Tropospheric atmospheric gravity waves and their relationship with geomagnetic activity

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Ground-level atmospheric gravity waves (GL-AGWs), recorded at Brisbane, Australia, from 1963 to 1966 by microbarographs, have been investigated for possible associations with geomagnetic activity. Two sets of well-defined GL-AGWs have been used. There were 54 events associated with the passage of cold-fronts at Brisbane, (frontal events), while another 67 well-defined GL-AGWs were called non-frontal events. Superposed-epoch analyses have been done to investigate (i) $AE$ indices, (ii) three-hourly $K_p$ indices and (iii) geomagnetic $\Delta H$ components at stations close to Brisbane's longitude, using these events as controls. Cross-correlation analyses have also been performed. For all these investigations, except for the cross-correlation analyses, it was found at a reasonably-high level of significance that the non-frontal events were delayed after geomagnetic activity by about 3 days and the frontal events by 4 days. It is suggested that these GL-AGWs may be associated with sub-auroral and high-midlatitude ionospheric absorption produced by charge particles which enter the radiation belt at times of geomagnetic activity, and diffuse to lower $L$ shells. The experimental evidence for the bifurcation of the associated enhanced geomagnetic events at specific local times, as well as the evidence for other delays around 1 or 2 days has also been reported.

1 Introduction

The analyses of the present study are concerned with ground-level atmospheric gravity waves (GL-AGWs), recorded at Brisbane, Australia, during night hours, using sensitive microbarographs, from June 1963 to December 1966, covering some sunspot-minimum years. The selection of these events for analysis and the subsequent subdivision into 'frontal' and 'non-frontal' sets have been described by Bowman and Shrestha. The events which were labelled 'frontal GL-AGWs' were those recorded one but mainly two days before the passage of cold fronts through Brisbane. The remaining events were classed as 'non-frontal GL-AGWs'. Similar results were found in an earlier study. There were 54 frontal events and 67 non-frontal events. The analyses by Bowman and Shrestha have shown that a statistically-significant relationship exists between the non-frontal GL-AGWs and ionospheric spread-F at various locations around the world, but not for the frontal GL-AGWs. This present paper reports on investigations into possible associations between these GL-AGWs and geomagnetic activity.

Considerable amount of work has been done in the past relating to possible associations between solar or geomagnetic activity and tropospheric weather conditions. As this present investigation is principally concerned with any association which might exist between geomagnetic activity and these GL-AGWs recorded at Brisbane, reference will now be made to some earlier works which appear to be relevant. According to Macdonald and Roberts, the statistical evidence from three successive winter half-years strongly indicates that, when the earth is bombarded by unusually intense solar corpuscular emission, certain troughs in the 300-mbar circulation are substantially amplified. These effects were registered two, three or four days after the corpuscular increases.
Similar results were recorded by Woodbridge. This investigation found well-defined trough enhancements for the 1956-1958 and 1964-1966 winters, three or four days after enhanced geomagnetic activity. Also using the parameter vorticity area index (VAI), Roberts and Olson found delayed VAI effects several days after geomagnetic activity. Delayed relationships were also reported between VAI changes and solar-magnetic sector boundaries. Reviews of earlier works on this subject have been reported by Roberts and Olson and Wilcox.

Delayed meteorological changes published earlier than those already quoted have been mentioned by Wilcox. An example of associated meteorological changes can be found in a report by Duell and Duell. Their results obtained by using superposed-epoch methods show that following ionospheric storm conditions (320 disturbed days associated with geomagnetic activity), for the winter months of 16 sunspot-minimum years from 1910 to 1935, the sea-level atmospheric pressure at Kiev (46.7, 104.1 corrected geomagnetic co-ordinates), and at 8 other stations is depressed by about 3 millibars, with delays between 3 and 5 days. Figure 1 is a reproduction of Fig. 3 of Duell and Duell. Similar results obtained when the data were divided by using odd and even years separately (Fig. 1), give some evidence of the statistical significance of these results. Craig, using more data, established that, for a certain location, a statistically-significant negative correlation exists between the variation of daily average surface pressure after geomagnetically disturbed days and the variation observed after geomagnetically quiet days.

Investigations into possible relationships between geomagnetic activity and tropospheric weather changes are continuing. Reviews embracing more recent work have also been made by Tinsley and Lastovicka. Arora and Padgaonkar and Arora have presented additional convincing evidence of the relationship between the solar magnetic sector boundaries and the VAI. Furthermore, they have shown that the solar geomagnetic tropospheric changes are time-dependent, and the occurrence probability is not consistently high. Associations between cloud cover and cosmic-ray fluxes have been found by Svensmark and Friis-Christensen, while Tinsley has shown that the solar wind influences the air-earth current density and has examined a mechanism by which these changes result in the formation of clouds with associated precipitation. Perturbations in the stratosphere by short-term changes in solar activity have recently been examined by Besprozvannaya et al.

The objective of the analyses has been to investigate statistically the level of geomagnetic activity relative to a small number of either frontal or non-frontal events. The results show that the associations are found mainly with geomagnetic activity at specific local times of the GL-AGW recording station. Local time at Brisbane is 10 h ahead of Universal Time. Table 1 lists the corrected geomagnetic co-ordinates of the stations considered in this paper.

![Figure 1](image-url) - Atmospheric pressure fluctuations associated with geomagnetic activity at Kiev (a) for all years, (b) for even years and (c) for odd years.

Fig. 1 — Atmospheric pressure fluctuations associated with geomagnetic activity at Kiev [(a) for all years, (b) for even years and (c) for odd years]
2 Methods of analysis

The columns of the arrays established using the superposed-epoch method (used for the analyses of the present study) are added and the mean is calculated with the standard-deviation of the columnar additions. The points on the plots to be presented are the standard-deviation displacements from the mean for each analysis, so that reasonable estimates can be made of the significance of any displacement. Only selected sections of the displacement points available are presented. Standard-error bars are also provided for some of the analyses. The use of these methods has been described in some detail elsewhere\textsuperscript{23-25}. Cross-correlation analyses have also been investigated.

### Table 1—Corrected geomagnetic coordinates

<table>
<thead>
<tr>
<th>Stations</th>
<th>Lat.</th>
<th>Long.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>deg.</td>
<td>deg.</td>
</tr>
<tr>
<td>Tixie Bay</td>
<td>65.8</td>
<td>195.5</td>
</tr>
<tr>
<td>Macquarie Is.</td>
<td>-64.6</td>
<td>245.3</td>
</tr>
<tr>
<td>Cape Wellen</td>
<td>62.5</td>
<td>242.9</td>
</tr>
<tr>
<td>Brisbane</td>
<td>-36.1</td>
<td>228.6</td>
</tr>
</tbody>
</table>

3 Results

3.1 \(\text{AE}\) indices

The frontal and non-frontal events (in days), have been used as key days to investigate the \(\text{AE}\) index levels before and after these days. The hourly values of this index were used with the centre hour being chosen arbitrarily as 0000 hrs UT on the control day in local time (LT). The date for the first half of the night was used for each key day. The analyses covered the centre hour ±700 h (i.e. 29.2 days). Figure 2(a), for the non-frontal controls and Fig. 2(b), for the frontal controls show small relevant sections of the final plots. The nighttime recording interval (1800-0600 hrs LT) is shown by the letters P and Q, with position A being located at midnight. For Fig. 2(a), significant peaks in the \(\text{AE}\) index are found to occur at 2200 and 0200 hrs LT, where LT=UT+10h. The interval AB represents 3 days delay between geomagnetic activity and the occurrence of non-frontal GL-AGWs. The results for the frontal controls [Fig. 2(b)] indicate peaks at 2300 and 0300 hrs LT with the delay this time (Ac) being 4 days. The geomagnetic activity remains enhanced for a

Fig. 2—\(\text{AE}\) index fluctuations relative to (a) non-frontal and (b) frontal controls [Position A is the local midnight of the recording interval PQ. B and C locate positions of enhanced geomagnetic activity]
period after these peaks, the period being about 12 h in Fig. 2(a) and 24 h in Fig. 2(b).

3.2 3-hourly $K_p$ indices

Figure 3 shows the results of superposed-epoch analyses which find the 3-hourly $K_p$ index relative to both sets of controls. Although for these particular analyses the period involved was the centre day (CD) ±20 days, only the central sections of the results are shown. Relative to midnight on the recording days, peak displacements are found for delays of about 2.7 days for the non-frontal events [Fig. 3(a)], and 3.7 days for the frontal events [Fig. 3(b)], corresponding approximately with the central positions of the disturbed geomagnetic intervals shown in Fig. 2. The significance of any geomagnetic enhancement can be assessed not only from the standard-deviation displacement, but also from the error bars. The mean levels are shown by the dashed lines.

3.3 Geomagnetic $\Delta H$ components

Another way to investigate these delays is to consider the hourly values of the $H$ component of geomagnetic displacement for stations close to the longitude of Brisbane. Macquarie Island is the most appropriate station to use. However, since the data from this station were incomplete, a near conjugate station (Cape Wellen) has been used. Tixie Bay (also in the northern hemisphere), at a longitude to the west of Brisbane's longitude, has also been investigated. Their longitude and latitude displacements relative to Brisbane can be appreciated from Table 1. Macquarie Island and Cape Wellen are displaced about 15° to the east, while Tixie Bay is located about 30° in longitude to the west (see Fig. 6 of Bowman and Shrestha). Brisbane is a mid-latitude station located several thousand kilometres from the auroral zone.

Superposed-epoch analyses have been performed using the key days and the hourly $H$ component of the geomagnetic field for these auroral-zone stations, covering a period from +3 to -10 days relative to 1200 hrs UT arbitrarily chosen as the reference time. This time represents 2200 hrs LT at Brisbane. After the superposed distributions were obtained, the average daily variation for each station was subtracted from the distribution points for each day, thus obtaining values representing departures from the average behaviour. Figure 4[(a) and (b)] gives the results for the two sets of key days for Cape Wellen, while the Tixie Bay plots are presented by Fig. 5[(a) and (b)]. As for the investigations, using $AE$ indices and $K_p$ values, for both the stations the delays are close to 4 days and 3 days for frontal and the non-
Fig. 4—Cape Wellen geomagnetic $\Delta H$ components relative to (a) frontal controls and (b) non-frontal controls (see also Table 3)

Fig. 5—Tixie Bay geomagnetic $\Delta H$ components relative to (a) frontal controls and (b) non-frontal controls (see also Table 3)
frontal events, respectively, for the maximum negative displacement in each case. These diagrams contain additional significant displacements, which are discussed later.

3.4 Cross-correlation analyses

Several analyses which compare different geomagnetic indices with the GL-AGW events have been performed using the cross-correlation method. The results were, generally, in agreement with those reported here using other parameters and another method. When the daily $A_p$ index was used, the cross-correlation coefficients were quite low. Because, as Fig. 2 shows the related geomagnetic events occurring preferentially in the late evening and early morning (local time), the Macquarie Island $K$-sum indices were used producing slightly better results. However, the best results, with the cross-correlation coefficient still low, were obtained by using the average $AE$ index values for each day from 1200 to 2300 hrs UT, which represents approximately 12 h of local time at Brisbane from 2200 hrs LT (see Fig. 2). Some comments on why the cross-correlation coefficients are low, are made in the discussion and conclusions section.

3.5 Bifurcation of associated geomagnetic activity

Although the key events were recorded at various times during the night, the associated geomagnetic enhancements could be identified with a time resolution of hours. It may not be a coincidence that similar associations have been found using ionospheric events recorded at Brisbane not only for the nighttime travelling disturbances (spread-F), but also for the daytime TIDs, which precede the nighttime events. These results are illustrated by Fig. 9 of Ref. 26, where the $AL$ index was investigated relative to both daytime and nighttime disturbances used in the same analysis as key days. Virtually the same results can be seen in Fig. 6 (presented here), where instead of the $AL$ index, the $AE$ index is used. Enhancements around specific local times of 0000 and 0400 hrs are recorded with a delay of about 3 days. There is also a delay of about 1 day peaking at 0700 hrs LT. Complete explanations of these results are not available. However, the daytime TIDs are considerably faster than those at night, and, furthermore, the nighttime speeds become progressively slower as the night progresses. Thus, these observations are at least consistent with a common source. These earlier results have been mentioned as they support further the experimental evidence for bifurcation presented here. Furthermore, Bowman and Shrestha find that ionospheric spread-F is associated with the GL-AGWs reported here. The local times of significant $AL$ index enhancements

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**Fig. 6**—$AE$ index versus Brisbane day and nighttime TIDs showing delayed bifurcation of enhanced geomagnetic activity
In the present results, which is common to those from other investigations is the recording of delays of around one or two days. As can be seen from Fig. 6, a delay of around 1 or 1.5 days depending on whether daytime or nighttime disturbances are considered, is recorded (see also Table 2). Shapiro and Stolov have investigated weather forecast skills as they relate to geomagnetic activity. They find that these skills are lower, particularly, one day after geomagnetic activity, but also for other delays centred around 4 days. The vorticity area index (VAI), relative to the solar-magnetic sector boundaries has been considered by Larson and Kelley. Their results show that the VAI (low pressure) maximizes at 3.5 and 8.5 days after the crossings. Since Wilcox and Ness estimate that enhanced geomagnetic activity can be expected 2 days after the crossings for the sunspot-cycle period considered, the delays after geomagnetic activity for these results can be estimated at 1.5 and 6.5 days, respectively.

The most detailed information from the various cases is found for the analyses involving the delays in the recording of GL-AGWs after geomagnetic activity. The significant enhancements shown in Fig. 2 occur for 2200 and 0200 hrs LT for the non-frontal events and 2300 and 0300 hrs LT for the frontal events. These specific local times of enhancement are even more evident in Figs 4 and 5 for the analyses relating to the hourly H components for Cape Wellen and Tixie Bay, respectively. The details are listed in Table 3 for Cape Wellen and Tixie Bay. Similar arguments, concerning different disturbance speeds, to those in the previous paragraph might apply to the results from the present analyses, as GL-AGW events were selected from any hour of the night. Despite this, enhancements at specific hours (also involving bifurcation) have been found as can be seen from Figs 2, 4 and 5.

### Table 2—Hourly AL indices relative to Brisbane daytime TIDs
and nighttime spread-F (after Bowman)

<table>
<thead>
<tr>
<th>Approx. delays (days)</th>
<th>Local time (hrs)</th>
<th>Significance (σ)</th>
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</thead>
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<tr>
<td>1</td>
<td>0100</td>
<td>2.1</td>
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<tr>
<td>1</td>
<td>0400</td>
<td>2.2</td>
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<td>3</td>
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<td>3</td>
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<tr>
<td>4</td>
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<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>0300</td>
<td>2.1</td>
</tr>
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### Table 3—Cape Wellen and Tixie Bay hourly ΔH displacement relative to Brisbane GL-AGWs

<table>
<thead>
<tr>
<th>Type</th>
<th>Delay (days)</th>
<th>Hourly ΔH displacement at Brisbane local time (hrs) for</th>
<th>Significance (σ) in brackets</th>
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</thead>
<tbody>
<tr>
<td>Frontal</td>
<td>0000 (2.1)</td>
<td>0500 (2.9)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0700 (3.0)</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>2300 (3.0)</td>
<td>0000 (1.8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0300 (2.1)</td>
<td>0300 (2.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0300 (4.5)</td>
<td>0400 (3.5)</td>
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</tr>
<tr>
<td></td>
<td>0900 (3.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-frontal</td>
<td>0300 (1.9)</td>
<td>0500 (2.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0800 (3.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0300 (1.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2300 (3.8)</td>
<td>0400 (4.8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0200 (5.4)</td>
<td></td>
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</table>

### 3.6 Evidence for delays around 1 or 2 days

The results presented here seem to provide experimental evidence at a statistically-significant level for an association between each set of GL-AGWs recorded at Brisbane and geomagnetic activity. Chrzanowski et al. reported on the associations between geomagnetic activity and not only infrasonic waves, but also those with periodicities in the range 3-15 min, these

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<th>Significance (σ) in brackets</th>
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### 4 Discussion and conclusions

The results presented here seem to provide experimental evidence at a statistically-significant level for an association between each set of GL-AGWs recorded at Brisbane and geomagnetic activity. Chrzanowski et al. reported on the associations between geomagnetic activity and not only infrasonic waves, but also those with periodicities in the range 3-15 min, these
periodicities being similar to those recorded\textsuperscript{2,3} in the range 5-20 min and investigated here. Both investigations report peak activity with periods around 12 min\textsuperscript{2,3,29}. These events were recorded by Chrzanowski \textit{et al.}\textsuperscript{29} at ground level at a high mid-latitude station. Concerning the waves with periodicities measured in min these workers\textsuperscript{29} state “Waves of this type are often present during intervals of magnetic activity \textendash;\textendash;” It is important to note that the distinction made between non-frontal and frontal events seems justified as the results are somewhat different for each set. This means that the 54 weather cold fronts which are recorded a day or two after the so-called frontal GL-AGWs, should also be related to geomagnetic activity. Although the results are not presented here, this has been found to be the case. For analyses results similar to those shown in Fig. 2, the $AE$ index plotted relative to the 54 frontal passages at Brisbane revealed significant standard-deviation displacements with delayed peaks located between $-4$ and $-6$ days. Also, related to sub-section 3.6, significant displacements around $3\sigma$ occur with delays of about 2 days, the maximum displacement being $3.8\sigma$ near $-6$ days. No such significant displacements were found for the 110 fronts, recorded from June 1963 to December 1966, which were not associated with these well-defined GL-AGWs.

The delays found are consistent with those found in the earlier investigations on associations between geomagnetic activity and tropospheric weather conditions\textsuperscript{4-15}. With the investigations which have gone before, it is not possible at this time to propose a well-documented mechanism which might explain the delays recorded here. However, it may be worth mentioning that similar delays are found for ionospheric absorption and spread-F occurrence\textsuperscript{30,31}, the phenomena which apparently are associated with the precipitation of electrons, delayed by several days following geomagnetic activity, by radial diffusion in the radiation belt.

Tinsley\textsuperscript{16,21,32-34}, with some collaboration with others\textsuperscript{35-37} has investigated extensively an hypothesis involving a mechanism relating to sun-weather relationships for the generation of clouds and subsequent rain precipitation. More specifically the mechanism considers the electro-freezing related to the solar wind modulation of the downward air-earth current density. This proposed mechanism is described briefly in a recent paper\textsuperscript{24}. However, with this present and other investigations an explanation of the delays does not yet seem available for this mechanism.

The low level of significance found for the cross-correlation analyses suggests that not all geomagnetic activities are associated with the GL-AGWs which have been recorded at a particular location displaced somewhat from the auroral zone. The results certainly indicate (see e.g. Fig. 2), that the related geomagnetic activity occurs generally at specific local times. Quite apart from this local-time dependence, only certain aspects of geomagnetic activity seem to be involved, particularly, the activity associated with “unusually intense solar corpuscular emission”\textsuperscript{4} such as that related to relativistic electrons\textsuperscript{21}. The superposed-epoch method is able to allow for geomagnetic activity which is not associated. Using key controls the related events are grouped together, while those not related are distributed at random across the final array. They are thus averaged out and have no appreciable influence on the results obtained.

As explained in sub-section 3.3 for the $\Delta H$ investigations, a northern hemisphere auroral station Cape Wellen was used instead of Macquarie Island (in the same longitude zone and hemisphere as Brisbane) because of insufficient data from Macquarie Island. These stations are near conjugate. Significant results were found using Cape Wellen as well as Tixie Bay, another northern hemisphere station. Quite apart from the positive results obtained, the use of these northern hemisphere stations seems justified as the studies by Mayaud and Romana\textsuperscript{38} and Mayaud\textsuperscript{39} indicate only small differences in the occurrence of geomagnetic activity between hemispheres.

For Brisbane, Tables 2 and 3 show eastern Australian Standard Times (local times) which relate to the 150°E geographic meridian. To convert to magnetic times there is a need to add 32 min for the equinoxes, 16 min for the December solstice and 39 min for the June solstice\textsuperscript{40}. Because the analyses provide times only at hourly intervals it would seem to be a good approximation to
simply add 30 min to the times listed to convert to magnetic times.

Acknowledgments
The authors would like to thank Mr. I Mortimer for his valuable assistance for the analyses. The daily weather charts used to identify cold fronts were made available by the Brisbane office of the Australian Bureau of Meteorology. The hourly geomagnetic $H$ components for Cape Wellen and Tixie Bay were supplied by the World Data Center - C2 for Geomagnetism, Kyoto, Japan.

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15. Craig R A, J Meteorol (USA), 9 (1952) 126.