
DAMIEN IRVING, IAN SIMMONDS, AND KEVIN KEAY

School of Earth Sciences, The University of Melbourne, Melbourne, Victoria, Australia

(Manuscript received 21 January 2010, in final form 11 May 2010)

ABSTRACT

Mesoscale cyclones play an important role in the weather and climate of the Southern Hemisphere (SH) mid-to-high latitudes. However, the relatively small size and short lifetime of these systems, combined with the lack of available conventional data in this region, means that there is a poor understanding of their climatological characteristics. In this study, the University of Melbourne cyclone-finding algorithm was applied to relatively high-resolution scatterometer-derived surface pressure fields, obtained from the Department of Atmospheric Sciences at the University of Washington, to produce a decade-long (1999–2008) seasonal climatology of mesoscale cyclone activity over the ice-free regions of the Southern Ocean.

The frequency of mesoscale cyclone activity was found to be highest just to the north of the sea ice zone, reaching a maximum over the Amundsen and Bellingshausen Seas (ABS), while the southern Indian Ocean was associated with systems of the largest depth, intensity, and momentum flux at the ocean surface. These spatial patterns in mean mesoscale cyclone characteristics showed a broad resemblance to those reported in existing synoptic-scale cyclone climatologies. Maximum wind speed data indicated that SH polar lows may be more frequent than the current literature suggests, while strong positive trends identified in mesoscale cyclone frequency over the ABS may represent a contributing factor to the rapid warming observed in that region over recent years. Partial correlation analyses indicated a link between mesoscale cyclone frequency and the southern annular mode.

1. Introduction

Our understanding of the atmospheric system in the sparsely populated and observed mid-to-high southern latitudes is particularly poor. This is especially true on the mesoscale, where a lack of conventional data combined with the small size and relatively short lifetime of mesoscale cyclones hampers the detection and diagnosis of these systems. The term mesoscale cyclone covers a wide range of weather systems from insignificant minor vortices with only weak surface circulation and no distinct cloud signature to the very active disturbances known as polar lows, which have been known to be associated with winds of hurricane force and heavy snowfall (Rasmussen and Turner 2003). With a diameter of less than 1000 km and a lifetime often less than 24 h, the incidence of mesoscale cyclone activity increases dramatically with latitude in both hemispheres, typically reaching a maximum in the vicinity of the polar front (Rasmussen and Turner 2003). In fact, it has been suggested that over half of all cyclonic activity in the extratropical regions of the Southern Hemisphere (SH) is mesoscale in nature (Yuan et al. 2009).

One of the most influential features of the SH in relation to mesoscale cyclone activity is the presence of the ice-covered and elevated Antarctic continent and the surrounding sea ice. Because of this distribution of glacial and sea ice, strong katabatic winds and/or large-scale synoptic weather systems can cause the northward channeling of substantial masses of cold polar air (Parish and Bromwich 2007). Once over the relatively warmer waters of the Southern Ocean, this cold air is associated with intense upward heat fluxes. These fluxes, in addition to the baroclinicity caused by the strong temperature contrast between the sea ice and open water as well as the instability caused by cold air over relatively warmer water, provide an ideal environment for mesoscale cyclogenesis (e.g., Yanase and Niino 2007).

The importance of mesoscale cyclones in the general circulation of the atmosphere and in the coupled atmosphere–ocean–ice system of the southern extratropics is still unclear (Rasmussen and Turner 2003). However, because they are so numerous, mesoscale cyclones
may make a substantial contribution to the poleward transport of heat and moisture and to the maintenance of the global atmospheric momentum budget, despite their small size. In fact, it has been estimated that the climatological contribution of mesoscale cyclones to sensible and latent heat fluxes at the air–sea interface over the entire Southern Ocean is comparable to that of larger synoptic systems (Yuan et al. 2009). In addition, it has been speculated that these heat fluxes, together with the surface wind stress associated with mesoscale cyclone activity, may help maintain the higher-latitude branches of the thermohaline circulation on decadal and longer time scales (Rasmussen et al. 1993; Condron et al. 2008).

One factor contributing to our relatively poor understanding of the importance of SH mesoscale cyclone activity is our limited knowledge of the climatological characteristics of these phenomena (Rasmussen and Turner 2003). Early research efforts in this field were observational in nature, with researchers making use of visible and infrared satellite imagery to locate cloud signatures indicative of mesoscale cyclone activity (e.g., Carrasco and Bromwich 1992; Turner and Thomas 1994). However, while these studies have made a significant contribution to our understanding, there are a number of limitations associated with such a methodology. For instance, the manual identification of mesoscale cyclones is a very time-consuming process, and hence observational studies for the SH have typically focused on regions of suspected high activity around the Antarctic coastline for periods of no more than 12 months. In addition, the subjective nature of manual cyclone detection introduces some degree of uncertainty when attempting to replicate findings. A large percentage of mesoscale cyclones can also go undetected because of problems associated with identifying cloud signatures during winter and over ice surfaces (Carleton 1995; Heinemann and Klein 2003).

In more recent times, the advent of various automated cyclone-finding and tracking algorithms (e.g., Murray and Simmonds 1991; König et al. 1993; Hodges 1995) has freed researchers from many of the issues associated with manual techniques. As such, a number of studies have applied these algorithms to reanalysis data to produce climatologies that provide a more complete understanding of SH cyclone activity over far greater temporal and spatial scales (e.g., Simmonds and Keay 2000a; Hoskins and Hodges 2005; Lim and Simmonds 2007). However, while these studies have provided a wealth of information regarding synoptic-scale cyclone activity, the relatively coarse resolution of current global reanalysis products (which vary in resolution from 2.5° × 2.5° to 1.125° × 1.125°) limits their ability to capture the full extent of mesoscale activity (Condron et al. 2006). It is therefore fair to say that the main factor limiting our climatological understanding of SH mesoscale cyclone activity today is the resolution of the spatial data used by automated cyclone-finding algorithms.

The enhanced understanding of SH mesoscale cyclone activity that could be obtained from higher-resolution data would greatly assist in the refinement of regional and global atmospheric models, could be used to guide future studies regarding the dynamics that lead to mesoscale cyclone formation, and would be of interest to those planning logistical and scientific operations in the mid-to-high southern latitudes. As such, the focus of this paper is to make use of relatively high-resolution scatterometer-derived surface pressure fields, in conjunction with an automated cyclone-finding algorithm, to assemble a decade-long seasonal climatology of mesoscale cyclone activity for the extratropical SH.

2. Data

One higher-resolution alternative to reanalysis data for the climatological investigation of SH mesoscale cyclone activity is operational numerical analyses. In fact, automated cyclone-finding methods have recently been applied to operational surface pressure fields of 60-km resolution from the Antarctic Mesoscale Prediction System (AMPS; Uotila et al. 2009) and 1.125° × 1.125° resolution from the European Centre for Medium-Range Weather Forecasts (ECMWF; Yuan et al. 2009). While the latter were of comparable resolution to some modern reanalysis products, they included enhanced mesoscale information from 25-km resolution satellite scatterometer data, which was injected into the fields via a wavelet-based method. However, the main focus of these two studies was not to obtain a climatological perspective of cyclone behavior. In fact, operational analyses are generally not a preferred data source for climatological studies, owing to the spurious trends that can arise because of frequent upgrades to the operational numerical model and new and improved data sources.

A somewhat less obvious source of high-resolution data for the extratropical SH is surface pressure fields derived from satellite scatterometer data. In particular, the National Aeronautics and Space Administration’s polar-orbiting Quick Scatterometer (QuikSCAT) satellite has been providing estimates of the surface wind over the ice-free global oceans since mid-1999, and the Department of Atmospheric Sciences at the University of Washington have made available to the public oceanic swath-based (as opposed to products of greater spatial coverage) surface pressure fields derived from these surface wind data [referred to as the University of Washington QuikSCAT (UWQS) pressure fields; available
online at http://pbl.atmos.washington.edu]. At a resolution of 0.5° × 0.5°, and having been derived from surface wind data of 25-km resolution, the amount of mesoscale detail contained in the UWQS pressure fields is arguably superior to that of any other fields currently available for the broad-scale investigation of SH cyclone activity. Because the process by which the fields are calculated from the QuikSCAT surface wind data has remained unchanged over time, they are also free of the spurious trends commonly associated with the use of operational surface analyses. With these considerations in mind, the UWQS pressure fields were considered an appropriate data source for the purposes of this study.

a. QuikSCAT surface wind data

The surface wind data used to produce the UWQS pressure fields derives from the 25-km resolution, level-2B QuikSCAT surface wind vectors distributed by the Jet Propulsion Laboratory of the Physical Oceanography Distributed Active Archive Center (PODAAC; available online at http://winds.jpl.nasa.gov/missions/quikscat/index.cfm). The SeaWinds instrument aboard the synchronous polar-orbiting QuikSCAT satellite is a scanning microwave radar that measures electromagnetic backscatter from the wind-roughened ocean surface. Wind speed and direction are estimated from the backscatter using a geophysical model function and are reported as the wind that would exist at 10-m height if the atmospheric static stability were neutral (Chelton and Freilich 2005). An important quality issue in this process is contamination by heavy rain and/or sea ice. Hence, PODAAC apply a QuikSCAT-derived sea ice mask to the data fields prior to making them publically available (e.g., Anderson and Long 2005), and wind vectors flagged for rain contamination (Hudleston and Stiles 2000) were disregarded in the production of the UWQS pressure fields. Validation analyses based on buoy comparisons (e.g., Ebuchi et al. 2002; Satheesan et al. 2007) have indicated that the standard contamination free level-2B QuikSCAT vector winds have a root-mean-square wind speed accuracy of 1.6 m s⁻¹ or better.

With an orbital period of approximately 100 min and an effective swath width of 1600 km, QuikSCAT is able to sample about 90% of the global oceans daily (Hoffman and Leidner 2005). In fact, most of the global oceans are sampled more than once in this time. At latitudes poleward of 45°, overlap between adjacent swaths ensures complete longitudinal data coverage roughly every 12 h. QuikSCAT has provided a record of oceanic surface winds since July 1999, and any data outages during this time have been relatively short and infrequent. It should be noted that the same scatterometer data used to produce the UWQS pressure fields were also used to determine the wind speed characteristics of each mesoscale cyclone identified in the current climatology.

b. UWQS pressure fields

Various methods have been developed to estimate the surface pressure field from a swath of surface wind vectors (e.g., Harlan and O’Brien 1986; Hsu and Liu 1996; Hsu et al. 1997; Zierden et al. 2000; Hilburn et al. 2003). The method used to derive the UWQS pressure fields (Patoux et al. 2003, 2008) begins by interpolating all QuikSCAT surface wind vectors occurring equatorward of 70° in both hemispheres onto a 0.5° × 0.5° latitude–longitude grid. At each extratropical grid point, the geostrophic wind at the top of the boundary layer is then estimated using a University of Washington two-layer similarity planetary boundary layer (UWPBL) model (Brown and Liu 1982; Brown and Levy 1986; Brown and Zeng 1994; Patoux 2009). An optimal zero mean surface pressure pattern is fitted to the resulting swath of pressure gradients by least squares minimization, and the absolute value of these zero mean pressures is then set by matching the mean UWQS pressure to the mean pressure of the closest-in-time ECMWF operational surface pressure analysis.

The UWQS pressure retrieval method has been extensively validated and utilized in both the operational and research meteorological communities. For instance, UWQS pressure fields are used in near real time at the National Oceanic and Atmospheric Administration (NOAA) Ocean Prediction Center (Von Ahn et al. 2006) and have been used to study the development of frontal waves over the Southern Ocean (Patoux et al. 2005). Patoux et al. (2008) established that the root-mean-square difference between the UWQS surface pressure fields and the closest-in-time ECMWF operational surface pressure analyses is on the order of 2 hPa in the midlatitudes, while their comparison between the UWQS pressure fields and buoy pressure measurements found an average correlation of 0.97.

3. Methods

a. Identification and characterization of mesoscale cyclone activity

The University of Melbourne (UM) cyclone-finding algorithm (Murray and Simmonds 1991; Simmonds et al. 1999) was the primary tool used in the identification of mesoscale cyclone activity (e.g., Fig. 1). The algorithm has been shown to perform well in case study comparisons with both manual cyclone identification (Leonard et al. 1999; Simmonds et al. 1999) and other automated methods (Leonard et al. 1999; Raible et al. 2008; Mesquita et al. 2009), and it has been used to produce a number of
high-quality cyclone climatologies for the extratropical SH (e.g., Simmonds and Keay 2000a; Simmonds et al. 2003; Lim and Simmonds 2007).

In addition to locating cyclonic activity, the finding algorithm characterizes each system it identifies in terms of its intensity, depth, and radius. The definition of these variables has been extensively described in the literature (Simmonds and Keay 2000a; Lim and Simmonds 2007); however, it is important to note that the precise value calculated for each depends upon the choice of input instruction parameters. These parameters allow the user to fine-tune the calculation of each variable according to the characteristics of the input pressure data and to ensure that nonmeteorologically significant systems are disregarded (via minimum intensity and depth thresholds). Uotila et al. (2009) applied the UM cyclone-finding algorithm to AMPS data of similarly fine resolution to the UWQS pressure fields [60 (90)-km resolution at the end (beginning) of their study period] and ran sensitivity experiments for 165 different instruction parameter combinations to determine the most appropriate values for each. Given the similarity in resolution between the AMPS and UWQS pressure fields, as well the fact that Uotila et al. (2009) also conducted their analyses over the mid-to-high southern latitudes, the parameter values decided upon by Uotila et al. (2009; listed in Table 1) were also considered appropriate for the current study.

In addition to the intensity, depth, and radius variables, all QuikSCAT surface wind vectors recorded over the “domain” of each mesoscale cyclone were used to calculate the maximum wind speed and the mean of the squared wind speed. This circular domain was defined as having a radius twice that of the finding algorithm defined radius, so as to ensure the inclusion of the region of highest wind speed. Wind vectors located within the domain of two or more systems (synoptic or mesoscale) were excluded from these calculations to avoid the assignment of overly high values to any weak systems occurring in the vicinity of a stronger system.

The relevance of the mean of the squared wind speed is apparent when considering that the instantaneous scalar wind stress (or momentum flux, $\tau$) acting on the ocean surface can be parameterized as
$$
\tau = \rho C_D u^2
$$
(e.g., Simmonds 1985), where $\rho$ is the air density, $u$ is the wind speed at some (near surface) reference level, and $C_D$ is the drag coefficient with respect to that level. The drag coefficient is assumed to be constant in this parameterization, and hence a recent climatological investigation of drag coefficient values over the global oceans (Kara et al. 2007) was consulted in selecting a representative value of $1.4 \times 10^{-3}$. Because temporal and spatial variations in air density are much smaller than for the square of the wind speed, it was also considered appropriate to approximate the air density by a constant value of 1.2 kg m$^{-3}$.

b. Data analysis

The feasibility of applying the UM cyclone-tracking algorithm (Murray and Simmonds 1991; Simmonds et al.
1999) to the set of mesoscale cyclone identifications was investigated; however, the swath-based nature of the UWQS pressure fields (i.e., consecutive fields are separate in both time and space) ultimately meant that tracking could not be performed in an automated fashion. As such, the climatological statistics presented can be thought of as the culmination of tens of thousands of unbiased, instantaneous snapshots of mesoscale cyclone activity. These statistics were calculated for the period September 1999–November 2008 and over all ice-free oceanic waters in the 30°–70°S latitude band (as previously mentioned, the poleward extent of the UWQS pressure fields is limited to 70°S in the SH). This region will be referred to as the “ice-free Southern Ocean.”

1) DEFINITIONS

It would be dynamically natural to define the boundary between synoptic and mesoscale cyclone activity by comparison with the Rossby radius of deformation (Vallis 2006). However, as there are no data available of similar resolution and temporal and spatial coverage to the UWQS pressure fields for determining the static stability of the atmosphere in the vicinity of each system, the Rossby radius could not be determined. This is a common problem in climatological investigations of mesoscale cyclone activity, and as such an upper radial limit of 500 km represents a convenient and commonly applied approximation to the upper limit of mesoscale activity (e.g., Heinemann 1990; Carleton 1995; Carrasco and Bromwich 1996; Heinemann 1996; Turner et al. 1996). While the methods used to determine the radius of a system differ between previous mesoscale cyclone studies and do not match the UM definition (due to their observational nature), 500 km was also considered an appropriate upper limit for the current study. Standard three month periods were used to define the SH summer [December–February (DJF)], autumn [March–May (MAM)], winter [June–August (JJA)], and spring [September–November (SON)] seasons, where summer was addressed according to the year during which January and February occurred (e.g., summer 2005 extended over the period from December 2004 to February 2005).

2) SYSTEM DENSITY

Given that each UWQS pressure field does not encompass the entire 30°–70°S latitude band, in addition to the fact that more data coverage is available toward the southern end of the study region (consecutive QuikSCAT measurement swaths overlap to a increasing extent at higher latitudes), any selection of fields will not have sampled each data point an equal number of times. As such, in assessing the frequency of mesoscale cyclone activity at one point relative to another, the raw count of the number of systems identified within the vicinity of each point would not be an accurate comparison. Conveniently, the UM cyclone-finding algorithm represents the frequency of cyclone activity via the calculation of a “system density” statistic, whereby cyclone contributions from all sampled pressure fields are summed and then normalized for area and the number of sampling times (Murray and Simmonds 1991). To account for the fact that not all data points were sampled an equal number of times in our study, each grid point was weighted in this normalization process according to the number of times a pressure value for that point was available in a UWQS pressure field. The system density statistic, as calculated in this way, was therefore a far more appropriate measure of mesoscale cyclone frequency than the raw system count and may be considered as a measure of the proportion of the time that a point was under cyclonic influence, despite being independent of the units in which time is measured.

3) GEOGRAPHIC DISTRIBUTION OF MEAN MESOSCALE CYCLONE CHARACTERISTICS

In generating geographical fields showing mean mesoscale cyclone characteristics, the UM cyclone-finding

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Chosen value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ni</td>
<td>Zonal size of PS grid</td>
<td>301</td>
</tr>
<tr>
<td>nj</td>
<td>Meridional size of PS grid</td>
<td>301</td>
</tr>
<tr>
<td>rproj</td>
<td>No. of intervals between the pole and equator (i.e., projection radius or PS grid resolution)</td>
<td>150</td>
</tr>
<tr>
<td>rdiff</td>
<td>Diffusive radius used in the smoothing of input data</td>
<td>1.5° latitude</td>
</tr>
<tr>
<td>nshell</td>
<td>No. of surrounding scanning points used for initial cyclone identification</td>
<td>12</td>
</tr>
<tr>
<td>dftl1</td>
<td>Min distance between systems</td>
<td>2.0 grid units</td>
</tr>
<tr>
<td>cvarad</td>
<td>Radius used to determine the area-averaged Laplacian</td>
<td>1.25° latitude</td>
</tr>
<tr>
<td>cmnc1</td>
<td>Min area-averaged Laplacian, closed systems</td>
<td>0.5 hPa (° latitude)⁻²</td>
</tr>
<tr>
<td>cmnc2</td>
<td>Min area-averaged Laplacian, open systems</td>
<td>1.3 hPa (° latitude)⁻²</td>
</tr>
<tr>
<td>rdincr</td>
<td>Radial increment used in radius determination</td>
<td>0.25° latitude</td>
</tr>
<tr>
<td>dpnn</td>
<td>Min depth</td>
<td>0.01 hPa</td>
</tr>
</tbody>
</table>
algorithm uses a Cressman-type data distribution scheme (Cressman 1959; Murray and Simmonds 1991; Jones 1994) on a regular latitude–longitude grid (0.5° × 0.5° for this study). This technique distributes the data associated with each individual cyclone to a series of surrounding grid points in a fashion whose weighting is inversely dependent upon the radial separation between the cyclone and the grid points and in a manner that conserves the cumulative sum of the data. By using such a procedure, a gridpoint value on the summer climatological mean mesoscale cyclone depth plot, for example, refers to the mean depth of all mesoscale cyclones that passed “close” to that grid point for the summers of 2000–08 inclusively. Data points in this example (as for all plots presented), for which no UWQS pressure data were available, would not be plotted (i.e., these points would not receive any shading and hence appear white). This situation could arise due to either the presence of land or the persistence of sea ice over the entire time period. As such, the region of missing data located immediately off the coast of Antarctica will be referred to as the “sea ice zone” in the discussion of results.

4) TRENDS AND CORRELATIONS

While there are numerous hemispheric factors that can influence the interannual variability of cyclone activity over the Southern Ocean (e.g., Simmonds and King 2004), the southern annular mode (SAM), El Niño–Southern Oscillation (ENSO), and the wavenumber-1 pattern in the SH pressure field are thought to be particularly influential with respect to mesoscale cyclone activity (e.g., Claud et al. 2009). To expose the degree of influence these three modes of variability have over the seasonal frequency of mesoscale cyclone activity, system density fields were produced for each individual season of each year and a time-synchronous (i.e., zero lag) correlation was calculated between each grid point of these fields and three indices that are commonly used to represent the amplitude and phase of the SAM, ENSO, and wavenumber-1 pattern, respectively. In particular, seasonal Antarctic Oscillation index (AOI) data (Marshall 2003) were obtained from the Ice and Climate Division of the British Antarctic Survey (available online at http://www.nerc-bas.ac.uk/icd/gjma/sam.html), Niño-3.4 index data (Rayner et al. 2003) from the Climate Diagnostics Center of NOAA (available online at http://www.cdc.noaa.gov/gcos_wgsp/Timeseries/Nino34/), and transpolar index (TPI) data (Pittock 1980, 1984; Jones et al. 1999) from the Climate Research Unit at the University of East Anglia (available online at http://www.cru.uea.ac.uk/cru/data/tpi.htm). Given the possibility for varying degrees of interaction between these modes of variability (e.g., L’Hereux and Thompson 2006), second-order partial correlation coefficients were calculated, which allowed for the correlation between two variables to be found after removing the influence of an additional two variables (e.g., Spiegel and Stephens 1999). For example, the correlation between system density and the Niño-3.4 index was found after removing the influence of the AOI and TPI.

In addition to the system density fields used in the partial correlation analyses, geographic mean fields of each mesoscale cyclone characteristic were also produced for each individual season of each year, so that seasonal trends in both system density and each mesoscale cyclone characteristic could be calculated via (least squares) linear trend analysis (e.g., Draper and Smith 1998). The statistical significance of all trends and correlations was quantified by the p value obtained from appropriate two-sided t tests (e.g., Von Storch and Zwiers 2001). The 90% confidence level was used to indicate statistical significance in all results presented.

4. Results

In total, 82,907 cyclonic systems were identified from the UWQS pressure fields over the period September 1999–November 2008, which represents an average of 0.87 systems per field per swath. The radius of these systems ranged from 0.41° to 11.08° latitude (46–1230 km), where ° latitude refers to degrees of latitude; however, because mesoscale cyclones were defined to have an upper radial bound of 4.5° latitude (500 km), the largest 15% were excluded (Fig. 2), leaving a final total of 70,354 systems (0.74 per field per swath). The radius of these systems ranged from 0.41° to 11.08° latitude (46–1230 km), where ° latitude refers to degrees of latitude; however, because mesoscale cyclones were defined to have an upper radial bound of 4.5° latitude (500 km), the largest 15% were excluded (Fig. 2), leaving a final total of 70,354 systems (0.74 per field) for further analysis. Open systems comprised 46% of all mesoscale cyclones identified. The geographic distribution of the trends observed in system density are discussed in this section; however, no areas of widespread strong and statistically significant trends were observed in any mesoscale cyclone characteristic (i.e., radius, intensity, depth, or any wind-related variable).
for any season, and hence these were neither discussed nor presented.

a. Mesoscale cyclone frequency: System density

In general, the climatological geographic distribution of the system density statistic for each season showed an arc of highest values located 5°–10° latitude north of the sea ice (or missing data) zone, extending from the south of Africa eastward to Drake Passage (Fig. 3). Maxima within this arc were most prominent over the Amundsen and Bellingshausen Seas (ABS) during summer and autumn and off the coast of Wilkes Land, south of Australia, during winter. Climatological area-weighted average system density values calculated over the entire study domain revealed autumn as the most active season, with an average of $2.02 \times 10^{-3} \left(\degree \text{ latitude}\right)^{-2}$. The average values for summer and winter were similar $[1.70 \times 10^{-3} \left(\degree \text{ latitude}\right)^{-2}$ and $1.75 \times 10^{-3} \left(\degree \text{ latitude}\right)^{-2}$ respectively], while the lowest climatological area-weighted average system density was observed during spring $[1.40 \times 10^{-3} \left(\degree \text{ latitude}\right)^{-2}]$.

The annual time series of the area-weighted average system density over the entire study domain showed a nonsignificant decline for autumn, winter, and across all seasons (not shown graphically). However, on a regional basis (Fig. 4), relatively strong and significant trends toward increased system density were observed over the ABS during autumn, winter, and spring and also off the coast of Wilkes Land (from approximately 80° to 100°E) during summer. Declining trends were observed throughout much of the remainder of the study domain, particularly over the South Pacific Ocean during summer and autumn.
Of the three analyzed indices of climate variability, the AOI displayed the most widespread regions of strong and statistically significant (partial) correlation with mesoscale cyclone system density (Fig. 5). Broadly speaking, a hemispheric, quasi-annular pattern of negative correlation was observed from 45° to 60°S, with regions of positive correlation often observed poleward of this latitude band. This pattern was most pronounced during summer and spring, with large areas of significant negative correlation of magnitude greater than 0.6 observed. Autumn showed the most dramatic departures from this general pattern, with relatively strong and significant positive correlations observed throughout much of the eastern South Pacific Ocean. Widespread regions of significant (partial) correlation were less common for the Niño-3.4 index and TPI (not shown), and there appeared to be little consistency across seasons.

b. Horizontal scale: Radius

The geographic distribution of the climatological mean radius was dominated by the occurrence of smaller values in the vicinity of land and the sea ice zone (Fig. 6). The South Pacific Ocean was generally associated with larger systems than the South Atlantic or Indian Oceans, with this difference most apparent during winter. However, besides these general features, the spatial distribution

---

**Fig. 4.** Seasonal trends (slope of the least squares line of best fit) in system density over the entire study period [contour interval is 10^3 (° latitude)² decade⁻¹]. Negative contours are dashed and the zero contour is highlighted in bold. Regions where the trend differs significantly from zero (at the 90% confidence level) are indicated by stippling, whereas trends that differ from zero by greater than one contour interval are indicated by successively darker shades of blue (negative trend) or red (positive trend).
of mean radius for each season was relatively uniform. As shown in Fig. 2, the most frequently observed radial categories over the entire study period were 3.2°–3.4° and 3.4°–3.6° latitude (~350–400 km). The difference between the highest (summer) and lowest (winter) seasonal mean radius averaged over all mesoscale cyclones was a mere 0.6° latitude (3.45° versus 3.39° latitude).

**c. Strength: Depth and intensity**

The climatological mean depth and intensity showed similar spatial variations across all seasons, and hence only depth is displayed graphically (Fig. 7). The largest seasonal mean values for both variables were observed during winter [5.0 hPa and 2.45 hPa (° latitude)^{-2} respectively], with the smallest observed for summer [4.6 hPa and 2.18 hPa (° latitude)^{-2}]. On a regional scale, the largest climatological mean intensity and depth values were typically centered over the southern Indian and eastern South Atlantic Oceans at approximately 55°S. An exception to this pattern was observed during spring, with a maximum containing the highest climatological mean values for any season located immediately north of the Weddell Sea.

**d. Momentum flux per analysis**

As previously outlined, for each system identified by the UM cyclone-finding algorithm the mean momentum

![Figure 5](image-url)
flux over the cyclone domain was estimated from QuikSCAT surface wind data. While the spatial distribution of the climatological mean of this variable would be an interesting analysis in itself, such a field would not take into account the frequency of mesoscale cyclone activity. For instance, consider two example regions (A and B) that have a mean mesoscale cyclone momentum flux of 0.3 and 0.1 N m$^{-2}$, respectively. If, for example, 50 and 750 systems pass through each respective region every year, then it is clear that on average mesoscale cyclone activity makes a far greater contribution to the overall climatological momentum flux in region B, despite the lower mean flux associated with individual systems. Hence, to estimate the geographic distribution of the mean mesoscale cyclone flux contribution at any given instant (i.e., the flux per analysis, which takes into account when a mesoscale cyclone was not present), the mean momentum flux at each grid point was multiplied by the fraction obtained by dividing the count of the number of times that the grid point was captured in a UWQS pressure field and located within the domain of one or more systems by the number of times that the grid point was captured in a UWQS pressure field (Fig. 8). The highest seasonal mean momentum flux per analysis values were typically located between 45°–60°S, moving north or south within this latitude band with seasonal fluctuations in the sea ice extent. During summer, maxima within this band of high values were relatively evenly distributed throughout the hemisphere; however, for all other seasons maximum values were typically located over the southern Indian Ocean, with the highest values of any season observed in that region during winter.

By calculating relevant spatial integrals, it was also possible to estimate the percentage of the total annual

**FIG. 6.** Climatological mean mesoscale cyclone radius (° latitude) for each season. The contour interval is 0.15° latitude.
momentum flux over the entire Southern Ocean that the mesoscale cyclone flux per analysis shown in Fig. 8 represents. The mean momentum flux across all QuikSCAT surface wind vectors analyzed over the period December 1999–November 2008, integrated over the entire area spanned by those vectors, was $5.9 \times 10^{19}$ N, whereas the same statistic calculated for only those wind vectors located within the domain of at least one mesoscale cyclone was $1.0 \times 10^{19}$ N. Hence, it can be estimated that mesoscale cyclones are responsible for 17% of the total annual climatological momentum flux over the entire Southern Ocean.

e. Maximum wind speed

The geographic distribution of the climatological mean mesoscale cyclone maximum wind speed across all seasons is shown in Fig. 9. Mean values exceeded 15 m s$^{-1}$ in all regions, with the highest observed reaching close to 30 m s$^{-1}$. These high mean values were located in the lee of the Antarctic Peninsula and off the eastern coastline of South America, South Africa, and Australia. Of all mesoscale cyclones included in the climatology, 88% recorded a maximum wind speed of $>15$ m s$^{-1}$, with this percentage decreasing to 28% and 5% for speeds $>25$ m s$^{-1}$ and $>35$ m s$^{-1}$, respectively. Notably, 606 mesoscale cyclones (~1%) recorded a maximum wind speed of 49.95 m s$^{-1}$, which is the highest speed that the QuikSCAT scatterometer is able to record.

5. Discussion

As previously discussed, there has been much research conducted into the climatological characteristics of SH cyclone activity, and it is important to consider the
findings of our study in the context of this past work. In particular, the relevant literature consists of (i) observational mesoscale cyclone climatologies, which involve the manual identification of mesoscale activity from satellite imagery over relatively short time periods and restricted spatial domains; (ii) automated cyclone climatologies based on reanalysis data that, owing to the relatively coarse resolution of current reanalysis products, essentially provide a multidecadal perspective on synoptic-scale cyclone activity over the entire extratropical SH; and (iii) studies that have applied a cyclone-finding algorithm to higher-resolution operational surface pressure fields and in doing so reported a limited selection of climatological statistics pertaining to systems of both synoptic and mesoscale size together.

Given the large percentage of mesoscale activity missed by cyclone climatologies based on global reanalysis products (Condron et al. 2006), it may not be obvious in the first instance why the findings of these studies are relevant to those presented here. However, changes in synoptic activity represent a change in the environment that mesoscale cyclones form, in addition to the fact that the development and intensification of both types of system requires similar environmental conditions. Furthermore, owing to the relatively high resolution of the UWQS pressure fields, it is possible that in some cases two or more closely located mesoscale systems identified in the current study would actually appear as a single synoptic system in coarser-resolution products. For these reasons, spatial patterns in mean synoptic-scale cyclone characteristics, including any related trends over time.
and associations with modes of climate variability, are likely to be linked, to some extent, to patterns in mesoscale cyclone activity. Because so little is currently known about the climatological characteristics of mesoscale cyclone activity, the results of the current study will allow for the testing of this hypothesis.

It is important to note, however, that, unlike the current study, previous reanalysis climatologies typically considered data pertaining to the last three to four decades of the twentieth century, whereas most observational studies analyzed imagery from the late 1980s and early 1990s. Given the low-frequency variability that has been identified in mean SH cyclone characteristics [among many other atmospheric parameters; see Simmonds (2003) and references therein], patterns of activity observed for two different time periods should not be expected to match exactly, even if all other extraneous factors (e.g., data resolution and cyclone identification methods) could be eliminated.

a. Mesoscale cyclone frequency

The geographic distribution of mesoscale cyclone system density documented in the current study is generally consistent with cyclone frequency data reported in previous studies based on both operational surface pressure fields (Uotila et al. 2009; Yuan et al. 2009) and reanalysis data (e.g., Simmonds et al. 2003; Hoskins and Hodges 2005; Wernli and Schwierz 2006). In addition, the spatial pattern of trends observed in system density is broadly similar to the trends observed in reanalysis data for the last three to four decades of the twentieth century (e.g., Simmonds and Keay 2000b; Fyfe 2003; Simmonds et al. 2003). However, despite this broad similarity, the strong and significant positive trends in mesoscale cyclone frequency observed over the ABS differ from the largely unremarkable trends identified for that region in the aforementioned studies. These ABS trends are of particular interest considering that the mechanisms responsible for the rapid rise in mean near-surface air temperature observed to the west of the Antarctic Peninsula over the past half century are yet to be fully comprehended (Vaughan et al. 2001; Turner et al. 2005).

Owing to the associated strong winds and large air–sea temperature differences, mesoscale cyclone activity generally yields an increase in sensible heat flux from the ocean to the lower atmosphere (Rasmussen and Turner 2003). In fact, in relating mesoscale cyclone trajectories with near-surface temperature anomalies over the western Antarctic Peninsula region, Lubin et al. (2008) revealed a tendency for positive temperature anomalies in the presence of mesoscale cyclones throughout much of the year. The trends identified in the current study, interpreted in light of the findings of Lubin et al. (2008) suggest that an increased frequency of mesoscale cyclone activity may represent a contributing factor to the rapid near-surface warming observed to the west of the Antarctic Peninsula over recent decades.

While one needs to be cautious in interpreting any identified correlation between two variables (as statistical correlation alone does not imply causation), particularly with regard to relatively short data series such as that used in the current study, the quasi-annular pattern of partial correlation identified between system density and the AOI is suggestive of a sound physical association. A positive phase of the SAM (indicated by positive AOI values) would be expected to be associated with a southward shift in the mesoscale cyclone storm track (e.g., Rao et al. 2003), which is consistent with the observed general pattern of regions of positive correlation located around the periphery of the Antarctic continent, coupled with regions of negative correlation immediately to the north, extending throughout much of the 45°–60°S latitude band. A similar pattern of correlation was also observed in a recent analysis of winter-time cyclone statistics derived from reanalysis data for the period 1979–2003 (Pezza et al. 2008).

It is important to note, however, that the aforementioned band of negative correlation identified in the current study tended to break down over the eastern South Pacific Ocean, with positive correlations predominating there during autumn and winter. This finding could possibly be explained by the fact that, as with the SAM, cyclonic activity over the eastern South Pacific...
Ocean is thought to be responsive to changes in stratospheric ozone. In particular, stratospheric ozone depletion has been linked to the recent positive shift in the SAM (Renwick 2004; Arblaster and Meehl 2006; Marshall 2009) and to the increase in depth of the Amundsen Sea low observed in recent decades (Turner et al. 2009). When interpreting these deviations from zonal symmetry in the correlation between system density and the SAM during autumn and winter, it is also important to note that the structure of the SAM itself shows considerable seasonality, exhibiting less zonal symmetry during winter than it does during summer (see Kidston et al. 2009 and references therein).

With regard to the recent shift toward a more positive phase of the SAM, Marshall (2009) shows a positive trend in annual AOI values for the period covered by the current study (2000–08) and for the previous half century (1957–2008). In light of this SAM behavior, it is also interesting to note the relatively high degree of geographic correspondence between the general pattern we observe in the SAM partial correlation with mesoscale cyclone frequency and the trends we observe in mesoscale cyclone frequency. It is clearly plausible from this observation that the trends in mesoscale cyclone frequency may be linked, to some degree, to the positive shift in the SAM.

b. Horizontal scale

The only previous climatological studies to examine the horizontal scale of a mesoscale subset of cyclone activity over the ice-free Southern Ocean have been observational in nature and focused on the seas surrounding the Antarctic Peninsula (e.g., Heinemann 1990; Turner and Thomas 1994; Turner et al. 1996; Carrasco et al. 1997). Given the obvious difference between the definition of system radius used in these and the current study, it is not possible to directly compare the absolute values of system radii observed. Systems occurring over the Bellingshausen Sea in these observational studies tended to have a slightly larger horizontal scale than those over the Weddell Sea (Turner and Thomas 1994; Carrasco et al. 1997); however, this feature was not perceptible in our findings. This may be because systems occurring over the sea ice zone were also included in these observational studies. The absence of any pronounced latitudinal or longitudinal structure in the geographic distribution of the climatological mean mesoscale cyclone radius differs somewhat from recent objective studies based on reanalysis or operational surface pressure fields (e.g., Simmonds and Keay 2000a; Simmonds et al. 2003; Lim and Simmonds 2007; Uotila et al. 2009); however, this discrepancy may be explained by the fact that we examined a restricted radial subset of all systems identified.

c. Strength

The spatial distribution of the climatological mean mesoscale cyclone depth and intensity presented in the current study is broadly similar to distributions of mean cyclone strength reported in studies based on both reanalysis and operational surface pressure fields. In particular, regions including the southern Indian and eastern South Atlantic Oceans have been associated with relatively high cyclone strength in studies that used both the UM definition for cyclone depth and intensity (e.g., Simmonds and Keay 2000a; Simmonds et al. 2003; Yuan et al. 2009) and other alternative definitions (e.g., Sinclair 1994; Hoskins and Hodges 2005). Winter was associated with the strongest systems in these studies, which is again consistent with the findings of the current study. However, the pronounced maxima in both mesoscale cyclone depth and intensity located immediately north of the Weddell Sea during spring has not been noted in any previous objective climatology. We speculate that this feature may be related to the fact that during spring the circumpolar trough in the Weddell Sea is stronger and further south than during the rest of the year (e.g., Fig. 3.15 in King and Turner 1997). This is associated with strong barrier winds along the eastern side of the Antarctic Peninsula (Kottmeier and Fay 1998), which help to rapidly transport cold, cyclonic air masses to the ice edge, where surface fluxes and baroclinicity set up conditions ideally suited to the enhancement of mesoscale cyclones.

d. Momentum flux per analysis

As previously mentioned, Yuan et al. (2009) constructed mesoscale cyclone tracks over the Southern Ocean for the period 1999–2006 from ECMWF operational surface pressure fields, into which they had injected scatterometer-derived surface pressure information via a wavelet-based method. From these tracks, estimates of the associated fluxes of sensible heat, latent heat, and momentum were made using the UWPBL model. The spatial pattern of wintertime mean mesoscale cyclone momentum flux per analysis presented in the current study is broadly consistent with a similar statistic reported by Yuan et al. (2009; only winter results were presented graphically); however, the distinct maxima over the Indian Ocean extended further west in their study. By computing spatial integrals of the momentum flux via a similar method to that used here, Yuan et al. (2009) estimated that mesoscale cyclone activity was responsible for approximately 13% of the annual momentum fluxes over the Southern Ocean, as opposed to the estimate of 17% reported in the current study. Keeping in mind that in comparison to our study Yuan et al. (2009)
used a different definition for the Southern Ocean (20°–80°S), cyclone domain, winter season (July–September), and distinguishing mesoscale cyclones from larger systems, in addition to the fact that they used coarser-resolution data and a relatively simple cyclone identification scheme that was only able to identify closed systems, the broad consistency between their findings and our own provide a useful validation of the results they obtained. These percentage estimates are a clear indication that mesoscale cyclones make a considerable contribution to the climatological momentum fluxes over the Southern Ocean.

e. Maximum wind speed

Mesoscale cyclones are typically classified as “polar lows” if they are associated with maximum surface winds exceeding 15 m s\(^{-1}\), have a diameter of less than 1000 km, and are located poleward of the main polar front (Rasmussen and Turner 2003). Because the availability of routine wind speed observations in the high latitudes of either hemisphere is limited, the climatological investigation of maximum winds (and hence the objective identification of polar lows) over large spatial domains has, until recently, not been possible. In fact, while Blechschmidt (2008) was able to identify polar lows occurring over the Nordic seas by associating mesoscale cyclones identified from satellite cloud imagery with satellite-derived surface wind speeds, no similar investigation has been conducted for the SH.

The polar front (or circumpolar trough) encircles the Antarctic continent between 60° and 70°S, with its precise location varying with both longitude and the time of year—it is generally furthest south during spring and autumn and moves north during summer and winter (Streten and Pike 1980; Simmonds and Jones 1998). While the amount of ice-free ocean located poleward of the polar front in any given season is therefore limited, it is noteworthy that 79% of all mesoscale cyclone activity identified poleward of 60°S had a maximum wind speed greater than 15 m s\(^{-1}\). Given the relatively high system density identified over many regions poleward of 60°S, in addition to the fact that SH polar lows are generally considered to be relatively rare in comparison to their Northern Hemisphere counterparts (Rasmussen and Turner 2003), the data presented indicate that the occurrence of polar lows in the high southern latitudes may be more frequent than the current literature suggests.

6. Conclusions

The amount of mesoscale detail contained in the UWQS pressure fields is arguably superior to that of any other data currently available for the climatological investigation of cyclonic activity in the southern extratropics. By using these fields in conjunction with the UM cyclone-finding algorithm, a decade-long (1999–2008), seasonal climatology of mesoscale cyclone activity over the ice-free regions of the Southern Ocean has been compiled, which allows, for the first time, a detailed hemispheric perspective of mesoscale cyclone activity.

The spatial patterns of mean mesoscale cyclone radius, depth, and intensity identified from the UWQS pressure fields, in addition to patterns of mesoscale cyclone frequency and their associated trends, show a close resemblance to those reported by existing synoptic-scale cyclone climatologies based on reanalysis data for the last three to four decades of the twentieth century. This finding suggests that synoptic and mesoscale cyclone activity are intimately linked, which is of particular interest considering that the dynamical processes responsible for the formation and intensification of mesoscale systems (particularly polar lows) is an area of ongoing, active research (Rasmussen and Turner 2003). However, despite the many similarities identified with existing synoptic climatologies, regional differences were apparent. One striking difference relates to the strong positive trends in mesoscale cyclone frequency observed over the ABS, which may represent a contributing factor to the rapid rise in mean near-surface air temperature observed to the west of the Antarctic Peninsula in recent years.

Analysis of QuikSCAT surface wind data indicates that mesoscale cyclone activity makes a substantial contribution (~17%) to the total climatological momentum fluxes into the Southern Ocean, and that the occurrence of polar lows in the high southern latitudes may be more frequent than the current literature suggests. In addition, our partial correlation analysis indicates a link between the frequency of mesoscale cyclone activity and the SAM.

Acknowledgments. The authors wish to thank Jerome Patoux for his assistance with the UWQS pressure data and Petteri Uotila for his advice regarding the UM cyclone-finding algorithm instruction parameters. We also thank two anonymous reviewers for their suggested improvements to the manuscript. Parts of this research were made possible by a grant from the Australian Antarctic Science Advisory Committee.

REFERENCES


