Diurnal pressure variations over continental Australia

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(Manuscript received October 1994; revised February 1995)

Four years (1989–1992) of three-hourly surface pressure data from 61 Australian stations have been analysed on a monthly basis using Fourier analysis. Four points are noted over regions of higher terrain. The three major components have enhanced amplitude; the diurnal component has earlier phasing; the semi-diurnal component has later phasing; and the ter-diurnal component has later phasing in summer and earlier phasing in winter. The diurnal amplitude peak occurs in spring over northern and eastern Australia, in summer and winter along the northwestern coastal region, and in summer over the western coastal region and interior Australia. In the extreme southern coastal region, no significant seasonal diurnal amplitude peaks can be found among the smaller diurnal amplitudes. In general, earliest diurnal phasing occurs in autumn over most of the continent, except in the extreme south where it occurs in spring. The semi-diurnal component has early spring and early autumn amplitude peaks of similar intensity, as well as late spring and late autumn phase peaks of similar value. The ter-diurnal component reverses phase from summer to winter, and has summer and winter amplitude peaks, with the winter peak being higher. Evolution of the mean daily pressure deviation pattern is included as an attempt to explain diurnal circulations.

Introduction

It is well known that diurnal pressure variation can obscure synoptic-scale and mesoscale pressure changes. Such variation must be removed in order to obtain the real pressure tendency at an observing station. The problem of providing reliable diurnal pressure correction values for stations in Australia is re-visited in this article and tackled using Fourier analysis and spatial interpolation. The results presented here are the outcome of this exercise.

The diurnal pressure variation can be resolved into a series of Fourier components. Each Fourier component is a simple harmonic oscillation. Each harmonic oscillation has its own amplitude, period and phase. The phase of a Fourier component implicitly indicates the time of occurrence of crests and troughs in the oscillation. The larger the phase the earlier is the occurrence and vice versa. The first three major Fourier components with periods of 24, 12 and 8 hours are known as the diurnal component, the semi-diurnal component and the ter-diurnal component respectively. These atmospheric barometric tides are attributed to daily solar heating (Chapman and Lindzen 1970). The atmosphere absorbs solar radiation directly through ozone about 20–70 km above the surface, and through water vapour from the surface to an altitude of about 15 km. It also absorbs solar radiation indirectly through near-surface heating due to eddy heat transfer and latent heat release. It is believed that the tidal oscillations are mainly produced by ozone absorption, and that water vapour contributes an effect of about one half that of ozone (Chapman and Lindzen 1970). The atmosphere has been shown to have poor response to the diurnal thermal harmonic (Chapman and Lindzen 1970) because the natural mode of the atmospheric diurnal oscillation has a smaller vertical wavelength compared to the forcing. However, the semi-diurnal

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mode is large (Hamilton 1981). As a result, the semi-diurnal oscillation becomes the main component of the surface pressure oscillation. The diurnal component is also attributed to near-surface heating (Zwiers and Hamilton 1986) which varies with location and season. Therefore, the diurnal component should be more susceptible to local influence. In fact, during the summer season, due to pronounced surface diabatic heating, the amplitude of the diurnal component is larger than that of the semi-diurnal at all stations over interior Australia. The much smaller ter-diurnal component is linked to the ter-diurnal harmonic in the daily oscillation of the thermal forcing (Chapman and Lindzen 1970).

This paper documents the spatial and temporal variations in the diurnal, semi-diurnal and ter-diurnal atmospheric tides over continental Australia. The spatial results for January and July are presented as typical examples for the summer and winter seasons respectively. Annual variations for all stations are also presented. Monthly mean diurnal pressure deviation patterns due to these atmospheric tides are analysed, and related to diurnal circulations such as land-sea breezes as well as slope winds.

Data analysis

Four years of three-hourly surface pressure data from 61 Australian stations (see Fig. 1(a)) in the period 1989 to 1992 were selected from the National Climate Centre archives. These 61 acceptable stations were among those stations taking seven or eight observations in a day. All data were scanned for errors and suspect readings deleted before Fourier analyses were carried out. All deleted and missing data gaps having four consecutive observations immediately before and after were interpolated using the cubic spline method. The same interpolation scheme was used to correct all daylight-saving time data to standard time. Monthly means of the standard time three-hourly surface pressure were calculated for each station. In order to take into account the thermally driven nature of the diurnal pressure variation, local mean solar time was used. Cubic spline interpolation was employed once again to correct each three-hourly monthly mean to a local mean solar time value. The three-hourly values were then analysed on a monthly basis using Fourier analysis to produce the monthly mean amplitudes and phases of the first three Fourier components for each station. The diurnal pressure variation \( p(t) \) is represented by the following Fourier series expansion as a function of time, \( t \),

\[
p(t) = m + \sum_{k=1}^{3} A_k \sin\left(\frac{2\pi}{T}kt + \phi_k\right).
\]

The first term on the right-hand side, \( m \), is the daily mean pressure, \( A \) is an amplitude and \( \phi \) is a phase angle. \( T \), the basic period of the diurnal pressure variation, has the value of 24 hours. This Fourier series provides an approximation to each monthly mean three-hourly (local mean solar time) surface pressure. An error can be estimated by subtracting a monthly mean three-hourly surface pressure from the corresponding Fourier approximation. For each of the 61 stations there are 12 monthly sets of eight three-hourly errors.
As a least-square-fit property, the three-hourly errors in each monthly set tend to form an alternating positive and negative pattern with respect to time. Of the entire set of absolute errors, 99.9 per cent are below 0.1 hPa, 97.7 per cent are below 0.06 hPa and 92.8 per cent are below 0.05 hPa. Therefore, for practical purposes, the Fourier series can be truncated after three terms. No attempt was made to apply the equation of time (Chapman and Lindzen 1970) to all phases, so that the non-uniform rate of the earth’s motion around the sun and the tilting of the earth’s rotating axis were ignored.

In a similar study for the United States, Mass et al. (1991) have shown that there was no statistically significant difference between the results calculated from four years worth of data and those from all available data over a longer period. Haurwitz and Cowley (1968) used 14 years of data from some Australian stations to produce seasonal mean values for the amplitudes and phases of the first three Fourier components at each station. There is a close agreement revealed by comparison of these seasonal mean values to the corresponding ones found in this study (see Table 1). Such a close agreement further justifies the use of four-year averages to represent mean values for longer periods.

### Table 1

Listed are the seasonal mean amplitudes (A in hPa) and phases (P in degrees) of the diurnal (1), semi-diurnal (2) and ter-diurnal (3) surface pressure components of six stations from Haurwitz and Cowley (1968) (first figure) and this study (second figure). Under each station, the first row is for May to August; the second row is for March, April, September and October combined; and the third row is for November to February.

<table>
<thead>
<tr>
<th>Station</th>
<th>A1</th>
<th>P1</th>
<th>A2</th>
<th>P2</th>
<th>A3</th>
<th>P3</th>
</tr>
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<tbody>
<tr>
<td>Darwin</td>
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<td>1.1</td>
<td>11</td>
<td>10</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Broome</td>
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<td>1.0</td>
<td>7</td>
<td>12</td>
<td>0.8</td>
<td>0.8</td>
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<tr>
<td>Rockhampton</td>
<td>0.8</td>
<td>0.8</td>
<td>16</td>
<td>7</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Alice Springs</td>
<td>0.8</td>
<td>0.9</td>
<td>16</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Kalgoorlie</td>
<td>1.1</td>
<td>1.2</td>
<td>2</td>
<td>5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Hobart</td>
<td>0.7</td>
<td>0.5</td>
<td>349</td>
<td>0</td>
<td>0.7</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Spatial amplitude and phase variations in summer and winter

The spatial amplitude and phase variations of the diurnal, semi-diurnal and ter-diurnal surface pressure components across continental Australia for January and July are presented in Figs 2 and 3. The annual amplitude and phase variations of all 61 stations are presented in Fig. 4. Throughout the year, the patterns of diurnal, semi-diurnal and ter-diurnal surface pressure amplitudes are strikingly topographically and thermally dependent. Larger amplitudes are observed consistently within regions of higher terrain, and over interior Australia where the existence of a larger diurnal temperature range is well known. Relatively smaller amplitudes are observed in all coastal regions.

The diurnal amplitude has a range of approximately 0.1 hPa to 1.5 hPa across continental Australia throughout the year (see Fig. 4). During summer, a stronger gradient of diurnal amplitude exists along all coastal regions and is enhanced where there is higher terrain immediately inland. At the same time, smaller diurnal amplitudes of less than 0.5 hPa are observed along the extreme southern coastal regions around Albany and Melbourne (see Fig. 1(b) for the locations of places mentioned in the text). In winter, when cloudy and rainy weather prevails, the 0.5 hPa isopleth moves about five degrees latitude northwards as the area of smaller diurnal amplitudes expands. In response to the seasonal change in diabatic heating, the two centres of large diurnal amplitude over the Great Dividing Range and northwestern Australia shift about five degrees latitude northwards from summer to winter. In winter, at the two centres, there is an amplitude drop of about 0.5 hPa from the summer value of about 1.5 hPa.
Fig. 2 Amplitudes (A) and phases (P) of the diurnal (1), semi-diurnal (2) and ter-diurnal (3) components of surface pressure in January. Amplitudes are in hPa and phases are in degrees.
Fig. 3 Amplitudes (A) and phases (P) of the diurnal (1), semi-diurnal (2) and ter-diurnal (3) components of surface pressure in July. Amplitudes are in hPa and phases are in degrees.
During summer, due to stronger diabatic heating, the amplitude of the diurnal component is larger than that of the semi-diurnal throughout interior Australia.

The semi-diurnal amplitude has a range of approximately 0.5 hPa to 1.5 hPa across continental Australia all year round (see Fig. 4). The semi-diurnal amplitudes tend to form a simple zonal pattern with larger values observed over the northern half of Australia throughout the year.

The ter-diurnal amplitude is generally one order of magnitude smaller than those of the other two components. It has a range of approximately 0.05 hPa to 0.2 hPa across continental Australia (see Fig. 4). Although there is a seasonal variation in the amplitude of the ter-diurnal component, it has a larger value in regions of higher terrain. It is of interest to note that a ridge of large ter-diurnal amplitude exists in the southern coastal region in winter, when cloudy and rainy weather prevails.

Compared to the three component amplitudes, all the component phases are more dependent on topography. Consistently, the Great Dividing Range, northern and western Australia are regions of either earlier or later phasing compared to the Darling River basin, the Simpson Desert and the Australian coastline.

Among the three major component phases, the ter-diurnal phase has the greatest spatial and temporal variability throughout the year. The ter-diurnal component reverses phase from summer to winter. In the tropical regions, the degree of reversal is less. The ter-diurnal component has later phasing in summer and earlier phasing in winter over regions of higher terrain.

Along the Great Dividing Range, and over northern and western Australia, the diurnal component has earlier phasing and the semi-diurnal component has later phasing. Such features of the diurnal and semi-diurnal components can also be
Annual amplitude and phase variations

Examination of annual amplitude and phase plots (Fig. 4) reveals the existence of one or more seasonal peaks. In general, all amplitudes of the semi-diurnal component possess two common seasonal peaks of similar intensity, one in early spring and the other in early autumn. Also, two common seasonal phasing peaks of similar value, one in late spring and the other in late autumn, exist among all the semi-diurnal phases.

All the ter-diurnal amplitudes have two common seasonal peaks, one in summer and the other in winter with the winter peak being slightly higher (see also Fig. 2 and Fig. 3). The ter-diurnal component reverses phase from summer to winter. The degree of reversal is less in the tropical regions. The ter-diurnal phases are around 360 degrees when the sun is over the northern hemisphere. They are reversed to around 180 degrees when the sun is over the southern hemisphere.

As the diurnal component is more susceptible to local influence, a common annual variation pattern does not exist among the annual diurnal amplitude traces or the phase traces. However, as shown in Fig. 5 (A1), borderlines can be drawn to divide continental Australia into at least four regions, each of which has one or more distinct seasons of maximum diurnal amplitude occurrence. Maximum diurnal amplitude occurs in spring across northern and eastern Australia from Darwin to Nowra before the onset of convective cloudiness and rain in summer. In these regions, minimum diurnal amplitude can be found from autumn to winter. However, in Darwin, the minimum diurnal amplitude occurs in summer when convective activity in the summer monsoon prevails. In the northwestern coastal regions around Broome and Port Hedland, maximum diurnal amplitude occurs twice in a year, once in summer and once in winter. Lack of significant seasonal diurnal amplitude peak is a general feature among the relatively smaller diurnal amplitudes along the extreme southern coastal regions around Melbourne, Mount Gambier and Albany. Otherwise, a summer maximum of the diurnal amplitude is a widespread feature that can be observed along the western coastal regions from Learmonth to Perth, and throughout interior Australia. Tasmania is a region of spring and summer diurnal amplitude maximum.

Fig. 5 Season(s) of occurrence of maximum diurnal amplitude (A) and earliest diurnal phase (P) of surface pressure.
As shown in Fig. 5 (P1), most of continental Australia exhibits an earliest diurnal phase in autumn. However, in Tasmania and the coastal regions around Perth, Adelaide, Melbourne and Sydney, an earliest diurnal phase occurs in spring.

Evolution of the daily pressure pattern in summer and winter

The diurnal, semi-diurnal and ter-diurnal components are oscillations about a daily mean pressure value. At any given time during the day each component has its own pressure deviation value from the daily mean. Summing the three deviations gives an excellent approximation of the total pressure deviation at a given time. Therefore, on a monthly basis, hourly total pressure deviations for all the 61 stations can be derived from eight data points. The daily total pressure deviation patterns at four-hourly intervals for January and July are presented in Figs 6 and 7 respectively. These figures serve to reveal the daily evolution of the pressure pattern created by the diurnal pressure variations alone. The time reference used in both figures is the local mean solar time along the 135 degrees east meridian, which is about midway between the east and west coasts of Australia. The local mean solar time takes into account the thermally driven nature of the diurnal pressure variation.

In January, due to diabatic heating during the day, an obvious pressure pattern reversal from higher pressure to lower pressure over a large part of Australia occurs from 0800 hours to 1600 hours (local mean solar time along 135 degrees east). However, at the same time the area including the Darling River basin and the Simpson Desert changes from an area of relatively lower pressure to an area of relatively higher pressure. At 0800 hours, a ridge of high pressure extends from southwestern Australia northeastwards into the central part of northern Australia, and then extends southeastwards along the Great Dividing Range into southeastern Australia. Pressure gradient force is directed from regions of higher terrain down-slope, and from land to ocean waters. At 1600 hours, the ridge of high pressure is replaced by a trough of low pressure. The direction of the pressure gradient force is reversed and is directed from ocean waters towards land, and up-slope towards regions of higher terrain. From midnight to noon, pressure is generally higher over the Australian continent. Pressure starts to fall along the east coast at 1200 hours. Subsequently, the Australian continent gradually becomes an area of low pressure. Following the apparent motion of the sun, all high and low pressure centres move from east to west. In response to the diurnal temperature variations, the lowest pressure occurs in the afternoon. It should be pointed out that there is a stronger pressure gradient in all coastal regions. In the southwestern, eastern and southeastern coastal regions, the pressure gradient is much stronger, suggesting a more significant land-sea breeze system in these regions. In the area including the Simpson Desert and the Darling River basin, the evolution of the pressure pattern suggests an up-slope wind component on a summer afternoon, and a down-slope wind component at night and in the early morning.

In July, the evolution of the pressure pattern closely follows that in January. However, two points are noted. First, the pressure gradient is weaker throughout the day in winter and is much weaker along the southern coastal regions. This setting suggests a weaker land-sea breeze system along the coastal regions, and a weaker slope wind system in the area including the Simpson Desert and the Darling River basin. Second, in response to the lower elevation angle of the sun in winter, the pressure ridge and trough shift slightly northwards.

Interested readers can refer to the study by Clarke (1955) who provided an early documentation on Australian sea-breezes.

Conclusions

The diurnal surface pressure variations over continental Australia were investigated using four years of data from 61 stations.

Four points are noted over regions of higher terrain. The diurnal, semi-diurnal and ter-diurnal components have enhanced amplitude; the diurnal component has earlier phasing; the semi-diurnal component has later phasing; and the ter-diurnal component has later phasing in summer and earlier phasing in winter.

The diurnal amplitude peak occurs in spring over northern and eastern Australia, in summer and winter in the northwestern coastal region, and in summer over the western coastal and interior Australia. No significant seasonal diurnal amplitude peaks can be found in the extreme southern coastal region where the diurnal amplitudes are smaller. Earliest diurnal phasing generally occurs in autumn over most of the continent, except in the extreme south where it occurs in spring.

The semi-diurnal component has amplitude peaks of similar intensity in early spring and early autumn, as well as phase peaks of similar value in late spring and late autumn.
Fig. 6 Mean daily pressure pattern evolution due to diurnal pressure variations in January. Isobars are in hPa. Time reference is local mean solar time along 135°E.
Fig. 7 Mean daily pressure pattern evolution due to diurnal pressure variations in July. Isobars are in hPa. Time reference is local mean solar time along 135°E.
The ter-diurnal phases display a summer-winter phasing reversal. The degree of reversal is less in the tropical regions. The ter-diurnal component has summer and winter amplitude peaks, with the winter peak being slightly higher.

In January and July, due to the diurnal pressure variations, the daily evolution of the pressure deviation pattern is capable of describing the land-sea breeze and slope wind systems.

Finally, grid-point values for the three major Fourier component amplitudes and phases were established on a monthly basis by the Cressman (1959) objective analysis scheme over continental Australia. Based on these grid-point values, a diurnal pressure correction table can now be constructed using spatial interpolation for any locality over continental Australia.

Acknowledgments

The author would like to express his warmest gratitude to Bob Brook, David Evans, Bruce Neal, Bob Seaman and staff members of the Observations and Engineering Branch of the Australian Bureau of Meteorology for their constructive comments. Special thanks are due to the staff members of the National Climate Centre of the Australian Bureau of Meteorology for providing the observational data.

References


