Identification and Climatology of Southern Hemisphere Mobile Fronts in a Modern Reanalysis

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ABSTRACT

Presented here is an objective approach to identify, characterize, and track Southern Hemisphere mobile fronts in hemispheric analyses of relatively modest resolution, such as reanalyses. Among the principles in its design were that it should be based on broadscale synoptic considerations and be as simple and easily understood as possible. The resulting Eulerian scheme has been applied to the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA)–Interim and a climatology of frontal characteristics, at both the 10-m and 850-hPa levels, derived for the period 1 January 1989–28 February 2009. The knowledge of the character of these features is central to understanding weather and climate over the hemisphere.

In both summer and winter the latitude belt 40°–60°S hosts the highest frequency of frontal points, but there are significant zonal asymmetries within this band. The climatology reveals that the longest fronts are in the Indian Ocean where mean lengths exceed 2000 km. The mean frontal intensity over the hemisphere tends to be greater at 850 hPa than at 10 m, and greater in winter than in summer. The frontal intensity also shows its maximum in the Indian Ocean. In the mean, the meridional tilt of these fronts is northwest–southeast over much of the midlatitudes and subtropics, and increases with latitude toward the equator. The tilts are of overwhelmingly opposite sign in the coastal Antarctic and subantarctic regions.

Broadly speaking, the number of fronts and their mean length and mean intensity exhibit maxima in winter in the midlatitudes (30°–50°S), but show a sizeable semiannual variation (maxima in fall and spring) during the year at higher latitudes.

1. Introduction

Atmospheric fronts and frontal systems are central components of weather (and hence climate) over much of the world. These frequent phenomena (every few days over many extratropical regions) are associated with, among other things, precipitation, dramatic changes in temperature and wind (direction and speed), and extreme events. Despite this importance, the atmospheric community has yet to arrive at an agreed upon and precise definition of what composes a “front” (e.g., de la Torre et al. 2008). The term has been used to refer to a broad range of features on scales ranging from local (e.g., gust fronts) to global (e.g., subtropical front) (Jenknerr et al. 2010). It follows that the nature of frontal systems to be found in an analysis will depend to some extent on the resolution. Frontal identification in high-resolution analyses is a somewhat difficult and ambiguous task. Such outputs (especially from models) often contain numerical noise, which makes identification difficult, boundary processes can influence near-surface meteorological structures, and complex frontal algorithms may not always faithfully reflect what one would regard as a true meteorological front (Jenknerr et al. 2010). There are a number of other aspects in which frontal diagnosis depends strongly on the resolution of the analyses available: see, for example, Patoux et al. (2005) and also Hewson (2009), who suggested the presence of a “diminutive wave stage” in a cyclone life cycle, a feature that can only be detected in high-resolution data.

Even at the synoptic scale, different approaches can lead to outcomes that are of considerable variance, and highly experienced synoptic analysts are often unable to agree on frontal analysis even when provided with data of high resolution in time and space (Sanders and Doswell 1995; Sanders 1999). One of the reasons for this, as McCann...
and Whistler (2001) and others have commented, is that even trained weather analysts have their personal biases and prejudices. To make matters even more complex, a number of studies have shown that the diagnoses of Southern Hemisphere (SH) synoptic systems (of central interest here) in different reanalyses are often considerably at variance (e.g., Bromwich et al. 2007).

The concept of a front dates back to the work of Bjerknes (1919) and can be understood in its simplest form as a (sloping) quasi-discontinuity in the density field. Over the twentieth century the concept was progressively refined. Among the important milestones in that development are the studies of Miller (1948), Scherhag (1948), Palmén (1951), and Godson (1951). Taljaard et al. (1961) defined a front as a narrow sloping layer with a vertical extent of at least 3 km across which the temperature changes sharply in the horizontal direction by a minimum of 3°C in subtropical latitudes, and 4°C–5°C in midlatitude and polar regions. Anderson et al. (1955) presented a refined definition that required (i) a 3D hyperbaroclinic zone with first-order discontinuities in the temperature and wind, (ii) a quasi-substantial surface that moves with the wind flow, and (iii) a reasonably continuous feature in both space and time. Their paper generated much discussion (see, e.g., Anderson et al. 1956) and questions were raised as to the extent to which the method tried to force the atmosphere into a strait jacket, to which it cannot conform. Over the last century the understanding of fronts has been a key component of the fundamental thinking in meteorology and climate and that remains so today. While fronts may be seen as becoming obsolete as an analysis tool, they will long remain a conceptual tool with which to communicate weather changes (see, e.g., McCann and Whistler 2001) and understand atmospheric and climatological structure.

With the development of computer technology and its rapid adoption by the atmospheric sciences, it became clear that comprehensive frontal analysis would benefit greatly from automatic, computer analysis. Given the difficulties discussed in connection with arriving at an accepted definition of a front, clearly designing a numerical scheme from 3D analyses to identify fronts and frontal zones is a task of even greater difficulty. Having said that, such schemes have considerable advantages over “traditional” techniques in that the analyses performed with them are reproducible and can be obtained very rapidly. This objectivity and speed means that such schemes could be applied to large numbers of case studies and to the outputs of weather and climate model simulations.

The initial efforts in the objective, computer-based identification of fronts were undertaken in the 1960s. Renard and Clarke (1965) and Clarke and Renard (1966) stressed the value in selecting “… a minimum number of conservative parameters for specifying the frontal zones” and their synthetic insight led them to define the “thermal frontal parameter” (TFP). The TFP maximum can be used to represent the front, and its gradients are able to reflect the strength of the transition zone. Independently, Kirk (1965, 1966, 1970) proposed the use of the Laplacian of basic weather elements (e.g., temperature) to identify fronts. The Laplacian was seen as valuable in that it took into account the changes in direction of the relevant gradient as well as the magnitude. As with Renard and Clarke (1965), he stressed that any parameter used for frontal identification should have an obvious physical interpretation and a simple mathematical form [points also made by Hewson (1998)].

Further progress was made in the form of a simple scheme by Radinović (1980), and Huber-Pock and Kress (1989) elaborated on the definitions of Anderson et al. (1955) and Renard and Clarke (1965) and how fronts might be defined objectively. They developed options in their objective frontal analysis by requiring extrema of the thermal frontal parameters to be associated with the humidity index exceeding certain critical values. The extent to which this component of the identification is useful is still subject to discussion in the atmospheric science community. Sanders and Doswell (1995, p. 507) have commented that satellite imagery, “… while effective for locating cyclone centers, especially at sea, of an extratropical cyclone, rarely indicates specifically the position of a front.” Huth (1991) explored the diagnostic value of a number of parameters in his objective frontal analysis investigation, and found that the best results were achieved when the thermal, dynamic, and moist characteristics of the atmosphere could find expression.

In the 1990s, Hewson (1997, 1998) developed a method that made use of a “locating” equation (based on the TFP formula) and “masking inequalities.” An advantage of his method is that it also permits the determination of frontal type. Kašpar (2003a,b) developed a method of objective frontal analysis for the small region of central Europe, extending Hewson’s method. McCann and Whistler (2001) suggested a modification to the TFP that more accurately reflected the strength of the front. They also suggested a complementary (to their TFP) frontal locator that permits the identification of (not uncommon) fronts that have a significant alongfront thermal gradient.

We close this brief background survey by mentioning some other techniques that lend themselves easily to calculation from digital analyses and hence relatively easy evaluation by computer. The (scalar) “Frontogenesis Function” developed by Petterssen (1936; see also chapter 11 of Petterssen 1956) has proved to be an insightful diagnostic. Keyser et al. (1988) generalized this concept to develop a vector frontogenesis function. We also note that
a number of studies have made use of pattern recognition methods to identify fronts (e.g., Fine and Fraser 1990; Pankiewicz 1995; Jann 2002; Dell’Acqua and Gamba 2003; Wong et al. 2008). These approaches appear to have considerable promise.

Fronts are frequently associated with cyclonic systems, and their influence can extend up to thousands of kilometers from a cyclone center. While extensive research has been conducted on the automatic identification and tracking of extratropical cyclones (e.g., König et al. 1993; Sinclair 1994; Simmonds and Murray 1999; Sickmüller et al. 2000; Simmonds and Keay 2000; Fyfe 2003), much less has been devoted to the automatic detection of frontal systems (Hewson and Titley 2010). A comprehensive understanding of frontal systems is an important component of the full comprehension of the behavior and role of transient systems.

Most of the research on objective frontal analysis has been directed toward case studies. While this is very important for the improvement of forecasting on short time scales, much less is known about the climatological behavior of frontal systems. Assembling a climatology of fronts is not a straightforward task, and one asks how a climatology of a collection of “lines” is assembled. Very few approaches to the problem have been attempted, but one can mention the early work of Reed and Kunkel (1960) and Serreze et al. (2001). These studies could only make use of techniques and datasets that were available at the time. Further, they were unable to consider the average of frontal characteristics such as length, orientation, and intensity. We also point out that virtually all the research on objective identification has been focused on the Northern Hemisphere (NH), and that synoptic characteristics there differ greatly from those in the Southern Hemisphere. [The large expanses of ocean in the SH, and the disposition of continents and topography (Barrett et al. 2009), give rise to heating patterns etc. that are very different to those of the NH where the Eurasian and American continents exert significant influence.] The studies of Piva et al. (2008) and Dal Piva et al. (2010) explored aspects of 500-hPa transient troughs in the SH identified in terms of the “Eulerian Centripetal Acceleration,” a quantity that can be thought of in terms of the flux of curvature vorticity. Recently, Berry et al. (2011), as part of their frontal analysis [undertaken with the TFP applied to the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40)], devoted some attention to fronts in the SH. Two key motivations for our study are the pressing need to develop objective methods for diagnosing frontal behavior in the SH and to determine the climatology of these features.

Another important task we address here is the tracking of fronts. Most of the works on this topic simply identify fronts. However, it is clear that the nature of frontal motion is a key component of their behavior. Another important aspect of this development is associated with the fact that fronts that appear only for a short time may have little influence on the circulation but can distort the counts of these features. Conversely, once a tracking protocol is established, one can determine for how long a front lasts, and hence compile statistics only for fronts that last a given minimum time (e.g., 1 day).

Briefly stated, in this work we develop an objective scheme for identifying, quantifying, and tracking SH extratropical mobile fronts. Key considerations are that the scheme should be conceptually and physically simple, and easily applicable to the modest-resolution global reanalysis products, as well as the outputs of global climate models (where, e.g., predicted changes of frontal structures in the future may be of central interest). Using this scheme, we develop a climatology of mobile fronts over the SH, including frequencies as well as a range of statistics that quantify many aspects of the morphology of these features.

2. Dataset and design of the frontal identification scheme

a. Analysis dataset

In the design of the frontal algorithm and in the assembly of our climatology we use the ECMWF Re-Analysis (ERA)–Interim (Dee and Uppala 2009; Dee et al. 2011). It is one of the best reanalyses produced to date. It was run at higher resolution than the earlier ERA-40 product (T255L60) and included improved model physics, a more sophisticated hydrological cycle (e.g., Betts et al. 2009), and data assimilation based on a 12-hourly four-dimensional variational analysis (4D-Var) that included adaptive estimation of biases in satellite radiance data. One of the concerns with using reanalyses for climate monitoring is that changes in the observing system, combined with the presence of biases in models and observations, can cause shifts and trends in reanalyses that may mask the true climate signal (Screen and Simmonds 2010, 2011). ERA–Interim is the first reanalysis to include an assimilation scheme that adjusts for biases that change in time, for instance due to changes in the observing network or the decay and drift of satellite orbits. This is of particular relevance to analyses in the SH and its paucity of conventional observations. The ERA–Interim data are available every 6 h on a 1.5° latitude–longitude grid, and the set used here covers the period 1 January 1989–28 February 2009.

b. Identification of fronts

As commented above the term front refers to a wide variety of meteorological phenomena. Accordingly, the
specific approach to be taken in identifying fronts should be made bearing in mind what features are to be investigated, and what their spatial scales are. Our interest here is in identifying the mean properties of SH mid-latitude mobile fronts as revealed in long global data series. The only feasible way in which to approach this task is to make use of quality reanalysis products and this, out of necessity, means that we must deal with analyses with resolutions less that those that may be available over limited areas [see also the comments of Naud et al. (2010)].

We tested out many of the objective algorithms referred to above as well as others, and compared their results to those that would have been obtained via conventional synoptic analysis. They all had various strengths and weaknesses. In particular, at high southern latitudes a myriad of small-scale features appeared when some of the algorithms were used, reflecting the complexity of the dynamic and thermal fields over a part of the world where features such as sea ice, steep topography, strong inversions, and local thermal contrasts can give rise to complex “frontal” patterns, which, however, may be of little relevance to large-scale mobile frontal characteristics. While such features can be numerically masked it is a little uncomfortable that this may need to be done in an a posteriori sense, particularly when we wish to design a scheme that is robust and needs no intervention.

In keeping with the desire to identify mobile SH fronts in as straightforward a manner as possible, we have also explored the value of examining the time rates of change of dynamic and thermal variables at grid points. [This Eulerian approach has been adopted in other contexts, e.g., by Fraedrich et al. (1986), Huang and Mills (2006a,b), and Ma et al. (2010).]

For this approach we also undertook a great deal of synoptic evaluation and testing of potential algorithms that could capture frontal structures within the reanalysis products. As an example of some of these investigations we show here the single, arbitrary case of 0000 UTC 21 August 2008 (Fig. 1). The Australasian region IR image (Fig. 1a) and the Australian Bureau of Meteorology manual analysis (Fig. 1b) both indicate the presence of cold fronts. As candidates for frontal identification, we show in Fig. 1c the points in the Australasian region at which the temperature at 2 m decreased by 1°C, by 2°C, and by 3°C between the ERA–Interim analyses at 0000 and 0600 UTC. In a similar fashion, in Fig. 1d we indicate all the points at which both (i) the 10-m winds changed from the northwest quadrant to the southwest quadrant, and (ii) the magnitude of the meridional component of the velocity change exceeded 2, 4, and 6 m s⁻¹. These criteria reflect a vigorous shift in the origin of the air mass to more southerly regions.

In general we found (as typified by the example here) that points identified solely by the temperature change criteria present quite complex patterns. There are points clearly associated with the diurnal cycle over the southern continents (see, e.g., Thomsen et al. 2009) (common but not shown in this winter example) and zonally oriented structures around the Antarctic coast. Even over the open ocean there are features identified by these thermal criteria that would not normally be regarded as midlatitude fronts. By contrast, the reanalysis grid boxes identified when the various criteria on the meridional wind component are applied reveal patterns that have a significantly more identifiable structure and bear similarity with those that would be identified as a front by a synoptician (see Fig. 1b). To be confident that a scheme based on these ideas was robust and reliable we undertook a large number of arbitrarily chosen case studies of the 6-h changes at the surface (10 m) and at 850 hPa (we include this level in our investigation because we are also interested in “deep” fronts). The associated evaluations were performed in both qualitative and quantitative senses. This evaluation made use of manual analyses (with fronts indicated) from the Bureau of Meteorology, the input of synopticians, and the interpretation of satellite cloud images. Quantitative evaluation included compiling statistics from the case studies, including the numbers of fronts, their length, etc., and comparing these statistics with those derived from the manual analyses. In the interest of brevity we do not show the results of the investigations, but they led to a clear overall best choice of parameters in our scheme. The criteria that best identified the frontal region were wind changes from the northwest quadrant to the southwest quadrant, and the change in $v$ to exceed 2 m s⁻¹. We point out that while this model was found to be optimal in an overall sense, it obviously would not be best in all cases. For example, in a few of the case studies a meridional wind change of 6 m s⁻¹ was seen to provide a better frontal representation. However, in most cases this results in an unrealistic fragmentation of a frontal region. For instance, to improve the spatial continuity of the frontal region for the event over southeast Australia (Fig. 1d), a change in $v$ that exceeds 2 m s⁻¹ (boxes marked 1) is preferable to 6 m s⁻¹ (boxes marked 3).

Basing our algorithm on the behavior of the meridional component of the winds is consistent with a number of studies that have shown that $v$, both filtered and unfiltered, essentially contains much dynamic information about synoptic processes. Among them may be mentioned those of Trenberth (1991), Berbery and Vera (1996), Yin and Battisti (2004), Hoskins and Hodges (2005), and Carmo and de Souza (2009).

In this, as in similar works, we face the issue of how we might group or cluster the identified grid boxes into
FIG. 1. (a) Australian region IR image at 0000 UTC 21 Aug 2008 and (b) manual analysis for the same time. The satellite image was originally processed by the Bureau of Meteorology from the Geostationary Multi-Functional Transport Satellite (MTSAT-1R) operated by the Japan Meteorological Agency. (c) Points at which the temperature at 2 m decreased by 1, 2, and 3°C between the ERA–Interim analyses at 0000 and 0600 UTC (with boxes marked 1, 2, and 3, and colored blue, dark green, and light green, respectively). (d) As in (c), but for points at which both 1) the 10-m winds changed from the northwest quadrant to the southwest quadrant, and 2) the magnitude of the meridional wind change exceeded 2, 4, and 6 m s⁻¹.
"frontal objects" within which we seek the fronts themselves. One of the early investigations on this general problem is the classic study of Ward (1963). A broad range of techniques have found applications in a number of areas of weather and climate research, as exemplified by the recent studies of Christiansen (2007), Casola and Wallace (2007), Philipp et al. (2007), Fereday et al. (2008), and Inatsu (2009).

In many of the methods the number of clusters to be identified has to be specified a priori, but the question of how many clusters is clearly nontrivial (Christiansen 2007; Fereday et al. 2008). [A number of approaches to this problem have been suggested (e.g., Tibshirani et al. 2001) but the situation is far from resolved.] In our context it is highly undesirable to specify in advance how many fronts our algorithm should find on a given synoptic map, when obviously the number of fronts varies with circulation type and differs from day to day. It is of considerable interest to diagnose the nature of temporal changes in the number of fronts [similar comments in the application of clustering schemes to examine trends have been made by Philipp et al. (2007)].

In light of the above considerations we employ a simple and robust technique for cluster analysis that does not require an initial specification of the number of such clusters. After the grid points have been flagged with the method discussed above we apply the component (or object) labeling technique (McAndrew 2004). We exploit the image processing concept of connectivity, which defines the relationship between adjacent pixels. This is done by employing a simple eight connectivity, which relates a given flagged pixel to its nearest eight neighbors; any such pixel in this neighborhood is considered to be eight connected to the given pixel. Such an approach is useful for connecting "stringy" objects (like fronts) and has been used to detect contrails in digital satellite images (e.g., Mannstein et al. 1999; Meyer et al. 2007).

For each frontal object so identified we use the eastern edge grid points to determine the location of the front. Applying this approach to all of the eastward edge points results in a set of latitude–longitude points that mark the location of the front (only one front is identified for each frontal object). Single-point fronts are deleted from our consideration. The choice of connectivity and an "edge" means that the latitude values will increase by one grid spacing along the set of points. Hence we effectively have a single series of longitude values that represents the frontal location. By construction, the longitude values for the front at this stage will have a stepwise character since it comprises regular gridpoint values. The longitude values may be treated as a simple series and smoothed in some way. We have opted for a resistant smooth method (Velleman and Hoaglin 1981) that is applicable to data that are (approximately) equispaced. This robust statistical technique comprises a set of short-window running median and running mean filters that are successively applied to the series. We employ the widely used 4253H for our smoother (Velleman and Hoaglin 1981, p. 171). This particular smoother starts with a running median filter of length 4, followed by a median filter of length 2 to recenter the data. We then resmooth by median filters of 5, then 3. Now that outliers have been removed, a Hanning filter, which in this case is a three-point running average based on the weights (0.25, 0.5, 0.25), is applied to give a first pass. This series is then polished by taking the residuals (original minus first pass) and subjecting them to the same procedure. This second pass is added to the first pass to give the final smoothed series, "4253H, twice." [As described, it can be seen that the number of data points needs to be at least seven. The method allows for the absence of data at the ends of the series by a linear extension based on the second and third smoothed values from the ends.] After smoothing we have a new set of longitude values at the original latitudes. We show in Fig. 2a the hemispheric fronts (and their component smoothed points) over the hemisphere derived from this procedure for the same date used above. We had mentioned above that we also have interest in frontal structures in the free atmosphere, particularly at 850 hPa. Figure 2b shows the fronts identified at this level by the same technique. It is a testament to our choice of algorithm that these placements are very similar to those that would be done by a synoptician. To allow a readily seen qualitative grasp of the hemispheric distribution of frontal structures and orientations, Fig. 2c displays every second (to avoid clutter) 10-m front identified in the period 18–24 August 2008. It should be noted that the scheme provides a very powerful method for the realistic placement and orientation of the identified features.

c. Definition and calculation of key frontal characteristics

For a number of years the meteorological community has appreciated the value of considering the characteristics of cyclones not in terms of a single number (e.g., number of cyclones per year), but rather with respect to a wide range of characteristics, such as depth, intensity, radius, etc. (e.g., Simmonds and Keay 2000; Paciorek et al. 2002; Raible et al. 2008; Simmonds et al. 2008; Ulbrich et al. 2009).

For similar reasons a comprehensive analysis of frontal structures must include information related to the morphology of these features; for example, while the number of fronts in a region may be informative, important physical processes (such as precipitation, meridional transports, etc.) are intimately associated with
location, meridional tilt, intensity, etc. We show in Fig. 3 a representation of a front comprising \( N \) points identified and smoothed with the processes described above. The front can be thought of as a series of \( N - 1 \) segments of lengths \( l_i, i = 1, N - 1 \). For each segment our algorithm calculates the angle, \( \alpha_i \), which that segment makes with the local meridian (measured positive in the clockwise direction). A number of other configuration statistics, as indicated in the figure, are calculated from the smoothed frontal points, including their center of gravity (CG). The latitude and longitude of the CG of the smoothed frontal points are given by, respectively,

\[
\theta_{CG} = \frac{1}{N} \sum_{i=1}^{N} \theta_i \quad \text{and} \quad \lambda_{CG} = \frac{\sum_{i=1}^{N} \lambda_i \cos \theta_i}{\sum_{i=1}^{N} \cos \theta_i},
\]

where \( \theta_i \) and \( \lambda_i \) are the latitudes and longitudes of the smoothed frontal points. Other derived measures include the length of the front,

\[
L = \sum_{i=1}^{N-1} l_i,
\]

and \( I \), a metric for the net frontal intensity, defined as

\[
I = \frac{\Delta \theta \times 111}{1000} \sum_{i=1}^{N} \frac{\sum_{j=1}^{6} [v_j(t + \Delta t) - v_j(t)]}{\Delta t},
\]

where the summation index ranges over the easternmost grid points of the frontal object. The normalization term makes an allowance for analyses of different (meridional)

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**Fig. 2.** (a) The 10-m hemispheric fronts at 0000 UTC 21 Aug 2008. The MSLP field (not used in the detection process) is shown to validate the performance of the frontal detection. (b) As in (a), but for 850 hPa and with geopotential height as a background field. (c) Every second 10-m front identified in the period 18–24 Aug 2008.
spatial and temporal resolutions (\(\Delta \theta\) and \(\Delta t\), respectively, these being 1.5\(^\circ\) and 6 h in our case). The number 111 in the numerator pertains to the number of kilometers covered by 1\(^\circ\) of latitude. The numerical value of the units of \(I\) is m s\(^{-2}\) (1000 km).

d. Tracking of fronts

Most frontal identification algorithms do not attempt the challenging task of tracking these features. The tracking of cyclones is a rather difficult task and can be subject to a range of ambiguities (Lim and Simmonds 2007). Following the evolution of fronts can be seen as many times more complex, as we are now tracking a line, rather than a point. However, tracking mobile fronts is important in obtaining a comprehensive picture of the SH mid-latitudes. It allows one to diagnose, for example, where fronts on average first appear and where they cease to exist, and provides an estimate of the lifetime of a given front. In addition, tracking allows one to identify ephemeral systems that last only a short time; such systems are probably not associated with the broadscale flow and would probably have little influence.

Rather than attempt to track each point on a front, we have taken the novel approach here of tracking the CG of the front. Seen in this way, the tracking problem is reduced to joining up points in a manner very similar to the tracking of cyclone centers. In fact our technique is borrowed from the approach of tracking cyclones (e.g., Simmonds et al. 2008) with appropriate changes. For input to the tracking stage we retain fronts that have at least two frontal points. Our experiments revealed that the shorter fronts have a role to play in improving the temporal continuity of the tracking process.

First, the tracking algorithm makes an estimate of the new position of each CG (system) at the next analysis time, and this predicted position is based on a weighted combination of a “steering velocity” and the velocity of the previous 6-h movement. In the cyclone-tracking case, we compute steering velocities from the MSLP or geopotential height field (Simmonds et al. 1999). For the fronts we found that a robust choice for the steering velocity was to use the local 500-hPa climatological mean monthly winds. For the analyses conducted here the steering velocity is used only to predict the position of a front 6 h after its initial identification (when no previous motion is available): for subsequent time steps the predicted position is based solely on the previous observed movement.

For the second part of the process, we calculate the probability of association (evolution) between all fronts at the current time \(t_c\) and their potential matches at the next analysis time, \(t_n\). To achieve this, we calculate the distances \(r\) between the predicted position (at \(t_n\)) of the CGs of the fronts and those of the candidate matches. The probability function is of a decaying exponential form involving \(r^2\) as described in Murray and Simmonds (1991) and later refined by Simmonds et al. (1999). The probability is set to zero if a candidate front at time \(t_n\) falls outside a “pass radius” of \(R_c\) (a distance expressed in terms of degrees of latitude) centered on the predicted position of the front. A value of \(R_c = 8.0\) was found to be optimum. In addition to the mandatory condition \(r\), we also require that \(|L-L_p| < 1500\) km where \(L_p\) is the “predicted” length of the front and \(L\) is the length of the candidate front. The value of \(L_p\) is based on a weighted combination of persistence and its previous tendency according to

\[
L_p = L(t_c) + w_p[L(t_c) - L(t_c - \Delta t)]
\]

[analogous to the predicted central pressure in the cyclone case (see Murray and Simmonds 1991, their Eq. (11))] and we use a weighting factor \(w_p = 0.2\).
Finally, among all the fronts at $t_c$ and at $t_n$ we find the highest probability of association. Any one front shall occur in association with at most one front at the subsequent time. These fronts are then removed from consideration and the next highest probability cases are examined in a similar manner, and so on. Fronts that are unmatched at the end of this process are deemed to have been born or decayed.

With these modifications the frontal tracking scheme worked well. All the subsequent analyses presented here are for fronts that lasted at least 1 day.

3. Climatological characteristics of fronts

First, we display the frequency distribution of all frontal points. The geographical structure of such points for fronts at 10 m in the summer [December–February (DJF)] is shown in Fig. 4a. The highest frequencies are seen in a belt between 40° and 60°S. Within this belt there are regional oceanic maxima east of Patagonia, southeast of southern Africa, and southwest of Australia. In winter [June–August (JJA)] (Fig. 4b) the belt of maxima exhibits subtle meridional shifts and tends to assume more modest values (although the frontal influence can be seen to be stronger in the lower latitudes). Farther to the north the effect of the winter SH split jet across the Pacific east of Australia (see, e.g., Bals-Elsholz et al. 2001) is particularly evident, with low values of frequency diagnosed across the western Pacific at about 45°S. The summer fronts diagnosed at the 850-hPa level (Fig. 4c) are somewhat less numerous than at 10 m, with the main features of note lying to the east of Patagonia and to the west of Tierra del Fuego, and in the eastern Indian Ocean. In contrast to the situation at the surface, there is a local minimum of frontal points to the southeast of southern Africa. The location of the regions of 850-hPa maxima...
changes considerably in winter, with the dynamic consequences of the split jet being apparent and high density now found at about 60°S to the south of New Zealand, and the high frequency of points to the west and east of the southern tip of South America no longer apparent (Fig. 4d).

As indicated above, information about the frequency of fronts and frontal points is valuable, but additional statistics are required to provide a comprehensive characterization of these synoptic features. One of these is the domain over which the frontal influence is felt, defined earlier as the length. To plot the mean distribution of this variable, the length of each front is ascribed to the geographical point of its CG. The resulting geographical scatter of values is then contoured, and the plots are presented in Fig. 5 (other frontal variables presented below are plotted with a similar procedure). As distinct from the frequency distribution of the frontal points, we note that at both levels and for both seasons the fronts with the greatest extent are found in the Indian Ocean (with the mean winter frontal length exceeding 2000 km in the central part of the basin). The fronts in summer (Figs. 5a,c) tend to be shorter than their winter counterparts (Figs. 5b,d), except perhaps across the Pacific. The structure of the mean frontal length at 10 m is similar to that at 850 hPa, but there are some interesting differences. For example, 850-hPa fronts whose center of gravity lies near the Great Australian Bight and the Tasman Sea tend to be longer than those at 10 m.

The frontal intensity was designed to capture a range of characteristics that present an indication of the "integrated" effect of a front. In a similar format to before, the distribution of $I$ is shown in Fig. 6. The structure of Figs. 6a–d shows a degree of similarity, but the magnitudes

![Fig. 5. As in Fig. 4, but for the distribution of mean frontal length $L$ [with the length of each front plotted at its CG (see text)]. The units are km.](image)
differ. All show their maximum in the west Indian Ocean, and display weaker maxima in the Atlantic and western Pacific. The mean frontal intensity tends to be greater at 850 hPa than at 10 m (Figs. 6c,d versus Figs. 6a,b), and in winter than in summer. In the southern Australian context, frontal systems are a key source of winter precipitation (e.g., Pook et al. 2006; Hope et al. 2006; Landvogt et al. 2008; Risbey et al. 2009). The winter plots (Figs. 6b,d) show strong mean frontal intensity to the southwest and south of Australia, particularly at 850 hPa.

The metric $\alpha$ provides valuable information with regard to the orientation of a front. All these values and their locations for a given period are determined, and the resulting mean of these values is plotted (note there is no necessity to relate this variable back to the location of the CG for each front). The resulting 10-m plot for summer is exhibited in Fig. 7a. The tilt angles are overwhelmingly negative (i.e., tilt toward to the west with decreasing latitude) north of the subantarctic. The magnitude of the tilt increases to the north (consistent with the eddy convergence of atmospheric angular momentum and the need to maintain the westerlies against surface frictional dissipation); this increase with decreasing latitude is most clear over the ocean basins as would be expected. In the subantarctic, the mean meridional tilt changes sign, and assumes large positive values in the coastal regions of the east Antarctic sector. The mean structure of the meridional tilts is rather similar in winter (Fig. 7b), although in that season the fronts can be seen to be much more meridionally aligned over and to the north of the Tasman Sea and, to a lesser extent, over much of the Pacific midlatitudes. The analogous plots at the 850-hPa level (Figs. 7c,d) show similar structures. However, it will be noticed that the northwestward tilts in the mid- and lower latitudes are somewhat more modest than those diagnosed at 10 m. On the other hand, the mean magnitude of the tilts on the

![Fig. 6. As in Fig. 5, but for frontal intensity $I$. The units are m s$^{-1}$ (1000 km).](image_url)
southern parts of fronts is greater and more spatially organized than we observed at the lower level.

We complement the above presentation with histograms showing the probability distribution function (PDF) for two key variables in two midlatitude belts of the SH. Figure 8a shows the frequency distribution of 10-m summer frontal lengths for Indian Ocean fronts that, at the midpoint of their life, have their CG in the 30°–50°S and in the 50°–70°S latitude bands. The distribution in the former (with bin widths of 250 km) has its maximum in the 1000–1250-km bin, and drops away fairly slowly (with a sizable number of fronts exceeding lengths of 3000 km). The distribution in the 50°–70°S band is dominated by shorter fronts. [Similar distributions are found in the Atlantic (not shown).] By contrast, the 30°–50°S distributions in the Pacific (Fig. 8b) are much more positively skewed (consistent with shorter mean frontal length in that basin), and are similar in the two latitude bands. About 40% of the Pacific fronts are shorter than 750 km. Similar displays for 10-m summer frontal intensity are presented in Figs. 8c,d. The remarks made above also broadly apply to this parameter, in that from 30° to 50°S the percentage of Indian Ocean fronts that are weak [say, \( I < 10 \text{ m s}^{-1} \) (1000 km)] is not as great as that in the Pacific. The PDFs of intensity in the 50°–70°S belt are rather similar in the two basins.

Figure 9 displays similar statistics for the winter season. The structure of the histograms is rather similar to that in summer, except that there is a noticeable trend for there to be less positive skew in winter.

4. Discussion

Our work has shown the characteristics of the Eulerian change in the meridional wind to be extremely helpful in
identifying mobile SH fronts. This wind component has been shown to be intimately associated with the key atmospheric dynamics (as mentioned earlier), and there are numerous investigations that have shown this parameter to be particularly valuable in diagnosing various aspects of cyclonic and frontal behavior (e.g., Inatsu 2009; Dal Piva et al. 2010). Air arriving from a different quadrant and the change in $v$ exceeding a certain magnitude can be seen in terms of a proxy for temperature and a different origin of the new air mass.

The technique developed here has identified a number of features of frontal behavior over the SH. One feature to be highlighted has been the seasonality of frontal systems, and how they have shown some interesting regional

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**Fig. 8.** (a) The PDF of 10-m summer frontal lengths for Indian Ocean fronts that, at the midpoint of their lives, have their CG in the (top) 30°–50° and (bottom) the 50°–70°S latitude bands. The units are km. (b) As in (a), but for the Pacific Ocean. (c),(d) As in (a),(b), but for 10-m summer frontal intensities. The units are m s$^{-1}$ (1000 km).

**Fig. 9.** As in Fig. 8, but for winter.
differences. Our analysis of the seasonality has been, out of necessity, brief and just confined to the summer and winter differences. The SH is known to exhibit a myriad of modes of variability (Simmonds 2003), one of which is the semiannual oscillation (SAO) (Simmonds and Jones 1998). It is associated with the differing thermal inertia of the Antarctic continent and the Southern Ocean, which in toto result in a SAO in meridional temperature gradients and vertical static stability (and hence baroclinicity) (Walland and Simmonds 1999). The SAO has its peaks in fall and spring, and dynamic considerations suggest that frontal behavior should be influenced by the SAO.

To display a summary of the seasonality of the identified 10-m mobile fronts (and possible SAO signatures), Fig. 10a presents a histogram of monthly means of the number of fronts per analysis (NFA) (red) and the length (green) and intensity (blue) of SH fronts whose CG halfway through their life lies in 30°–50°S, which for ease of comparison have been scaled by 1, 0.005, and 0.5, respectively. The seasonality in NFA exhibits maxima (in excess of seven fronts) in early winter and early summer. Both L and I exhibit sole maxima in winter. Figure 10b shows an analogous plot for the 50°–70°S latitude belt, and the character of the seasonality is rather different. All three parameters exhibit an SAO structure, with peaks in fall and spring.

Figures 10a,b indicate that, on average, about 12 fronts are identified over the SH between 30° and 70°S. Figures 10c,d show similar displays to those above, but the counts are only conducted over the Indian Ocean. It will be seen that an average of three fronts is identified in this domain. The Indian Ocean seasonality in the 30°–50°S belt is rather similar to that exhibited over the entire hemisphere; a similar comment may be made for the southern belt (Fig. 10d), and again the SAO is particularly evident in all frontal indices. The Atlantic and Pacific sectors (Figs. 10e–h) exhibit mean seasonal behavior broadly consistent with that documented in the Indian Ocean (with, in particular, the SAO appearing in many of the histograms). However, there are some notable differences, such as the absence of strong winter peaks in L and I in the Pacific between 30° and 50°S. Almost half (about five) of the fronts are found over the Pacific sector but, of course, this is the largest of the subdomains considered here.

5. Concluding remarks

Atmospheric fronts play a central role in the weather and climate systems over the Southern Hemisphere. Hence it is important that the frequency and character of these features be documented. We here present an algorithm designed to identify, characterize, and track mobile fronts. Our criteria in constructing the algorithm were that it be physically based while being as simple and easily understood as possible. Also required is that it should be able to faithfully identify fronts in long hemispheric analyses of modest resolution (e.g., reanalyses) covering an extended period. We have conducted exhaustive tests on a variety of schemes. The one we have chosen [an Eulerian scheme that requires that between sequential 6-hourly analyses, the wind shifts from the northwest quadrant to the southwest quadrant, and that the change in the (signed) meridional wind component exceed 2 m s⁻¹] allows us to identify fronts in the vicinity with considerable veracity.

The frontal and tracking algorithm has been applied at the 10-m and 850-hPa levels in the ERA–Interim reanalysis, covering the 21-yr period of 1 January 1989–28 February 2009. The resulting climatology has revealed that the highest frequency of frontal points is found in the 40°–60°S latitude belt in both summer and winter, although there are a number of zonal asymmetries in oceanic regions in the vicinity of Patagonia, southern Africa, and southwest of Australia. The influence of the winter SH split jet across the Pacific east of Australia is apparent in our results. Our scheme also determines the length, intensity, and meridional slope of each front. The longest fronts are found, in the mean, in the Indian Ocean (mean lengths exceeding 2000 km). The climatological frontal intensity also shows its maximum in the (west) Indian Ocean. Mean intensity tends to be greater at 850 hPa than at 10 m, and greater in winter than in summer. The mean meridional tilt of the mobile fronts is northwest–southeast over much of the midlatitudes and subtropics, and increases with latitude toward the equator. (This latter feature emphasizes the important role that mobile fronts play in the angular momentum budget of the SH, in providing atmospheric momentum convergence to offset the effect of surface friction in the westerlies.) In the coastal Antarctic and subantarctic, the meridional slopes assume the opposite orientation, reflecting the atmospheric export of momentum from their high-latitude (surface easterly) source region.

We have explored the mean seasonality (month to month) of 10-m frontal behavior averaged over two latitude belts, namely 30°–50°S and 50°–70°S. The nature of the seasonality of frontal numbers, mean length, and mean intensity differs between these two belts. Broadly speaking, the former belt tends to show maxima in winter, whereas there is a strong SAO (maxima in fall and spring) aspect to these diagnostics in the 50°–70°S band. The SAO is a very characteristic feature of seasonal variability in the high southern latitudes.

The scheme described here was originally developed for a comprehensive climatological investigation of fronts in analyses of resolution on the order of 100 km. However,
FIG. 10. (a) Histogram of monthly means of the number of 10-m fronts per analysis (NFA), and the length and intensity of SH fronts whose CG halfway through their lives lies in the 30°–50°S band. (These parameters have different dimensions and typical values; for ease of representation we have scaled them by 1, 0.005, and 0.5, respectively.) (b) As in (a), but for 50°–70°S. (c),(d) As in (a),(b), but for the Indian Ocean. (e),(f) As in (a),(b), but for the Atlantic Ocean. (g),(h) As in (a),(b), but for the Pacific Ocean.

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considerable interest centers on the performance of the scheme when applied to high-resolution SH analyses, such as those used by, for example, Irving et al. (2010) and Uotila et al. (2011). Some limited testing has revealed that the scheme performs well at higher resolution, but care must be taken with the choice of criteria and thresholds. We are at present developing simple rules that will develop the appropriate criteria depending on the temporal frequency of the analyses used, and on both the resolution at which the model was run and at which the data are presented. [On this latter point we are guided by the results of Jung et al. (2006), who find, in the case of cyclones, that both aspects of spatial resolution are important in determining the number of synoptic systems that are found.] Our expectation is that, in a climatological sense, more fronts will be found in higher-resolution analyses but many of these extra systems will tend to be of smaller scale.

Of relevance to this issue is the extent to which the present scheme could be applied in an operational environment. We have stressed that an important element of the algorithm is that it is conceptually simple and appealing, and also easy to apply. Discussions have taken place with synopticians at the Australian Bureau of Meteorology in this connection, and such schemes seem to have great potential for forecast guidance.

We commented earlier that fronts are frequently associated with cyclonic systems to the south, while others are related to troughs. Future work with our innovative frontal scheme will be directed at quantifying the proportion of fronts that fall into the first category (and exploring the complex front–cyclone links in general). For that group we will explore the relationships between a range of properties of the cyclone and the front, and particularly the length scales of the two. While these two scales are distinct, one expects some dynamic association between them. The asymmetry of extratropical cyclones is a characteristic of baroclinic systems (Hart 2003; Rudeva and Gulev 2011), and is intimately tied to the presence of a front. Part of our future work will focus on exploring the dynamic links between the scales of cyclones [as determined with the algorithms of Simmonds (2000) and Rudeva and Gulev (2007)] and the frontal lengths determined with the present approach.

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