THE SEMI-ANNUAL OSCILLATION AND ANTARCTIC CLIMATE.  
PART 3: THE ROLE OF NEAR-SURFACE WIND SPEED AND CLOUDINESS

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ABSTRACT
The interactions between the semi-annual oscillation (SAO), near-surface wind speed and cloudiness at seven Antarctic stations are described, as is how near-surface temperature is affected. A firmly established half-yearly wave, in both the mean annual cycle of wind speed and of cloudiness, was found at two stations with limited local disturbances: Halley and Faraday. Following a significant weakening of the SAO since the late 1970s, the annual cycles of wind speed and cloudiness at these stations have changed accordingly: increased wind speed and cloudiness in solstitial months and a decrease in the equinoctial months. At Halley, where no significant long-term temperature trends are detectable, this explains the observed changes in the seasonal temperature cycle. At Faraday, annual mean wind speed and cloudiness are negatively correlated to SAO strength, and as a result both have recently increased. Based on the correlation between wind speed and temperature changes, we estimate a "background" (independent of circulation changes) Antarctic warming trend of 1.29 ± 0.48°C per century. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: Antarctic climate; semi-annual oscillation; wind speed; cloudiness

1. INTRODUCTION

The semi-annual oscillation (SAO) consists of the twice-yearly contraction and expansion of the circumpolar pressure trough (CPT) (Figure 1). This occurs in response to the differences in energy uptake between Antarctica and its oceanic surroundings, resulting in a half-yearly wave in baroclinicity and depression activity (Van Loon, 1967; Meehl, 1991; Walland and Simmonds, in press). The strength of the SAO shows significant variability on interannual to decadal time scales (Van Loon et al., 1993; Hurrell and Van Loon, 1994; Simmonds and Jones, 1998). Because of the three-wave character of the SAO, this variability introduces longitudinal differences in meridional air exchange between Antarctica and its surroundings and, hence, differences in temperature trends between stations (Van den Broeke, 1998a,b; Van den Broeke, M.R. ‘On the interpretation of Antarctic temperature trends’, J. Climate, submitted). This might explain why Antarctic stations do not show uniform temperature trends: while the west coast of the Antarctic Peninsula (AP) has warmed by 2.5°C over the last 40 years (King, 1994; King and Harangozo, 1998), some East Antarctic stations actually showed cooling.

Of course, local temperatures are influenced by processes other than advection alone. In the Antarctic winter, and in the absence of horizontal advection, a balance at the surface is set up between cooling by net longwave radiation and warming by the downward turbulent transport of sensible heat. As a result of this balance, a surface temperature inversion develops, varying in strength between 2 K at exposed coastal stations to 25 K at the high plateau of East Antarctica (Connolley, 1996). Under these conditions,

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near-surface temperatures are sensitive to changes in cloud cover (which changes the longwave radiation balance at the surface) and/or near-surface wind speed (which influences the sensible heat flux). With the exception of Dumont d’Urville (see Section 3), annual mean temperature and wind speed/cloudiness are indeed positively correlated (Figure 2), but with a wide variety of slopes and significance. At Halley, the correlation is striking both for wind speed and for cloudiness, while at Macquarie Island the influence of cloudiness and at Faraday the influence of wind speed is not significant. This is not surprising, given the absence of a significant surface temperature inversion at the latter two stations. Temperatures at Faraday experience a strong feedback from sea ice extent in the Amundsen and Bellingshausen Seas (ABS).

The scope of this paper is to find relationships between variations in the strength of the SAO and changes in local cloudiness and wind speed at selected stations in Antarctica, and to study how these relationships influence near-surface temperatures. This can aid in the better understanding of the differences in temperature trends between, for instance, the AP region and East Antarctica. Other potentially useful applications are the detection of SAO signals in Antarctic firn/ice cores and the testing of General Circulation Model (GCM) performance at high southern latitudes.

In Section 3, an attempt is made to identify the signature of the SAO in the wind speed and cloudiness climatologies of these stations, and to test how sensitive they are to interannual variations in the SAO.
THE SEMI-ANNUAL OSCILLATION AND ANTARCTIC CLIMATE. PART 3

2. DATA AND ANALYSIS METHODS

Monthly averages of near-surface pressure ($P$, in hPa), 2 m temperature ($T$, °C), 10 m wind speed ($V$, m s$^{-1}$) and observed total cloudiness ($N$, in octas) for the period 1957–1995 at seven stations were used (Figure 1): Halley, Mawson, Davis, Casey, Dumont d’Urville (all coastal East Antarctica), Macquarie Island (sub-Antarctic) and Faraday (AP). Monthly totals of continuous plus intermittent precipitation reports (Prec) at the time of observation at Faraday were also used (Turner et al., 1997). Because the largest variability typically occurs in winter, time series of consecutive monthly means cannot be considered homogeneous (King, 1994). This problem is avoided by considering either annual mean time series or separate series for each month.

Not all time series are continuous and/or homogeneous. For Davis, no data are available for January 1957, November 1964–February 1969, the year 1980 (missing page in Russell-Head and Simmonds, 1993) and October/November 1990. Because of these considerable gaps, limited use has been made of the Davis data. No cloudiness data are available for Dumont d’Urville prior to 1960. Unless otherwise mentioned, the corrected wind speed series for the Casey and Dumont d’Urville stations are used, as proposed by Murphy and Pettitte (1999).

3. RESULTS FOR SELECTED STATIONS

We define the strength and timing of the SAO by the amplitude and phase of the second harmonic in the annual cycle of near-surface pressure, $H_2(P)$. A base period is defined during which the SAO was well developed (1957–1979, $N = 23$). The mean annual cycles for this period were subjected to a harmonic analysis (Table I). Second, the time series of the amplitude of $H_2(P)$ was correlated for the entire period (1957–1995) with the amplitude of $H_2(T)$, $H_2(V)$ and $H_2(N)$, and with annual means of $V$, $T$ and $N$ (Table II). To highlight changes on multi-annual timescales, 5-year running means of the annual cycle...
Table I. Mean, amplitude, phase (1 January = 0.0) and variance explained by the first \( (H_1) \) and second \( (H_2) \) harmonics of the 1957–1979 mean annual cycle of pressure, wind speed, cloudiness and precipitation reports (Faraday only)

<table>
<thead>
<tr>
<th>Station (variable)</th>
<th>Mean</th>
<th>Amplitude ( H_1 )</th>
<th>Phase ( H_1 ) (month)</th>
<th>Variance ( H_1 ) (%)</th>
<th>Amplitude ( H_2 )</th>
<th>Phase ( H_2 ) (month)</th>
<th>Variance ( H_2 ) (%)</th>
<th>Total variance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Halley</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure (hPa)</td>
<td>989.1</td>
<td>1.88</td>
<td>3.0</td>
<td>24</td>
<td>3.14</td>
<td>0.5</td>
<td>68</td>
<td>92</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>−18.5</td>
<td>11.71</td>
<td>0.9</td>
<td>95</td>
<td>2.46</td>
<td>0.1</td>
<td>4</td>
<td>100</td>
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<tr>
<td>Wind speed (m s(^{-1}))</td>
<td>6.8</td>
<td>0.72</td>
<td>7.2</td>
<td>41</td>
<td>0.81</td>
<td>3.6</td>
<td>53</td>
<td>94</td>
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<tr>
<td>Cloudiness (octas)</td>
<td>5.4</td>
<td>0.67</td>
<td>0.6</td>
<td>81</td>
<td>0.29</td>
<td>3.5</td>
<td>15</td>
<td>96</td>
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<td><strong>Mawson</strong></td>
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<tr>
<td>Pressure (hPa)</td>
<td>987.2</td>
<td>2.91</td>
<td>3.9</td>
<td>62</td>
<td>2.14</td>
<td>0.2</td>
<td>34</td>
<td>96</td>
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<tr>
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<td>0.8</td>
<td>90</td>
<td>2.92</td>
<td>0.4</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Wind speed (m s(^{-1}))</td>
<td>11.5</td>
<td>1.14</td>
<td>6.4</td>
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<td>0.56</td>
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<td>0.1</td>
<td>85</td>
<td>0.15</td>
<td>0.9</td>
<td>9</td>
<td>94</td>
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<td>Pressure (hPa)</td>
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<td>2.58</td>
<td>2.8</td>
<td>33</td>
<td>3.51</td>
<td>0.2</td>
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<tr>
<td>Temperature (°C)</td>
<td>−9.4</td>
<td>7.71</td>
<td>1.0</td>
<td>92</td>
<td>2.26</td>
<td>0.7</td>
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<td>100</td>
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<tr>
<td>Wind speed (m s(^{-1}))</td>
<td>6.2</td>
<td>1.14</td>
<td>7.2</td>
<td>85</td>
<td>0.14</td>
<td>1.5</td>
<td>1</td>
<td>86</td>
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<tr>
<td>Cloudiness (octas)</td>
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<td>0.13</td>
<td>0.9</td>
<td>24</td>
<td>0.10</td>
<td>2.2</td>
<td>14</td>
<td>38</td>
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<td><strong>Dumont d’Urville</strong></td>
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<td></td>
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<td>Pressure (hPa)</td>
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<td>3.65</td>
<td>0.4</td>
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<td>1.0</td>
<td>91</td>
<td>2.33</td>
<td>0.6</td>
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<td>1.02</td>
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<td>61</td>
<td>0.68</td>
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<td>88</td>
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<tr>
<td>Cloudiness (octas)</td>
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<td>3.3</td>
<td>11</td>
<td>0.34</td>
<td>2.1</td>
<td>56</td>
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<tr>
<td><strong>Macquarie Island</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pressure (hPa)</td>
<td>999.2</td>
<td>1.98</td>
<td>5.3</td>
<td>48</td>
<td>1.76</td>
<td>1.3</td>
<td>38</td>
<td>86</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>4.8</td>
<td>1.85</td>
<td>1.8</td>
<td>95</td>
<td>0.42</td>
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<td>5</td>
<td>100</td>
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<tr>
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<td>9.2</td>
<td>0.35</td>
<td>6.2</td>
<td>18</td>
<td>0.64</td>
<td>3.2</td>
<td>63</td>
<td>81</td>
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<tr>
<td>Cloudiness (octas)</td>
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<td>0.0</td>
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<td>0.02</td>
<td>0.0</td>
<td>1</td>
<td>32</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure (hPa)</td>
<td>989.5</td>
<td>1.47</td>
<td>5.6</td>
<td>20</td>
<td>2.88</td>
<td>0.7</td>
<td>77</td>
<td>97</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>−4.5</td>
<td>5.51</td>
<td>1.4</td>
<td>97</td>
<td>0.75</td>
<td>4.7</td>
<td>2</td>
<td>99</td>
</tr>
<tr>
<td>Wind speed (m s(^{-1}))</td>
<td>3.8</td>
<td>0.73</td>
<td>7.9</td>
<td>43</td>
<td>0.80</td>
<td>3.7</td>
<td>52</td>
<td>95</td>
</tr>
<tr>
<td>Cloudiness (octas)</td>
<td>6.5</td>
<td>0.40</td>
<td>0.4</td>
<td>65</td>
<td>0.28</td>
<td>3.7</td>
<td>34</td>
<td>99</td>
</tr>
<tr>
<td>Precipitation reports ( c )</td>
<td>38.8</td>
<td>3.49</td>
<td>8.9</td>
<td>23</td>
<td>5.87</td>
<td>3.6</td>
<td>65</td>
<td>89</td>
</tr>
</tbody>
</table>

Last column: total variance explained by the first two harmonics.
served as a basis both for the harmonic analysis and the subsequent correlations with annual means (leaving $N = 35$ and 33 degrees of freedom for the correlations). Because the stations differ so widely in geographical setting and climate, it was decided that the results should be discussed separately for selected stations.

### 3.1. Halley

Halley (75.5°S, 26.7°W, 32 m a.s.l.) is situated near the edge of the Brunt Ice Shelf in the Weddell Sea region (Figure 1). On the nearly flat ice shelf, some 40 km away from the slopes of the inland ice sheet, the station is not under the direct influence of katabatic winds. Although local winds could be affected by the continuous drainage from the inland slopes, the easterly near-surface winds are mainly forced by the large-scale pressure gradient. In the absence of katabatic winds, the strength of the surface temperature inversion reaches approximately 10°C in winter (King and Turner, 1997). This explains the low annual mean temperature (−18.5°C), which is comparable with other East Antarctic ice shelf stations (such as SANAE and Neumayer) but some 8°C colder than stations further to the east which are situated at the foot of the ice cap (such as Mawson and Casey; Table I).

The annual variation of $P$, $V$ and $N$ at Halley (1957–1979) can be well described by the sum of its first two harmonics $H_1 + H_2$ (Figure 3(a−c)), explaining 92–99% of the total variance (Table I). The half-yearly wave is a very important component in the signal and explains more than 50% of the total variance for pressure and wind speed. For cloudiness, the signal is dominated by the annual wave, because the water-holding capacity of the air is determined by its absolute temperature, which causes a pronounced winter minimum in cloud cover. But, here also, the amplitude of the half-yearly wave is large enough and its phase sufficiently stable to generate a double maximum in the annual cycle (Figure 3(c)). Note that $H_2(V)$ and $H_2(N)$ are out of phase with $H_2(P)$, i.e. high cloudiness and wind speeds are observed in the contraction phases of the SAO, which is what is intuitively expected.

$H_2(T)$ is out of phase with $H_2(N)$ and $H_2(V)$, which is not expected from the dependency of temperature on wind speed and cloudiness in Figure 2(a, b). Note that $H_2(T)$ reflects the influence of several processes: first, the contraction of the pressure belt in the equinoctial months (March and September) decreases the transport of warm air from lower latitudes towards continental Antarctica (Figure 1); second, locally increased cloudiness and wind speed will enhance temperatures in these months. Finally, the position of the station determines the length and depth of the ‘coreless winter’: at higher latitudes and in the interior, the duration of winter is longer and the temperature minimum deeper; this means that the annual temperature curve deviates more from a sine curve, increasing the amplitude of $H_2(T)$ and forcing the phase towards a mid-winter maximum. Phillpot (1997) showed that continentality and latitude are the main predictors for the amplitude of $H_2(T)$. Apparently, the latter effect is dominant at Halley. Comparing the amplitudes of $H_2(T)$ between stations must, therefore, be carried out with care, and is only allowed if the stations have similar latitude and continentality.

### Table II. Linear correlation coefficient of the amplitude of $H_2(P)$ with the amplitudes of $H_2(T)$, $H_2(V)$, $H_2(N)$ and $H_2$(Prec) and annual mean values of $T$, $V$, $N$ and Prec, based on 5-year running means (1957–1995)

<table>
<thead>
<tr>
<th></th>
<th>$H_2(P)$</th>
<th>$H_2(T)$</th>
<th>$H_2(V)$</th>
<th>$H_2(N)$</th>
<th>$H_2$(Prec)</th>
<th>$T$</th>
<th>$V$</th>
<th>$N$</th>
<th>Prec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halley</td>
<td>$0.30^*$</td>
<td>0.25</td>
<td>$0.29^*$</td>
<td>—</td>
<td>0.15</td>
<td>0.46**</td>
<td>0.21</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mawson</td>
<td>0.57**</td>
<td>$-0.18$</td>
<td>0.00</td>
<td>—</td>
<td>0.12</td>
<td>0.26</td>
<td>$-0.10$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Casey</td>
<td>0.35*</td>
<td>0.35*</td>
<td>0.12</td>
<td>—</td>
<td>$-0.12$</td>
<td>$-0.02$</td>
<td>$-0.13$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Dumont d’Urville</td>
<td>0.32*</td>
<td>$-0.05$</td>
<td>0.32*</td>
<td>—</td>
<td>0.01</td>
<td>$-0.06$</td>
<td>0.57**</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Macquarie Island</td>
<td>0.27</td>
<td>0.19</td>
<td>0.22</td>
<td>—</td>
<td>$-0.24$</td>
<td>$-0.20$</td>
<td>$-0.13$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Faraday</td>
<td>0.05</td>
<td>0.84***</td>
<td>0.63**</td>
<td>0.73***</td>
<td>$-0.06$</td>
<td>$-0.51$**</td>
<td>$-0.62$***</td>
<td>$-0.31$*</td>
<td>—</td>
</tr>
</tbody>
</table>

* Confidence levels (one-sided test) are 95–99%.
** Confidence levels (one-sided test) are 99–99.9%.
*** Confidence levels (one-sided test) are better than 99.9%.
For further explanation see text.
Figure 3. Observations (black dots), first harmonic $H_1$ and second harmonic $H_2$ (dashed lines) and $H_1 + H_2$ (solid line) of the 1957–1979 Halley mean annual cycle of (a) surface pressure $P$, (b) 10-m wind speed $V$ and (c) cloudiness $N$.

Most of the inter-annual temperature variability at Halley can be attributed to variations in cloudiness and wind speed (Figure 4). Local temperature changes are driven both by large-scale advection and/or changes in the local surface energy balance but, because these processes are coupled, it is difficult to identify the essential driving mechanism. A multiple regression predicting annual mean temperatures at Halley as a function of annual mean wind speed and cloudiness shows that wind speed variations explain more than 70% of the temperature variability. The correlation between temperature and wind speed/cloudiness stems completely from the winter months. In December and January, net shortwave radiation dominates the energy balance at the surface and the planetary boundary layer is near-neutral stratified (Van den Broeke and Bintanja, 1995).

The inter-annual variations of wind speed at Halley are large, compared with those for cloudiness (Figure 4): the ratio of S.D. to the mean is 11% for wind speed and less than 5% for cloudiness. This translates into a large difference between the windiest and the calmest years at Halley, with 8.5 m s$^{-1}$ in 1976 and 5.4 m s$^{-1}$ in 1962, respectively. A possible explanation for this is the stable stratification of the planetary boundary layer which, in the absence of a significant slope, feeds back negatively on wind speed near to the surface; under weak wind conditions, stability increases which further prohibits vertical exchange of near-surface air with the free atmosphere, et cetera.
The Halley climate is not very sensitive to inter-annual variations in the SAO. Only the amplitudes of $H_2(T)$ and $H_2(N)$ and annual mean wind speed $V$ are (weakly) correlated with the amplitude of $H_2(P)$ at Halley (Table II), and this correlation stems mainly from the months in the contraction phases of the SAO. A possible explanation is that the station is situated relatively far to the south of the Atlantic Ocean, which in itself represents the weakest branch of the SAO (Van Loon, 1972). Air masses that are advected to Halley will, therefore, have lost some of their maritime characteristics.

3.2. Mawson and Casey

Mawson and Casey are situated in the Indian Ocean sector of Antarctica (Figure 1), both near sea level and bordering open ocean or sea ice. The climate of Mawson is dominated by katabatic winds from the slopes of the inland ice sheet; in summer, these winds decrease in strength and show a pronounced diurnal cycle. Streten (1990) reports a winter surface temperature inversion of 2 K at Mawson, which is considerably less than at Halley. As a result, temperature at Mawson depends less critically on wind speed and cloudiness, although they still correlate positively in a significant way (Figure 2).

Casey winds are weaker and probably more representative of the large-scale pressure gradient. Unfortunately, the location of Casey has changed several times over the last decades, so that time series of wind data are not homogeneous and are of limited value for this study. Climate maps of sea level pressure show that in the equinoctial months (March and September), depression activity in the Indian Ocean sector is greatest in the Casey region; this explains why mean sea level pressure increases and temperature and cloudiness decrease westwards towards Mawson (Table I).

In the expansion phase of the SAO, the low pressure centre moves away from the continent towards the northwest, and ends up at the longitude of Mawson, but considerably further north (Figure 1). Consequently, the amplitude of $H_2(P)$ is largest at Casey and decreases towards Mawson, while the opposite is true for $H_2(T)$ (Van den Broeke, 1998a; Table I). As a result of the large zonal displacement of the CPT and the associated circulation changes, the positive correlation found between $H_2(P)$ and $H_2(T)$ at Mawson is more significant than at Casey. The most significant correlation exists for $H_2(P)$ at Casey with $H_2(T)$ at Mawson ($R = 0.80$).

The amplitudes of $H_2(V)$ and $H_2(N)$ are small at Mawson and Casey, and the annual cycle of wind speed and cloudiness are relatively poorly described by their first two harmonics (Table I). Moreover, the phase of the second harmonics is not in agreement with that of the SAO. No significant relations were found between $H_2(P)$ and the annual mean local climate variables (Table II). Local effects, such as the katabatic winds at Mawson, and the large local topographic and climatological gradients of these stations could be responsible for this.
3.3. Dumont d’Urville

Dumont d’Urville (66.7°S, 140.0°E, 43 m a.s.l.) is situated on a rocky outcrop, some 5 km away from the continental ice slope. Interpretation of the wind climate at the station is complicated because of its offshore location and the presence of islands between it and the coast (Mather and Miller, 1967). The wind measured at Dumont d’Urville is a mix of katabatic winds advected from the ice sheet and the synoptic-scale circumpolar easterlies. Cold air is advected towards the station when katabatic winds from the ice sheet penetrate over the ocean/sea ice. This is the reason why high wind speeds bring low temperatures, in sharp contrast to the other stations in this study (Figure 2(a)).

Although the semi-annual wave is well-established in the seasonal pressure cycle, the first two harmonics relatively poorly describe the annual march of wind speed and cloudiness; nor is the phase of the second harmonic consistent with that of the SAO (Table I). Despite this, a significant positive correlation is found for the amplitude of $H_2(P)$ with annual mean cloudiness (Table II), which mainly stems from the equinoctial months.

3.4. Faraday

Faraday (65.3°S, 64.3°W, 9 m a.s.l.) is situated at the western edge of the AP, and experiences on average southwesterly winds. No ‘coreless’ winter is observed at Faraday: the thermal lag of the ocean and the annual cycle of sea ice cover force a late-winter temperature minimum. This explains the absence of a well-defined half-yearly wave in temperature (Table I). Winter temperatures at Faraday are very variable, owing to feedbacks with sea ice concentration in the ABS (King, 1994; Jacobs and Comiso, 1997; King and Harangozo, 1998). The influence of the SAO on sea ice extent in this area is discussed by Van den Broeke (1999).

For all variables except temperature, the half-yearly wave is well-established in the Faraday 1957–1979 climatology and in phase with the SAO (Table I, Figure 5(a–c)). Note that $H_2(P)$, $H_2(V)$ and $H_2(N)$ have comparable amplitudes and are in phase with those of Halley, and that almost all of the variance is explained by the sum of the first two harmonics. The half-yearly wave in precipitation frequency at Faraday $H_2(\text{Prec})$ is in phase with $H_2(N)$ (Figure 5(c); see also Turner et al., 1997).

The amplitude of $H_2(P)$ at Faraday is significantly correlated to the half-yearly waves of other variables as well as to their annual mean values (Table II), temperature excluded. This means that the Faraday climate is sensitive to inter-annual changes in the strength of the SAO. A striking feature is the negative correlation of $H_2(P)$ with annual mean wind speed, cloudiness and precipitation frequency: in years where the SAO is poorly developed, annual mean wind speed, cloud cover and precipitation at Faraday are above normal. This could be associated with a limited meridional movement of the CPT in years with a weakly developed SAO, as was suggested by Van Loon et al. (1993); associated with this is a higher occurrence of cyclones in the ABS. The implications of this are discussed in the next section.

4. RECENT CHANGES

Probably as a result of the natural decadal variability of the Southern Hemisphere climate, the SAO has weakened significantly in the decades following the late 1970s (Van den Broeke, 1998a). In this section, whether and how this has influenced the annual mean and cycle of wind speed and cloudiness at Antarctic stations is investigated. Table III lists the changes in the annual means and cycles of the two periods, 1980–1996 (weak SAO) minus 1957–1979 (well-developed SAO). The change in the annual cycle is quantified by correlating changes in the individual monthly means $\delta X_i$ with the contribution of the SAO to the signal in the base period, $H_2(X_i)$, where $i$ runs from 1 to 12 and $X$ represents $P$, $T$, $V$, $N$ or Prec. If changes in the annual cycles are to be consistent with a weaker SAO, a significant negative correlation of these two quantities would be expected.
4.1. Halley

At Halley, no significant changes are found in annual mean temperature, wind speed or cloudiness. Although King (1994) reports a warming trend at Halley of 0.32 K per decade over the period 1957–1990 (significant at the 95% confidence level), a cold period after 1990 has made this trend insignificant (1994 was a record cold year with an annual mean of −21.0°C). However, there have been changes in the annual cycle of pressure, wind speed and cloudiness that are consistent with a weaker SAO (right column in Table III), i.e. lower wind speed and cloudiness in the equinoctial months and the opposite change in the solstitial months (Figure 6(a)). Temperature changes have closely followed these changes in wind speed and cloudiness, which suggests that local changes in the energy balance have dominated over changes in advection.
Table III. Left column: change in annual means (1980–1995 minus 1957–1979) and confidence level for a two-sided test \((N = 39\) but \(N = 36\) for Casey, \(N = 30\) for Davis); right column: linear correlation of changes of monthly means with 1957–1979 contribution to annual cycle of \(H_2\), and confidence level (one-sided test, \(N = 12\))

<table>
<thead>
<tr>
<th>Station (variable)</th>
<th>Change in annual means</th>
<th>Change in annual cycle: correlation with (H_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halley</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure (hPa)</td>
<td>-0.53</td>
<td>-0.62*</td>
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<tr>
<td>Temperature (°C)</td>
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<td>+0.33</td>
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<tr>
<td>Wind speed (m s(^{-1}))</td>
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<td>-0.77**</td>
</tr>
<tr>
<td>Cloudiness (octas)</td>
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<tr>
<td>Mawson</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure (hPa)</td>
<td>-0.80</td>
<td>-0.19</td>
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<tr>
<td>Temperature (°C)</td>
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<td>-0.27</td>
</tr>
<tr>
<td>Wind speed (m s(^{-1}))</td>
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</tr>
<tr>
<td>Cloudiness (octas)</td>
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</tr>
<tr>
<td>Casey</td>
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<td></td>
</tr>
<tr>
<td>Pressure (hPa)</td>
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<tr>
<td>Temperature (°C)</td>
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<tr>
<td>Wind speed (m s(^{-1}))</td>
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<tr>
<td>Dumont d’Urville</td>
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<td></td>
</tr>
<tr>
<td>Pressure (hPa)</td>
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<tr>
<td>Temperature (°C)</td>
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<td>Cloudiness (octas)</td>
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<tr>
<td>Macquarie Island</td>
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<tr>
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<td>-0.21</td>
</tr>
<tr>
<td>Wind speed (m s(^{-1}))</td>
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</tr>
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<td>Faraday</td>
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<td>Pressure (hPa)</td>
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<tr>
<td>Precipitation reports</td>
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<td>-0.61*</td>
</tr>
</tbody>
</table>

* Confidence levels (one-sided test) are 95–99%.
** Confidence levels (one-sided test) are 99–99.9%.
*** Confidence levels (one-sided test) are better than 99.9%.

4.2. Mawson, Casey, Dumont d’Urville and Macquarie Island

The two stations that are subject to katabatic winds from the inland ice (Mawson and Dumont d’Urville) have both experienced a significant drop in wind speed (Table III). At both stations, the change in the annual cycle suggests a positive correlation to the SAO (although the confidence level is only 90% at Mawson), indicating that wind speed decreased most in the solstitial months. Tentative explanations are the altered synoptic pressure gradient and/or decreased cooling of air over the inland ice sheet, leading to weaker katabatic winds near to the coast. The latter explanation is not supported by concurrent cloudiness changes at coastal stations, and requires further study of changed cloud conditions at inland stations.

At Macquarie Island, the annual cycle of cloudiness changed in accordance with a weakened SAO (Table III).
Figure 6. Changes in monthly means (1980–1995–1957–1979) of surface pressure $dP$, temperature $dT$, wind speed $dV$, and cloudiness $dN$ (all on the right axis), smoothed by a 3-month running mean.

4.3. Faraday

The strongest signals of change are once again found at Faraday. One of the most outstanding features of the Faraday climate since the beginning of observations at this station is the increase of mean annual temperature by about 0.6°C per decade. Significant autocorrelation of annual temperatures (King, 1994) suggests that slow circulation changes could be responsible for these trends. Not only has the temperature increased significantly at Faraday, but also wind speed and cloudiness (Table III). If we take into account the slope of the correlations, 75% of the wind speed and 77% of the cloudiness increase can be ascribed to the decrease of $H_2(P)$.

The increase of wind speed and cloudiness at Faraday are signatures of an increased occurrence of cyclones in the Bellingshausen Sea. Marshall and King (1998) note that warm winters at Faraday are associated with increased depression activity in the Bellingshausen Sea, inducing a north–south directed circulation anomaly over the region. At the same time, depression activity has decreased in the south.
Pacific to the northwest (their figure 3). The 500 hPa height anomalies which Marshall and King (1998) present for warm winter conditions are remarkably consistent with a suppressed wintertime expansion phase of the SAO. The changes in the annual cycles of wind speed, cloudiness and precipitation reports at Faraday show a clear half-yearly wave, another signature of the weakened SAO (Table III, Figure 6(b)). In contrast, the temperature increase at Faraday is strongly peaked in winter. The positive feedback with sea ice cover in the Bellingshausen Sea is probably responsible for this (Van den Broeke, 1999).

4.4. All stations

The prevailing stable stratification of the Antarctic atmospheric boundary layer and the high reflectivity of the surface mean that wind shear-generated turbulence and net longwave radiation are the main sources of heat transport towards the surface. Circulation changes and the associated changes in near-surface wind speed and cloudiness, for instance those described above, are therefore likely to influence temperature (trends) in Antarctica.

Figure 7(a, b) presents temperature changes at the seven stations in this study (1980–1995 minus 1957–1979) as a function of changes in wind speed and cloudiness. Retaining the uncorrected Casey wind speed data and excluding Dumont d’Urville (for reasons described in the Section 3.3), it is found that temperature changes at the six remaining stations are significantly positively correlated with local wind speed changes ($R = 0.93$, 99% confidence, Figure 7(a)). The correlation with changes in cloud cover is not significant (Figure 7(b)), although it is noteworthy that cloud cover increased at all stations except Dumont d’Urville.

The same result is obtained if trends of temperature and wind speed, instead of the means of two periods, are correlated. If it is assumed that changes in the SAO are translated to wind speed changes near the surface, a background warming trend of $1.29 \pm 0.48^\circ C$ per century can be derived, independent of changes in the SAO (abscissa in Figure 7(a)). Although this result should be interpreted with great care, the magnitude is consistent with an estimated Antarctic warming during the past century of $1^\circ C$ by Jones (1990) and a value of $1.14 \pm 0.39^\circ C$ found by Van den Broeke (submitted).
5. SUMMARY AND CONCLUSIONS

In this paper, whether and how the SAO influences near-surface wind speed and cloudiness at seven Antarctic stations, and how this impacts on near-surface temperatures, was studied. Only at Halley and Faraday was a firmly established half-yearly wave in the mean annual cycles of wind speed and cloudiness found; local disturbances, such as katabatic winds from the inland ice (Mawson), multiyear data gaps (Davis), changes of station location during the observation period (Casey) and large local climatic gradients and advection processes (Dumont d’Urville), must be partly responsible for the noisy signals at the other stations. Following a significant weakening of the SAO since the late 1970s, the annual cycles of wind speed and cloudiness at the Halley and Faraday stations have changed accordingly: an increase in the solstitial months and a decrease in the equinoctial months.

At Halley, where no significant long-term trends were detected in the annual means, monthly mean temperatures closely follow changes in cloudiness and wind speed. Following a weakening of the SAO since the late 1970s, Faraday wind speed and cloudiness have increased. Faraday temperatures show an anomalous large response in the winter months, probably as a result of the feedback with sea ice cover in the Bellingshausen Sea (Van den Broeke, 1999). Based on the correlation between wind speed changes and temperature changes, a ‘background’ (first order corrected for wind speed change) Antarctic temperature trend of $+1.29 \pm 0.48^\circ$C per century is tentatively suggested.

Using the data of a 1000-year low-resolution GCM run, Simmonds and Walland (1998) demonstrated that decadal/centennial variability of the SAO is part of the variability of the Southern Hemisphere climate. Meehl et al. (1998) showed that simultaneous with the recent weakening of the SAO, meridional temperature gradients in the southern ocean have decreased. Nevertheless, the mechanism responsible for decadal variations in the strength of the SAO presently remains unknown.

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REFERENCES


Walland, D.J. and Simmonds, I. in press. 'Baroclinicity, meridional temperature gradients and the southern semiannual oscillation', *J. Climate*.