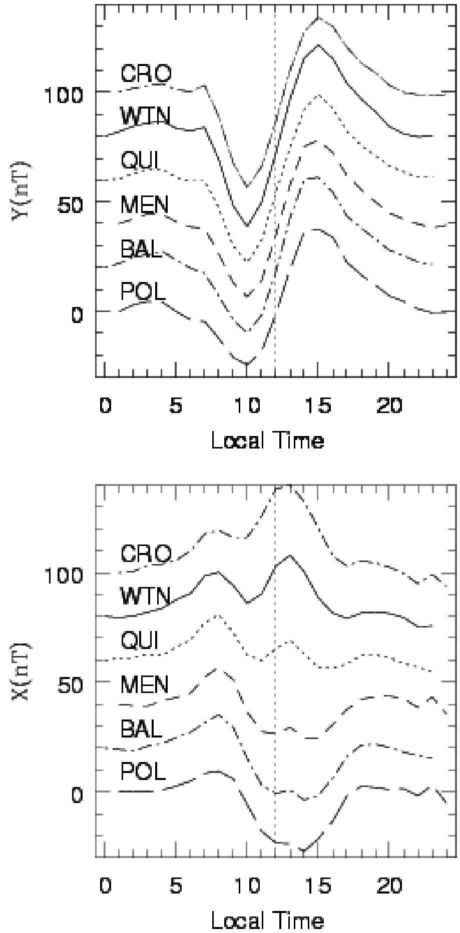

Fig. 8. Magnetic variations from 15 May 1990, plotted every half hour, as for Fig. 2.

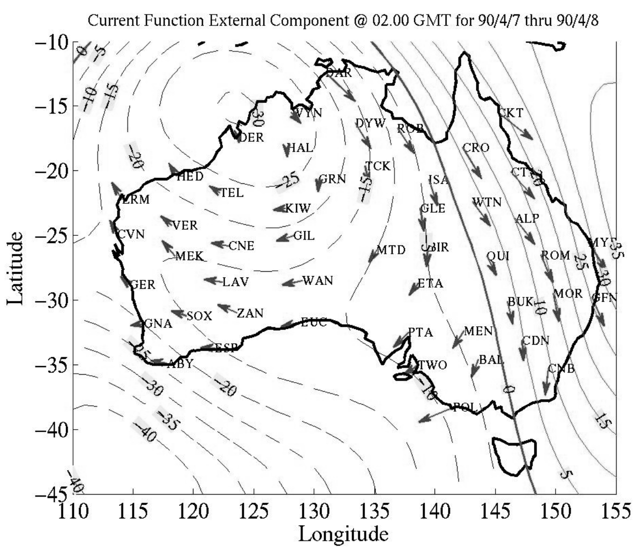

Fig. 7. Current system at 2.3 h UT on 8 April, 1990, as for Fig. 3.

negative at this time at CRO and WTN (Fig. 10). There are decreases in Z around this time also at MEN and POL but it does not turn negative. The difference between the X variations from two stations separated in latitude is also included in these plots. As shown in Stening and Reztsova (2007), the Z variations largely arise from the gradient with latitude in the eastward current flow: this eastward current is mostly detected by the X variations. The normal Z variation in the Southern Hemisphere is positive, indicating a decrease with latitude of the eastward current. A negative Z variation indicates the presence of a current system with increasing eastward amplitude towards higher latitudes, or maybe a field aligned system giving a similar effect. In the case presented the deviation in the X differences is quite small at the morning time when the Z deviation is apparent.

A similar analysis has been performed by Torta et al. (1997) using European observatories. The location of the observatories is shown in Fig. 11 and the derived current functions in Fig. 12. An examination of the magnetic variations on 21 April at particular stations, shown in Fig. 13,

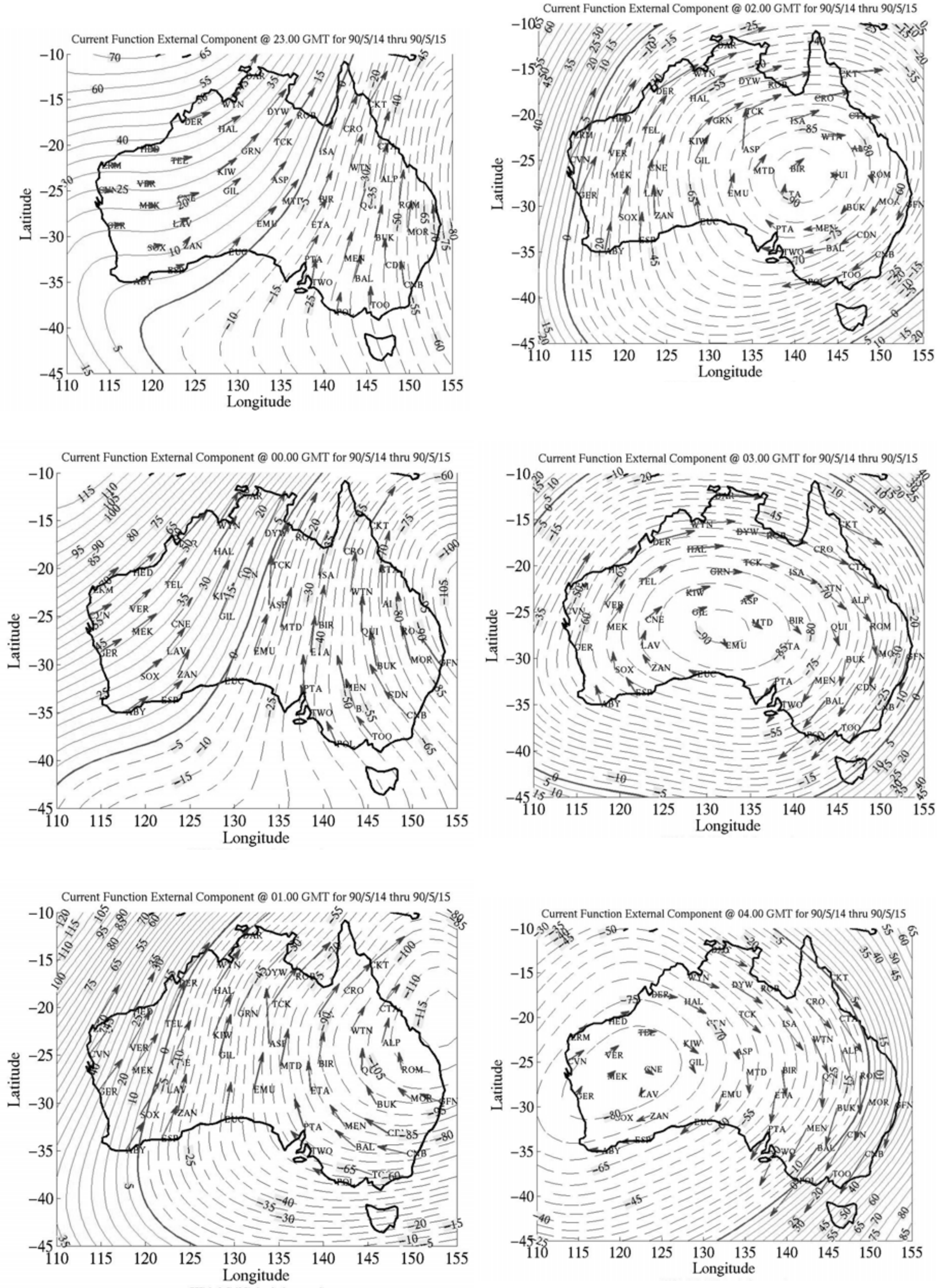

Fig. 9. Current systems on 15 May 1990, as for Fig. 3. The universal times of the plots range from 23.8 h (labelled 23.00 GMT) on 14 May to 5.8 h (labelled 05.00 GMT) on 15 May.

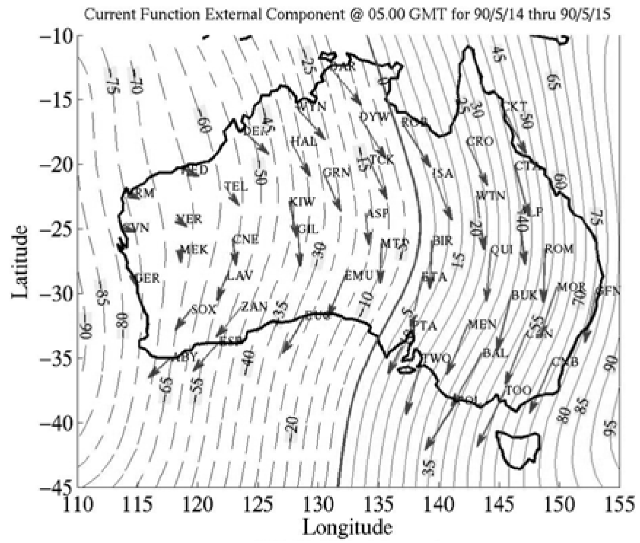

Fig. 9. Continued.

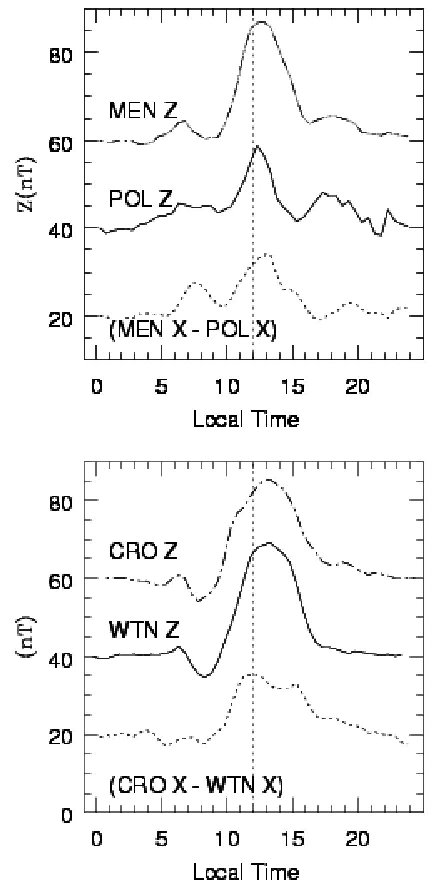

Fig. 10. Magnetic Z variations on 15 May 1990 together with the differences between the X variations at MEN and POL (top) and at CRO and WTN (bottom) – plotted every half hour.

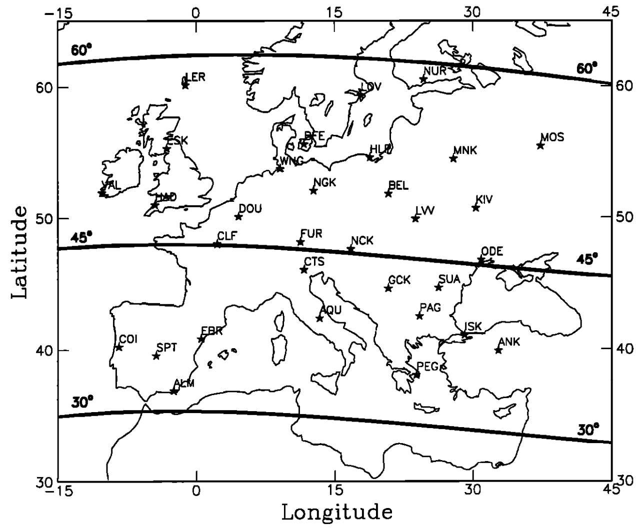

Fig. 11. Locations of observatories used in the European study by Torta et al. (1997). Dip latitude lines are shown for 30°, 45° and 60°.

reveals, at AQU, two maxima separated by a minimum. The morning maximum may well be due to a south-eastward current system rather similar to that seen over Australia, as can be seen at 7 h UT in Fig. 12. The expected time of the focus on 21 April at the longitude of AQU was estimated by finding the time that the D (declination) variation at AQU went to zero (as recommended in Stening et al., 2005a). This time is indicated in Fig. 13 by the vertical line. Since at that time H is negative at AQU, the focus must be south of that station. The minimum and following maximum are likely due to the tilt of the current whorl, fairly well depicted in Fig. 12 at 11 h UT. This is an example of Mayaud's T_l^m system.

Istanbul Kandilli (ISK) is an hour further east than the other stations. It has an H variation similar to that at L'Aquila (AQU) on 21 April. The vertical line indicating the focus should be shifted an hour earlier for ISK, putting it very close to the centre of the focus.

Data from the two days surrounding 21 April are included to show how much change there is from day to day. 20 April is disturbed with K_p up to 4, but 22 April has a largest K_p value of 2, the same as 21 April. The variation of H at AQU is quite different on 22 April.

But the form of the daily variations in X can be deceptive. On 16 May 1990 the K_p values were very low all day, 1^- or less. Figure 14 shows that the midlatitude station WTN has a morning maximum and an afternoon minimum. However at the time of the focus passing through, the ΔX trace is fairly flat and a close examination of the current map shows a fairly symmetric current whorl with little or no tilt. How should we explain the maximum at WTN? Examination of current maps at early times shows the probable presence again of the different current system giving eastward flows in the morning.

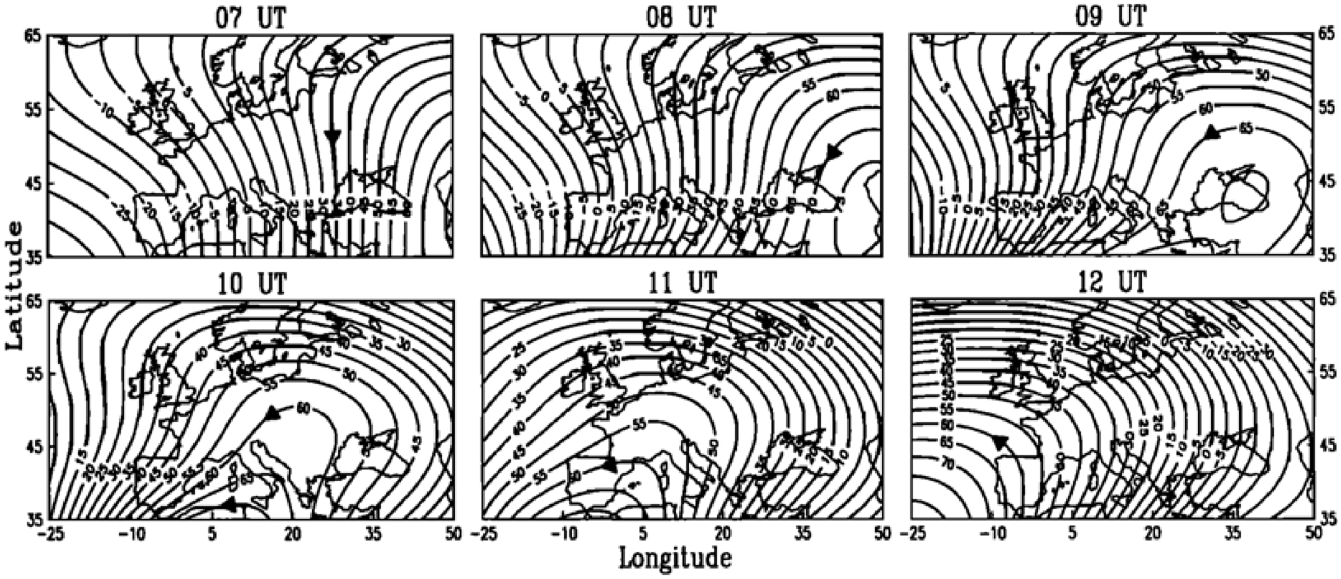

Fig. 12. Equivalent current function contours on 21 April 1987, in the European region for various Universal times – from Torta et al. (1997).

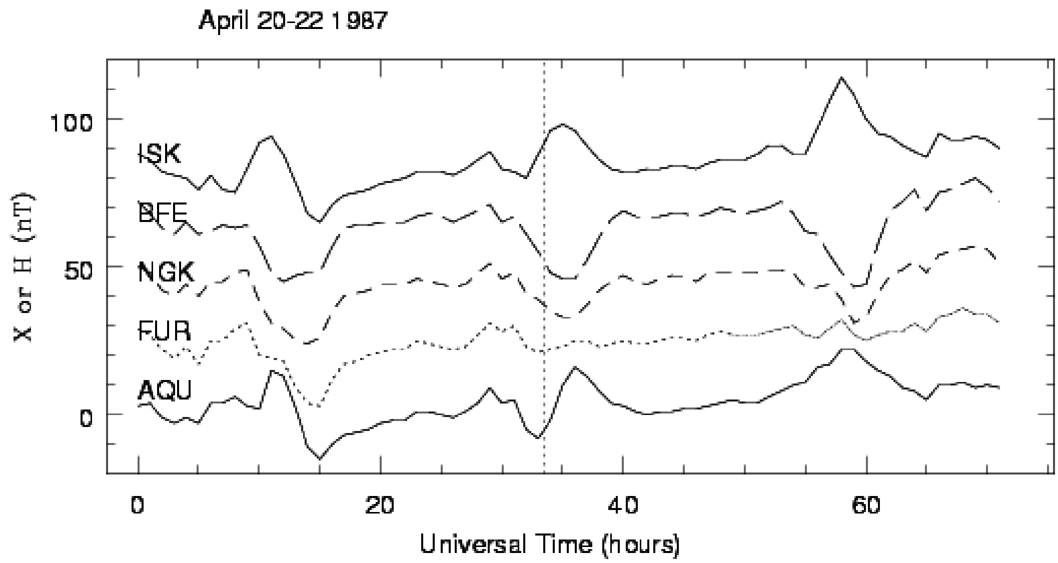

Fig. 13. Magnetic variations in X or H, plotted hourly, at five stations in Europe from 20 to 22 April 1987. The vertical dashed line represents the time of the focus at AQU on 21 April.

In the afternoon, ΔX at CRO can be seen to swing negative and even CKT, further north, is negative for a short time just before sunset when ΔY still has an appreciable positive value. Again this looks more like a separate current system from the *Sq* whorl than the evidence of a tilt.

3 Discussion

Patil et al. (1983) examined a chain of stations at Indian longitude and found, in the annual means, a later time of maximum of ΔH moving northwards from about 20° geographic latitude. This is the opposite to the second feature noted regarding Fig. 1 and so indicates a tilted current system of the T_l^m type. Except during D months (around December), the station near the focus, Gulmarg, has a morning minimum, followed by an afternoon maximum. The authors also infer a tilted current system.

Similarly Walker and Kannangara (1982), using a chain of stations at Japanese longitude, found that generally the time of maximum of ΔH became later going northwards and they infer a current system tilted towards the east, that is of the T_l^m type.

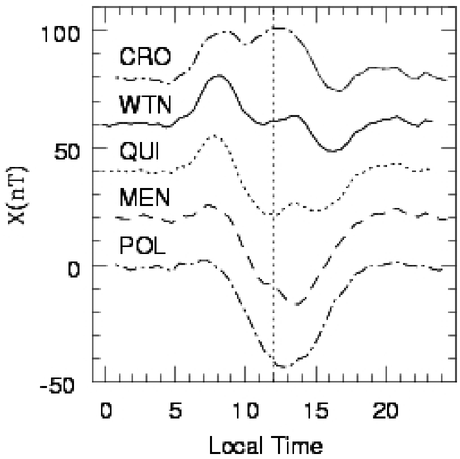

Fig. 14. *X* variations on 16 May 1990, plotted every half hour. Vertical line indicates time of focus passage. As for Fig. 2.

Mayaud (1965) illustrates global harmonic analyses with a diagram from Price and Wilkins (1963) which shows tilted current flow lines crossing the equator. Similar flow lines across the equator also appear in one of the analyses of the solar geomagnetic tide by Winch (1981). However in both of these diagrams the flow lines become more parallel to the equator in the region of the focus, certainly poleward of the focus. By contrast the current system for a single day from Van Sabben (1964) shows the tilted lines extending all the way from the Southern Hemisphere, across the equator to poleward of the northern focus. It is this latter region which we have been examining in this paper. Many of these representations relate to Mayaud's "invasion" phenomenon in which the winter hemisphere is "invaded" by the summer hemisphere system and is particularly evidenced in the Y component variations. Whereas the invasion phenomenon can be clearly seen at a station such as Port Moresby (9.4° S, 147.1° E), it does not appear to reach as far south as the Australian mainland.

The origin of the extra morning current system remains uncertain. The polar quiet current system Sq^p may have been considered responsible but most studies of this system are confined to latitudes higher than 45°. By selecting appropriate Legendre polynomials from their analysis, Campbell et al. (1994) were able to isolate Sq^p current effects. Their Fig. 5 shows some evidence of morning eastward currents at 45° N latitude in March and June but not in September or December. As these morning currents frequently occur, and in both hemispheres, one would expect them to appear in the Campbell et al analysis, but this does not really help us to determine their origin.

The presence of early morning peaks in average diurnal variations of *H* at Australian observatories (Stening and Hopwood, 1991) indicates that this is a frequently occurring phenomenon. While no statistical study has been done, peaks and troughs also appear later in the day in average plots of ΔH and so are likely to indicate relatively frequent occurrence of tilted whorls.

4 Conclusions

Data from an array of magnetometer stations show that tilted current systems of the type suggested by Mayaud are indeed sometimes present. Evidence for these is shown both in Australia and in Europe and the most frequently encountered type is T_l^m in which the current lines are lower in the morning.

Whereas the presence of a minimum and a maximum in the variation of *H* or *X* at a station near the focus often indicates the existence of a tilt, an extra current system in the morning may also be responsible for another maximum at a focal station and this is not related to the shape of the *Sq* system at all.

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