Modeling Coastally Trapped Wind Surges over Southeastern Australia. Part I: Timing and Speed of Propagation

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ABSTRACT

During the spring and summer months, the southeast coast of Australia often experiences abrupt southerly wind changes, the leading edge being known locally as a ''southerly buster.'' The main characteristic of this phenomenon is the sudden shift in wind direction, usually from north or northwesterly to southerly. Associated with this wind surge is a significant temperature drop and sea level pressure rise. A severe southerly buster has wind speeds exceeding gale force (17 m s^{-1}) and poses a threat to human safety.

Southerly busters have been the subject of a number of studies over several decades. These have focused on the development and propagation of the wind surge. The aims of this study are quite different, namely, to assess the ability of a real-time, high-resolution, numerical weather prediction (NWP) model to simulate some of the key features of the southerly buster, notably the time of passage and strength at various locations along the southeast coast and at two inland stations.

A large number (20) of case studies of southerly wind changes along the east coast of New South Wales has been selected to verify 40 simulations from the numerical model. The focus of the case studies was on quantifying the skill of the model in simulating the timing and speed of propagation of the southerly buster. The measure of skill adopted here was one based on a direct comparison of model predictions with observations. It was found that the performance of the model was good overall but was highly case dependent, particularly according to season and time of day, with some poor and some excellent simulations. This ability of the NWP model to provide predictions within an acceptable error has positive implications as a useful tool in real-time forecasting.

1. Introduction

A southerly buster is a sudden, squally, southerly wind surge that affects the southeastern coast of Australia. These surges occur predominantly during the spring and summer months of the year and form ahead of a cold front interacting with the Great Dividing Range (see location map, Fig. 1). In section 2, a more detailed description of the nature of the southerly buster is presented. This phenomenon is similar to those elsewhere in the world that arise from air masses interacting with orography. Blocking effects of mountains on cold fronts leading to orographic jets, cold-air damming providing a mechanism for a surge, and anticyclonic deformation of fronts near mountains are among the triggers for cold air surges around the globe (Egger and Hoinka 1992).

Southerly busters are generally considered to be orographic jets, as are the more extreme southerly changes for New Zealand, several southerly flows on the west coast of North America, a flow to the east on the northern side of the European Alps, and also some easterly flows on the northern flank of Pyrenees. The cold air surge of the Tibetan Plateau is similar to an orographic jet but is on a much larger horizontal scale. This kind of surge is also known to occur on the eastern side of the Rockies and the eastern side of the Andes. The eastern slopes of the Appalachians experience a northerly surge that has developed from cold air damming in the winter. This is different from cold front deformation, which leads to an orographic jet, as it generates its own quasi-stationary front. The summer months also experience ''backdoor'' cold fronts (Egger and Hoinka 1992) that propagate southward along the Appalachians in a manner reminiscent of an orographic jet.

Anticyclonic deformation occurs in the European Alps, Australia, and New Zealand. A possible compounding effect of these surges is the prefrontal conditions, often with a föhn effect. This is known to happen with the chinook regime in the Rockies; the pampero sucio of the Andes; prefrontal föhn flow down the Appalachians; and föhn flows occurring at the eastern slopes of the Australian Alps are terminated by the southerly buster (Egger and Hoinka 1992). South Africa experiences a coastal disturbance. The surges mentioned above are all characterized by a sudden shift in wind direction with a squally onset, a significant drop in temperature, and a rise in sea level pressure (SLP) (Gill 1977).

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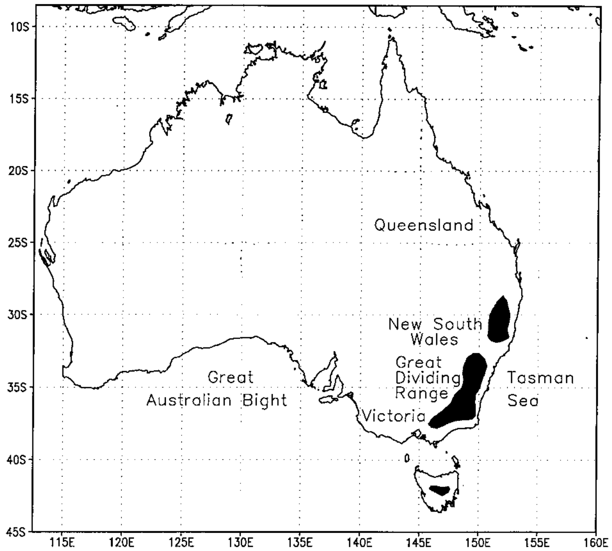


FIG. 1. Map of Great Dividing Range in southeast Australia, showing the location mentioned in the text. The area indicated is above 600 m.

In recent years numerical models have been applied to the simulation of southerly busters (see, e.g., Holland and Leslie 1986; Howells and Kuo 1988; McInnes and McBride 1993). A very high resolution NWP model (known as HIRES), developed at the School of Mathematics, University of New South Wales, is employed here to carry out case studies of southerly busters. HIRES allows a more accurate simulation of weather systems, so that the southerly buster can be studied in greater detail than previously possible. Section 3 provides an overview of the details of the model.

As already mentioned, the main aim of this paper is to assess the ability of the high-resolution numerical model, outlined in section 3, to simulate significant aspects of southerly busters. Section 4 introduces the 20 case studies, 5 of which have their results presented in more detail. These cases were selected with a view to checking the arrival times of the southerly buster at various locations. A comparison of the model against observations will be presented in section 5. Discussion of these results, in section 6, summarizes the findings in this study and suggests directions for further studies of the nature of southerly busters.

2. Southerly busters

a. Definition of southerly busters

Southerly busters have been observed for many decades and descriptions of this phenomenon have been recorded. From these observations comes the defining characteristic of the southerly buster, a sudden squally wind surge up the east Australian coast bringing a southerly wind change to replace the continental northwesterly winds. These southerly winds must reach 15 m s^{-1} or greater (see the anemograph, Fig. 2a) to be classified as a southerly buster and have been known to gust up to 35 m s^{-1} (Colquhoun et al. 1985). The postfrontal flow remains as a strong southerly. The arrival of the gust front is occasionally accompanied by a spectacular roll cloud but usually does not produce precipitation, apart from light drizzle or an occasional thunderstorm. The synoptic pattern is also to be without a major Tasman Sea low.

Preceding the buster the winds are generally northwesterly, ranging from warm to hot and are very dry as the flow is offshore and continental. As a result of the southerly buster passage, and the associated postfrontal cold air, a significant fall in temperature is experienced (thermograph, Fig. 2b), usually by 10°–15°C within minutes (Howells and Kuo 1988; Mass and Albright 1987). A rise in SLP (barograph, Fig. 2c) also occurs with the passage of the southerly buster, as the pressure ridge moves northward along the coast. The depth of the surge is generally less than 1 km and therefore is below the average height of the Great Dividing Range.

The generally accepted explanation is that a southerly buster is generated when a cold front is blocked and also experiences anticyclonic deformation near the Great Dividing Range, propagating northward as a coastally trapped orographic jet. The surge of air travels up the east coast of Australia, the duration of the southerly buster usually being less than 24 h, from the time the cold front reaches the Great Dividing Range to its dissipation on the north coast of New South Wales (NSW), or southern coast of Queensland. Section 4d presents NWP model output of a simulation of a ‘‘classic’’ southerly buster.

b. Development of the surge

There are many forcings that could have a role in the development of a southerly buster. However, the role that each plays is still not known fully. The general synoptic situation is believed to affect the development of the southerly buster, but the extent of this influence is unclear. A general rule for a southerly buster to occur is that a cold front approaching the southeast of Australia should lie between two high pressure systems, one in the Tasman Sea and the other in the Great Australian Bight.

Australia is unique in possessing a midlatitude (about 35°S) coastline, running almost due west–east for 3000 km. It plays an important role in the dynamics of a cold front moving across the southern coastline of Australia. It is possible that the consistent land–sea thermal contrast has a significant effect on the evolution of a cold front and in the formative stages of a southerly buster. Colquhoun (1981) has identified four different types of southerly busters, the study of which would require simulations at higher resolution.

When considering the possibility of a cold front being

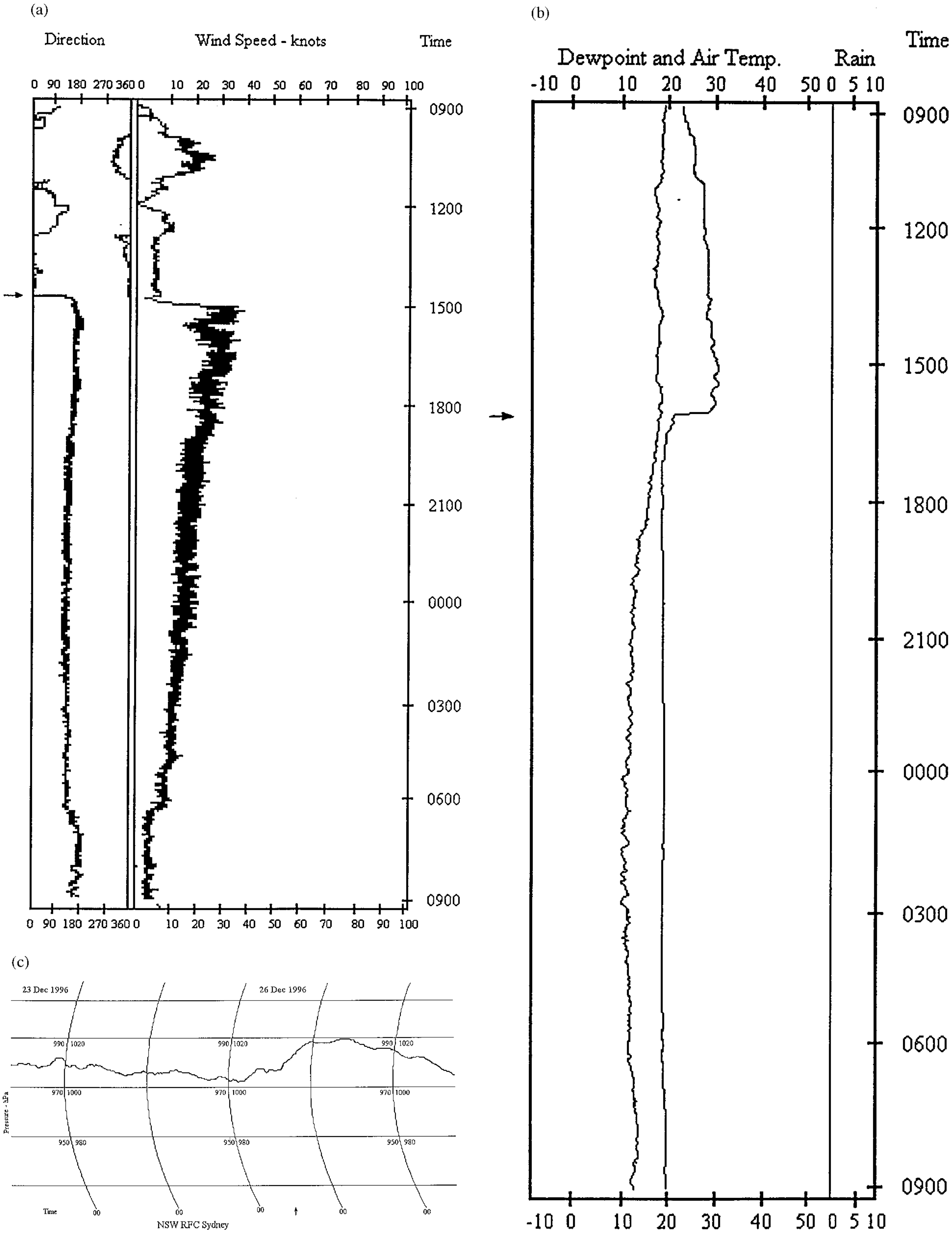


FIG. 2. Typical/representative features of a southerly buster: (a) an anemograph showing a sudden change in wind direction and strength, (b) a thermograph that indicates a sudden drop in temperature (and some precipitation), and (c) a barograph with a steady rise of SLP associated with the passage of a southerly buster. The arrows indicate the time of passage of the southerly buster.

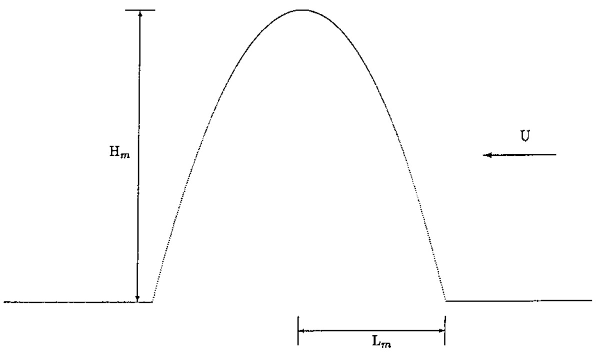


FIG. 3. Diagram illustrating U, L_m, and H_m used in calculating the Rossby and Froude numbers, Ro and Fr, respectively, where U is the upstream velocity scale, L_m is the mountain half-width, and H_m is the mountain height.

blocked by the Great Dividing Range, Reason (1994) cites the Rossby $\mathrm{Ro} = U/fL_m$, and the Froude number, $\mathrm{Fr} = U/NH_m$, and their ratio as essential indicators. Here, U is the upstream velocity scale, f is the Coriolis, L_m is the mountain half-width, N is the Brunt–Väisälä frequency, and H_m is the mountain height (Fig. 3). For the mountain barriers considered in Reason (1994), the initial adjustment will be similar to the nonrotating case with strong blocking if $\mathrm{Fr} \leq 1$. This blocking may persist beyond a dimensional time of $1/f$ in the case of small Ro if $\mathrm{Ro/Fr} \geq O(1)$ and, for the large Ro case, if $\mathrm{Fr} \leq 1$. For $\mathrm{Ro} = O(1)$, there is a transition between these regimes.

For southeast Australia, these values are as follows: L_m (km) = 75, H_m (m) = 600, N (s^{-1}) = 0.027, lat = 37°S, Ro = 0.8, Fr = 0.3, and Ro/Fr = 2.7. Since both $\mathrm{Fr} \ll 1$ and $\mathrm{Ro/Fr} > O(1)$, the initial blocking for these $\mathrm{Ro} = O(1)$ mountains will be maintained on a timescale of $1/f$. These dimensionless ratios clearly indicate that blocking of a shallow cold front would be expected by the Great Dividing Range. Various models that have been applied to simulate southerly buster–type phenomena in the southeast of Australia indicate that the topographic barrier provided in the form of the Great Dividing Range is necessary to the development of the surge. ‘‘Both analytical (Baines 1980) and numerical (Gauntlett et al. 1984) models indicate that the buster depends on the topographic barrier of southeast Australia’’ (Mass and Albright 1987).

Baines constructed his model so that the front is perpendicular to the mountain and hence blocked. However, this blocking is not total as there are gaps in the Great Dividing Range, so the equations of motion were linearized to obtain an analytic solution. As a result of this modification, there is a uniform speed along the front, together with a bulge in the mass field along the mountain, which characteristically has a width of a Rossby radius (Egger and Hoinka 1992). Baines (1980) regarded this flow as an orographic jet and states that, ‘‘it is apparent that the coastally trapped current will have the character of a gravity current’’ (Baines 1980). Mass and Albright (1987) mention the clarification ‘‘Baines suggested that this phenomenon is a topographically trapped gravity current initiated by synoptic scale disturbances.’’ McInnes (1993) concludes that the cold air that is blocked by the Great Dividing Range results in a breakdown of geostrophy and the dominance of the across-front pressure gradient forces reorienting the flow to a southerly surge with characteristics of a gravity current. The motion of this flow is controlled by the cold-air depth and the difference in temperature between the warmer and colder air. In summary, it is now generally accepted that a southerly buster is the result of a cold front being blocked by the Great Dividing Range, forming a surge of cold air that propagates northward along the coast of NSW as a density current.

3. High-resolution numerical model

This section provides a brief overview of the numerical weather prediction model that has been used in this study. This model has been widely employed in other case studies (see, e.g., Leslie and Skinner 1994) so only an outline is required here.

a. Model overview

Previous documentation (Leslie et al. 1985) provides most of the details of the model *numerics*, some of which is included here to give an overview and also mentioned are the modifications that have been implemented in the model to improve its simulation of the atmosphere. The model is formulated in terms of the primitive equations for the momentum, mass, moisture, and thermal energy. These equations are written in advective form. The integrations are carried out on the staggered Arakawa C grid using a split semi-implicit time-differencing scheme. Sigma coordinates are used in the vertical because of the need in this study for terrain-following coordinates. The model *physics* has been upgraded significantly, especially the representation of the surface and planetary boundary layer formulations. The main model features are listed in Table 1.

b. Computational information

Computational stability is achieved by using semi-implicit time integration and energy-conserving spatial differencing on advective terms. Gravity wave terms therefore are treated implicitly and advective terms explicitly. The time step is chosen so that it is always no higher than 80% of the Courant–Friedrichs–Lewy computation stability criterion. A grid with 78×51 grid points in the horizontal and 16 levels in the vertical requires approximately 20 min for a 24-h prediction, on a Silicon Graphics Inc. Indigo 2 workstation.

TABLE 1. Summary of features of the NWP model used in the present study.

Model feature	Description
Horizontal resolution	20 km
Vertical resolution	Sigma coordinate, 16 levels
Temporal differencing	Split semi-implicit
Spatial differencing	Arakawa C grid
	Advective form of momentum equations with third-order differencing on advective terms, fourth order on pressure gradient
Initialization	Vertical mode initialization
Parameterization of physical processes	1) Mellor–Yamada level-2.25 surface scheme for surface layer;
	2) stability-dependent boundary layer, with eddy diffusivities functions of bulk Richardson number;
	3) surface heat budget with prognostic equation for surface temperature;
	4) large-scale precipitation;
	5) modified Kuo convection;
	6) weekly average sea surface temperature

c. Data and analysis

The data and corresponding initial analysis and boundary conditions were obtained from the Bureau of Meteorology archives of the 75-km horizontal resolution Regional Assimilation and Prognosis (RASP) or the Limited Area Prediction System (LAPS) model (Leslie et al. 1985; Puri et al. 1992). The fields are interpolated to the 20-km grid used in this study, simply by using biquadratic interpolation. The predictions are genuine ‘‘forecasts’’ in that they employ the operational initial data available at the time and the boundary conditions from the operational RASP or LAPS model.

4. Southerly buster events

The case studies presented here were chosen by using synoptic charts to identify a deformed cold front on the east coast of Australia in the spring and summer months. Model simulations were run to confirm which of those selected actually developed the coastal surge typical of a southerly buster. In fact, each of the cases tested in this paper produced a southerly coastal surge. For each of the 20 case studies selected, two simulations, initialized 12 h apart, were carried out providing a total of 40 simulations to be presented in this study. As a means of confirming the simulations, anemographs were obtained from the Bureau of Meteorology for various coastal locations. This is the most stringent test one can apply in that it is a direct comparison of model output with accurate local observations. Comparison of the observations with the model output will be addressed in subsequent sections of this paper. While having the defining feature of the southerly surge in common, each case is different from any other and gives rise to the thoughts of different classes of southerly busters, as mentioned earlier. Section 5 will discuss the nature of the case studies.

a. Overview of case studies

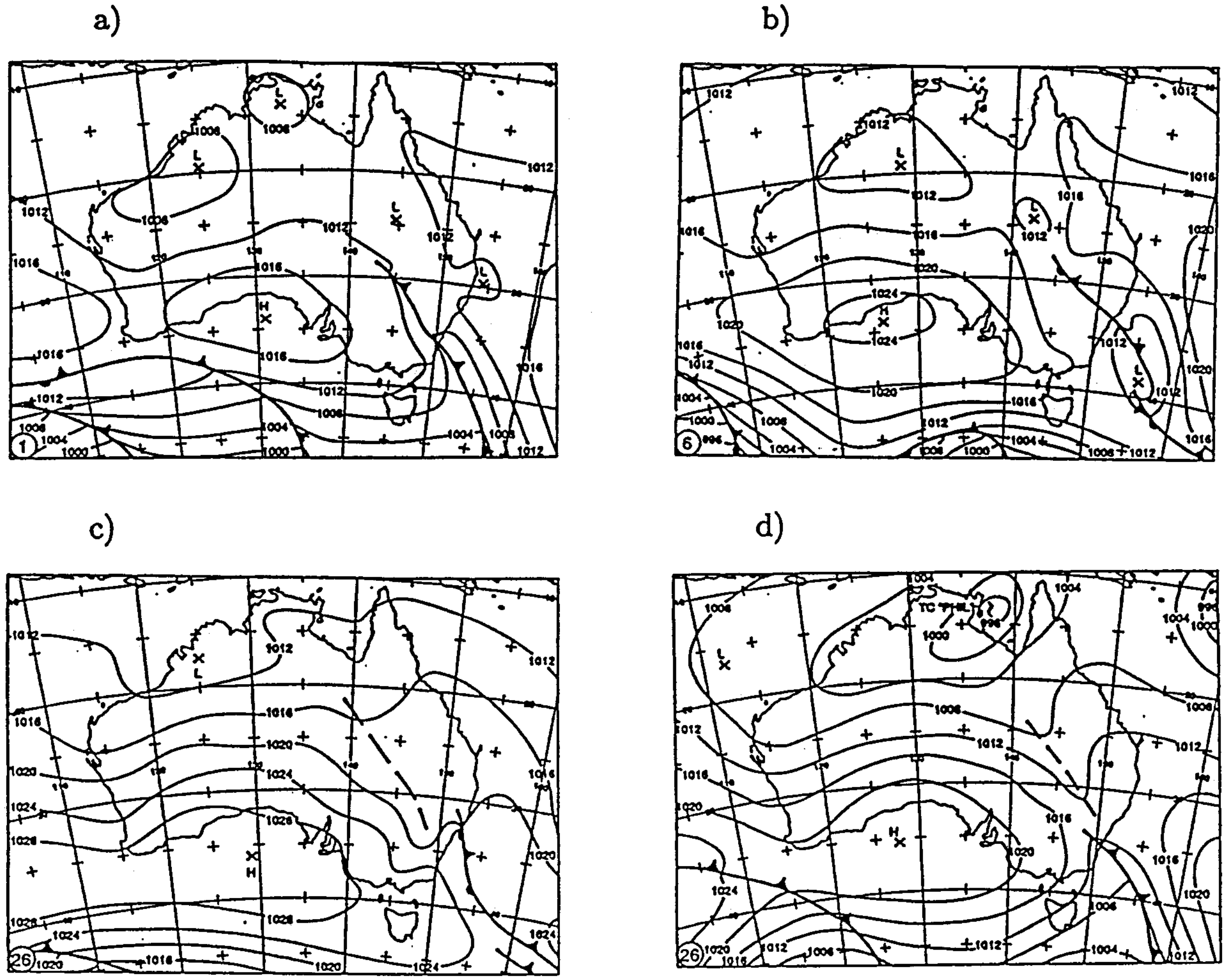
As mentioned previously, the 20 case studies were initially chosen by searching the archives for deformed cold fronts in the spring or summer months, as this is characteristic of the formation of a southerly buster. A series of SLP charts are included here (see Fig. 4) for the five cases that are presented in more detail. These charts are broadscale and are therefore unable to show the exact location of the southerly buster; however, they provide an overview of the synoptic conditions in which each southerly buster was embedded.

Table 2 summarizes the features of the SLP analyses for the 20 case studies to determine if there is a common synoptic situation in these cases.

As expected, there are several common features in the SLP analyses for each case, the main one being the presence of high pressure cells in the Great Australian Bight and also the Tasman Sea, which have a cold frontal system between them (refer to Fig. 4). This is consistent with previous studies (Gentilli 1969). A few exceptions show a local low off the east coast. Note the constraint in the definition of a southerly buster, ‘‘which is not associated with a major depression over the Tasman Sea at New South Wales latitudes’’ (Colquhoun et al. 1985). However, this does not quantify the depth of a major depression and so we can consider that the basic requirements for a southerly buster are met in each of the cases included in this study. Also included in Table 2 are the time of day and general change of the wind direction, from a northerly to a southerly.

b. Model initial states

For each of the 20 southerly buster events studied in this paper, two simulations were run at the standard analysis times of 0000 and 1200 UTC. The 40 simulations were each run at 20-km horizontal resolution over a domain that encompassed the region of southeast Australia from 40° to 29°S and 140° to 157.5°E, covering New South Wales, Victoria, and part of the Tasman Sea. (See Fig. 7 for the domain covered.) Each of the cases was nested in the southeast Australian region model of the Bureau of Meteorology. According to the date of the case study, either the RASP or LAPS was used. RASP was replaced in July 1996 by LAPS, which has improved physics and data assimilation cycle. Both RASP and LAPS are run at 75-km horizontal resolution over the Australian region. Table 3 provides a summary of nesting model, initial time, and duration for the five studies presented in more detail. The durations of model simulations differ depending on the length of forecast available, which is 36 h for RASP and 48 h for LAPS. However, for one of the LAPS runs only a 30-h archive was available. For each case two simulations have been initialized 12 h apart to compare how individual model runs treat the same southerly buster event. Once again there is an exception with one case having a 24-h period between



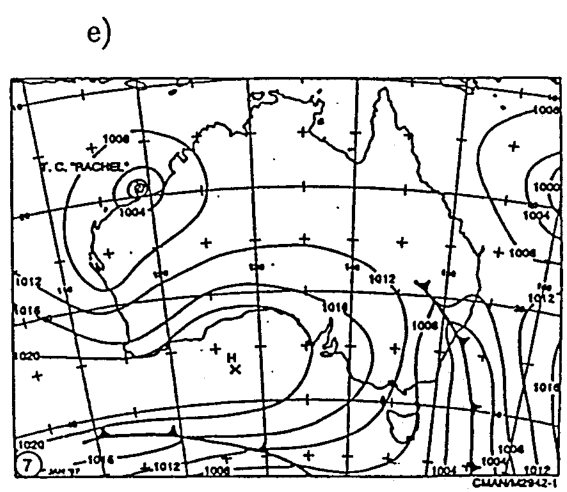


FIG. 4. Sea level pressure analyses for the five case studies: (a) event 1, 1 Dec 1995; (b) event 2, 6 Oct 1996; (c) event 3, 26 Oct 1996; (d) event 4, 26 Dec 1996; and (e) event 5, 7 Jan 1997.

the successive simulations due to an incomplete archive. Labels A to J are introduced to define the 10 simulations covered in more detail that will be used throughout and are summarized in Table 3.

c. Model skill in southerly buster prediction

The five case studies to be described below in sections 5a–e provide different situations to test the ability of

TABLE 2. Synoptic features for each of the 20 case studies, listing the common and expected features associated with the formation of a southerly buster. The wind information covers the prevailing wind direction before, and the subsequent wind direction after the southerly buster and is a composite derived from the coastal locations used in sections 5a–e. Also included is the time (local, UTC + 11) of day of the change. Where H is high pressure system, L is low pressure system, TC is tropical cyclone, PFT is prefrontal trough, QS is quasi-stationary, and Qld is Queensland.

Feature	H in bight	H in Tasman	Front	Qld trough	NW Aust. L	Wind	Time
1 Dec 95	Yes	Yes	Cold	No	Yes	N → S	Mid-PM
6 Oct 96	Yes	L develops	Cold	Yes	Yes	NW → S	Late AM
26 Oct 96	Yes	Yes	PFT, cold	Yes	Yes	NE → S	Overnight
7 Dec 96	Yes	Yes	Cold	Yes	Yes	N → S	Mid-PM
23 Dec 96	Yes	Yes	QS	No	Yes	NW → S	Late AM
26 Dec 96	Yes	Yes	Cold	Yes, TC	Yes	NE → S	Mid-PM
7 Jan 97	Yes	Yes	Cold	No	Yes, TC	NW → S	Mid-PM
16 Jan 97	Yes	L develops	PFT, cold	No	Yes	NW → S	Late AM
11 Nov 97	Yes	Yes	Cold	No	Yes	NW → S	Late PM
28 Nov 97	Yes	Yes	PFT, cold	Yes	Yes	N → S	Mid-AM
30 Nov 97	Yes	Yes	Cold	No	Yes	N → S	Mid-AM
3 Dec 97	Yes	L in SW	Cold low	Yes	Yes	N → S	Late PM
22 Dec 97	Yes	Yes	Double cold	Yes	Yes	NW → S	Early PM
27 Dec 97	Yes	Yes	PFT, cold	Yes, TC	No	NE → S	Late PM
5 Jan 98	Yes	Yes	PFT, QS	No, low	Yes	N → S	Early AM
15 Jan 98	Yes	Yes	Cold	No, TC	Yes	NE → S	Mid-PM
18 Jan 98	Yes	Yes	PFT, cold	No, TC	Yes	NE → S	Mid-PM
28 Jan 98	Yes	Yes	Low cold	No	Yes, TC	N → S	Overnight
13 Feb 98	Yes	No	Cold	Yes	Yes, TC	E → S	Mid-PM
27 Feb 98	Yes	Yes	Cold	No, TC	Yes	NE → S	Early AM

the NWP model to simulate meteorological events. Section 5f also contains a summary of a further 15 case study results to provide a more comprehensive view of the model's performance. However, to make useful conclusions, a measure of skill needs to be defined. Previous methods that have endeavored to do this have often been based on skill scores. The S_1 skill score, rms error, and spatial correlation have been used by McInnes et al. (1994). The definition of skill scores works from an average of the whole domain rather than a specific area, and McInnes et al. (1994) observed that the lowest levels of skill demonstrated were in the vicinity of significant meteorological features and that little useful information was conveyed about the model's ability in forecasting certain types of severe weather events such as cold fronts.

The limitations mentioned suggest that for the southerly buster other measures need to be considered. The results presented in section 5 focus on two aspects, the predicted time of arrival and the speed of propagation, which are able to be compared directly to the observations. These were chosen (mentioned above) because they are regarded by forecasters as the most valuable predictions. Intensity is also important. The skill of the forecasts of the first two of the variables is measured in terms of the error ranges shown in Tables 5 and 6. Included in the list of factors to be considered when discussing the concept of an error range are a ''reasonable'' level of performance expected of a numerical model (or any other forecasting tool), and an acceptable error level when considering direct application to operational forecasting of southerly busters. As southerly busters produce large changes in winds and temperatures over short time periods, accurate forecasts, including the arrival time, are needed for marine and airport operations. This suggests that application of the NWP simulations to extreme events requires an error rating with direct application to real-time forecasting, rather than a broad statistical measure.

TABLE 3. Details of each of the 10 simulations presented in more detail, denoted by the labels A to J. Here, LST = UTC + 11.

Event	Case	Nested in	Initial time	Duration (h)	Label
1	1 Dec 95	RASP	2300 LST 29 Nov 95	36	A
			1100 LST 30 Nov 95	36	B
2	6 Oct 96	LAPS	2300 LST 4 Oct 96	48	C
			1100 LST 5 Oct 96	30	D
3	25–15 Oct 96	LAPS	1100 LST 24 Oct 96	48	E
			2300 LST 24 Oct 96	48	F
4	26 Dec 96	LAPS	2300 LST 24 Dec 96	48	G
			1100 LST 25 Dec 96	48	H
5	7 Jan 97	LAPS	2300 LST 5 Jan 97	48	I
			1100 LST 6 Jan 97	48	J

The sections 5a–e address the skill of the model with respect to the actual time of the southerly wind change, and hence the passage of the southerly buster, and the overall speed of the front by comparing the time differences between locations along the coast. A third prediction, namely, maximum wind gusts, is also included to provide a brief check on the simulated intensity.

This study has been limited in its prediction time with only hourly data extracted from the simulations to be compared with the observations. A quantitative measure of the difference between the observations and prediction could provide a way to consider the error of the

TABLE 4. A measure of the difference of the simulation with respect to the observations. An ''excellent'' rating is noted when the observation is within an hour of the NWP model, ranging through to ''poor'' when the simulation is more than 4 h early or late.

Difference	0–1 h	1–2 h	2–3 h	3–4 h	>4 h
Skill	Excellent EX	Very good VG	Good G	Fair F	Poor P

TABLE 5. A measure of the consistency of a simulation and the speed of the southerly buster up the coast. A ''good'' speed is noted for simulations that maintain the particular difference of each simulation, to within 2 h from the time of the surge reaching the specified locations. Based over the distance from Bellambi to Coffs Harbour.

Change	2 h	2–4 h	4 h
Speed	Good	Fast/slow	Very fast/slow

NWP model. An error range, which accommodates the factors mentioned above, is now proposed. Table 4 outlines the error band classification as used in this paper.

Table 5 has a scale to rate how accurately the NWP model simulates the speed of the southerly buster along the coast. This is a more difficult measure, as for some cases the southerly buster simulation is not consistently earlier or later than the observed event. As the simulated southerly buster passes the specific coastal locations, there may be a different delay in arrival time from one location to the next. It should be noted that while the timing of the surge is good, the speed may not be well represented, and vice versa. A 3-h ''change'' may result when there is a delay of 1 h in arrival time at one location and then 2 h early farther up the coast, and this would be classified as being faster than the observed event while still having very good arrival time at each location.

d. Model output of a ''classic'' southerly buster

The case of 26 December 1996 has been chosen to demonstrate the model's general ability to simulate the characteristic features of a southerly buster. In Fig. 5, two different times have been selected to indicate the development and progress of the southerly buster up the coast of NSW. Of note are the strong coastal southerly winds and the deformation of the SLP isobars into the characteristic ''S shape.'' Figure 6 is the model simulation showing the change in wind direction at the specified coastal locations. A vertical profile along the NSW coast (Fig. 7a) is shown in Fig. 7b. There is clear definition of the lower-level surge penetrating significantly farther north before the middle levels turn to a southerly wind of lesser magnitude. The depth of the surge corresponds with the approximate height of the 850-hPa level and the strongest winds are clearly behind the mixing region of the frontal line, a feature that is observed in anemographs of southerly busters.

5. Results

From the 40 (starting times 0000 and 1200 UTC) simulations of the 20 events introduced in the previous sections, the wind direction was extracted from the model at various locations chosen to be close to the anemographs. The anemographs are from the NSW coastal locations: Bellambi, Fort Denison, Norah Head, Williamtown, and Coffs Harbour (see location map, Fig. 8). Also included are Richmond, which is not coastal and had observational data for only one case, and Canberra, which is inland of the Great Dividing Range. From each anemograph the strength of the observed southerly change has been extracted, as well as the time of the change, which are both of primary interest here to verify model output. Both observational data and

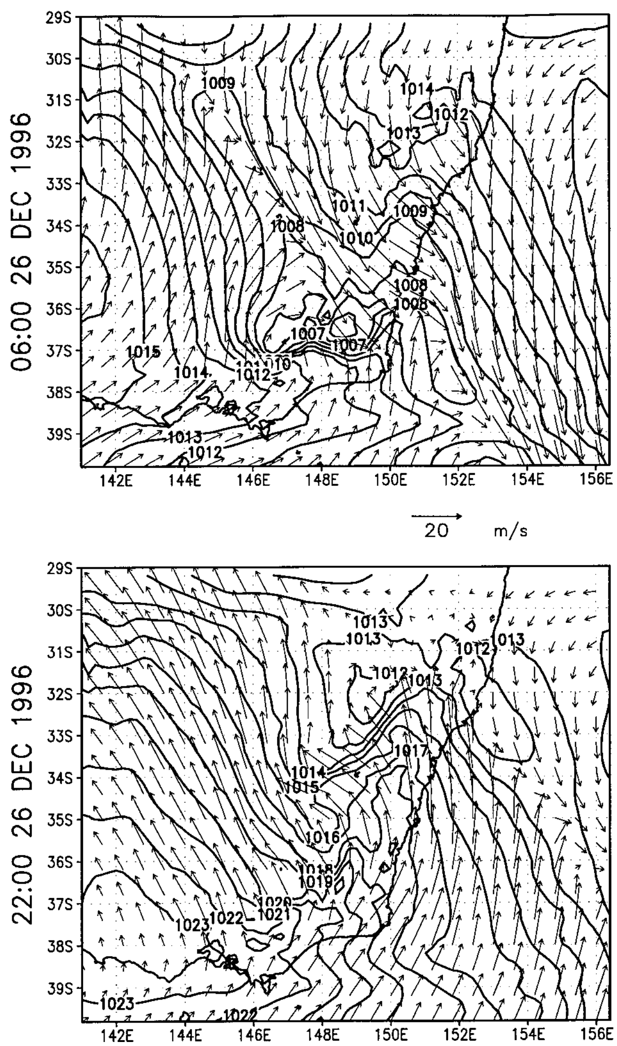


FIG. 5. Model output from 26 Dec 1996 at two different times. Wind vectors and SLP isobars are plotted. Note the strong southerly winds along the coast and the deformation of the isobars at the coast. Winds are in m s^{-1}.

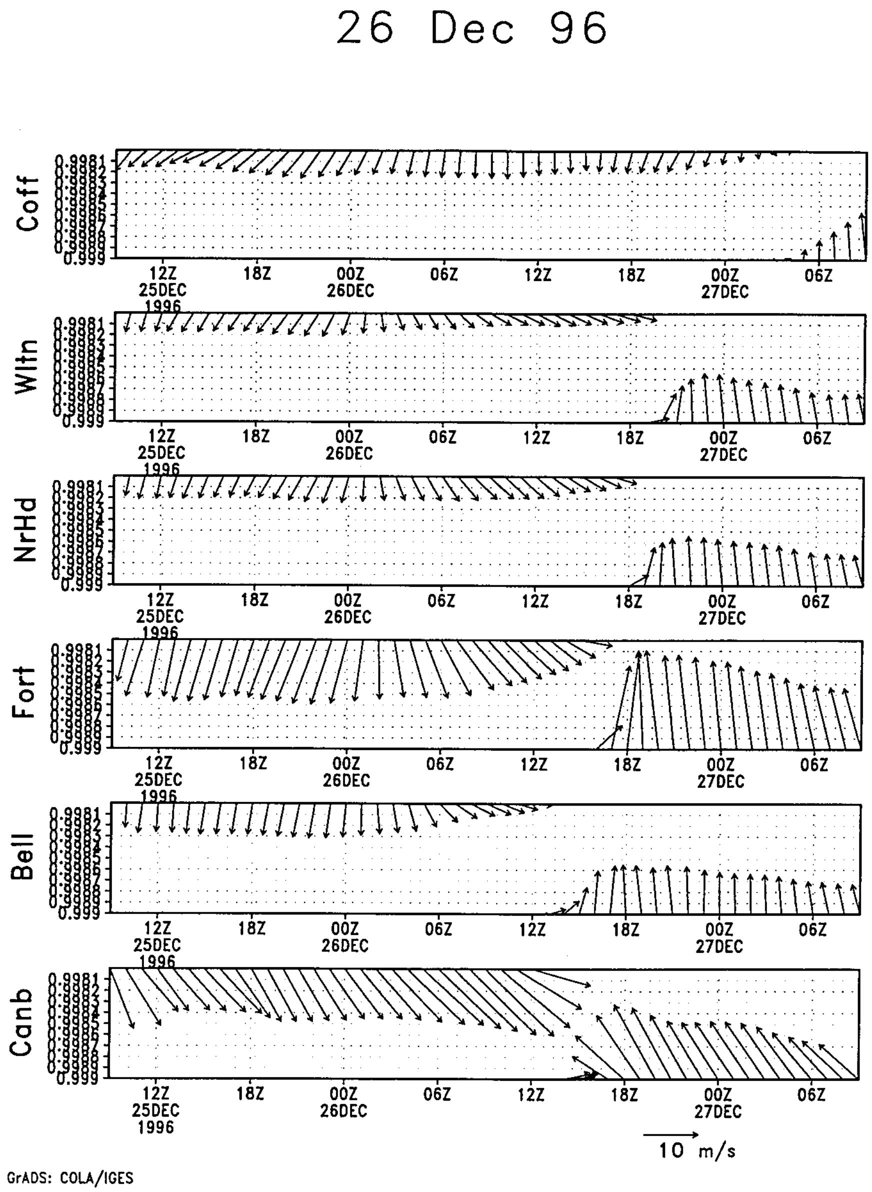


FIG. 6. Model output from 26 Dec 1996 showing the wind direction and the change experienced at the specific locations chosen for verification purposes. Winds are in m s^{-1}.

model output are presented in this section with a view to comparing the observed time of arrival of the southerly buster, as well as the time it takes for the southerly buster to travel northward between locations, a measure of the speed of propagation. These will be discussed in section 5. The simulated intensity is mentioned for interest, and further studies on mean wind and maximum gust will address the issue in more detail.

Each of sections 5a–e contains a summary table for a designated case study. These tables outline the wind direction, speed, and time of arrival of the southerly change. The speed is included because the definition requires that the southerly buster produces gusts of at least 15 m s^{-1}. The latter columns of each table indicate an approximate time (to within an hour) that the model predicted for the arrival of the southerly buster and maximum wind speed, and are labeled according to the listing in Table 3. Section 5f contains a brief overview of the model skill.

a. Event 1: 1 December 1995

On 1 December 1995, a southerly buster moved north along the east coast of NSW and passed through Sydney in the early afternoon. In this case, the north to northeasterly wind was replaced by a southerly with maxi-

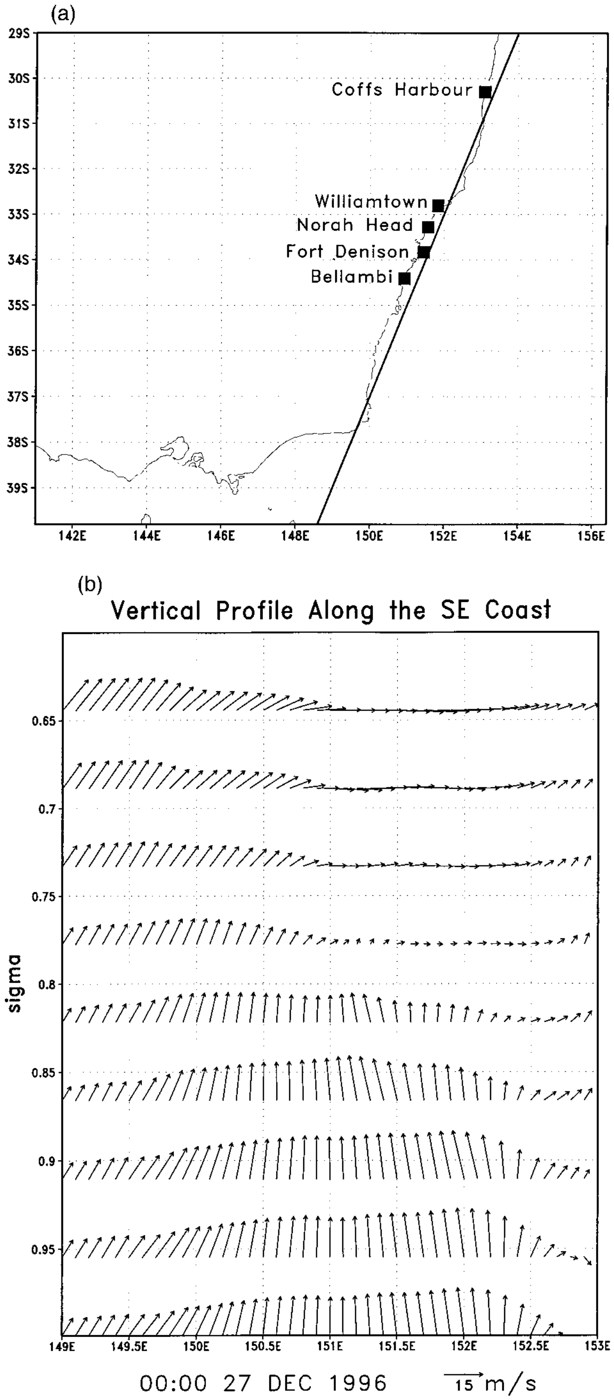


FIG. 7. (a) Domain of the model simulations showing the line along which the vertical coastal cross section used in (b) was taken; (b) vertical profile indicating the advance of the lower levels of the coastal surge relative to the middle (and upper) levels.

mum gust speeds from 10 up to 17 m s^{-1}. Table 6 contains a summary of the observations and model output for this case.

Simulation B provides a good to excellent arrival time frame, with Fort Denison, Richmond, Norah Head, and

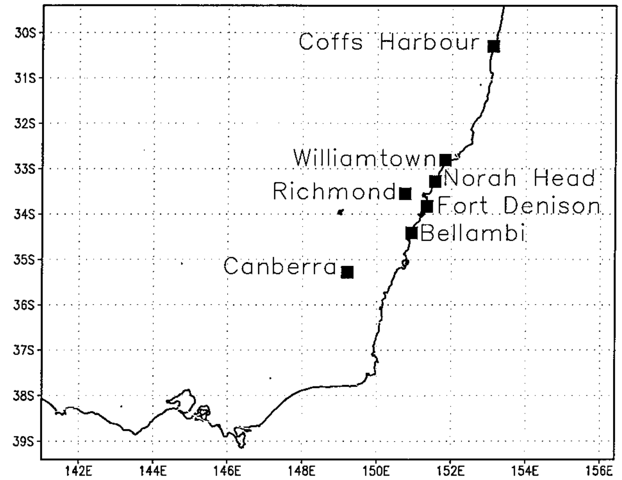


FIG. 8. Locations of anemograph stations: Canberra, Bellambi, Fort Denison, Richmond, Norah Head, Williamtown, and Coffs Harbour.

Williamtown having the simulation time frame in agreement with the observation. The southerly change that is predicted by simulation A is poor, being earlier than the observation by approximately 10 h. Also the movement of the surge along the coast is much faster than the observed event. Simulation B has the correct time for all locations and so overall has the southerly buster moving at approximately the same speed as the observed event. It also has the wind speed in the range of 13–16 m s^{-1}, which is comparable with observations.

b. Event 2: 6 October 1996

The case for 6 October 1996 had a west to northwesterly wind changing to southerly during the morning, with maximum gusts ranging from 3 to 16 m s^{-1}. Details are contained in Table 7.

Both C and D have a good speed but only D has the actual time of arrival correct. Here, C is consistently 3 h later than the observed southerly buster. The speed of the wind in both simulations fall in the range of observations with them being 10–15 and 8–13 m s^{-1}, respectively.

c. Event 3: 25–26 October 1996

In this case, the southerly change occurs overnight of 25 October and continues into the morning of 26 October 1996. Ahead of the southerly winds the flow ranged between WNW and ENE at the coastal locations. However, this southerly did not penetrate as far north as Coffs Harbour. Maximum gusts ranged from 8 to 14.5 m s^{-1}, possibly not a strict southerly buster, and this case is listed in Table 8.

Simulations E and F did not provide a correct time for the passage of the southerly buster, although simulation F is closer to the time of the observations. Both

TABLE 6. Event 1, 1 Dec 1995: Results from simulations A and B at various locations listing wind direction before and after the southerly buster, mean and maximum gust of wind of the southerly buster, time of the observed wind change, the simulated times of the wind change, a measure of skill, and simulated mean wind speed. The speed of propagation is shown in the bottom row and is developed over the distance from Bellambi to Coffs Harbour. Times listed are local time, which is UTC + 11.

Place	Prior	After	Mean (m s⁻¹)	Gust (m s⁻¹)	Obs time	A Timing	A Skill	A m s⁻¹	B Timing	B Skill	B m s⁻¹
Canberra	NNW	E	10.2	10.4	1730	—	—	8.6	1700	VG	10.5
Bellambi	ENE	SSE	15.3	17.1	1340	0700	P	7.2	1200	VG	15.6
Fort Denison	E	S	12.8	15.5	1540	0700	P	7.8	1400	VG	16.1
Richmond	NE	SE	10.2	11.4	1640	0700	P	8.4	1700	EX	13.7
Norah Head	NE	SSW	15.3	16.6	1900	0900	P	8.6	2000	EX	15.8
Williamtown	N	SSW	10.2	130	2120	0900	P	7.8	2200	EX	14.5
Speed of propagation							Very fast			Good	

simulations are approximately 8 h late and are too slow. This error is also reflected in the simulated intensity with both simulations placing the strength of the wind below observed values.

d. Event 4: 26 December 1996

A southerly buster with maximum gusts ranging from 10 to 27 m s^{-1} moved up the coast of NSW during the afternoon of 26 December 1996. Surface winds ahead of the buster were not a consistent northerly (owing to a sea breeze) and were replaced by a strong southerly. The observational summary for this case is in Table 9.

Simulation G varies in its error with good to excellent arrival times at the majority of locations. However, its overall speed was slow as the simulated surge is early at Bellambi and late at Coffs Harbour. By contrast, simulation H is generally very good with respect to the arrival time, being approximately 2 h ahead of observations. The difference between the model and observations decreases from being 2 h early at various locations to just 1 h by the time the simulated surge reaches Coffs Harbour and is moving with approximately the same speed as the observed southerly buster. While the larger wind gusts were not determined by either simulation, the range predicted corresponds to observations.

e. Event 5: 7 January 1997

The case of 7 January 1997 is a complex one with a double front marked on the analysis chart. The first frontal line marked is actually due to prolonged (3 h) thunderstorm activity in the vicinity of Bellambi with the outflow causing a steady southerly wind to be recorded at Bellambi. However, this southerly flow is not maintained and returns to the northwest. Other coastal locations have a similar anemograph but with a shorter thunderstorm period. During the afternoon, another change of wind to the south occurs and remains, indicating that the southerly buster proper has passed through. This continuing flow has maximum gusts ranging from 8 up to 24 m s^{-1} and is listed in Table 10.

Despite the significant thunderstorm band, the model did not resolve such fine structure. Simulation I is earlier than the wind change by 7 h. Simulation J is 3 h early at Bellambi and 3 h late at Coffs Harbour. So while I is good with respect to the speed of the flow, J is only able to simulate some arrival times with reasonable accuracy. Simulation I was unable to place the wind intensity in the corresponding range to observations, while J only overlapped observations at the slower speeds.

f. Skill of the case studies

The 20 cases chosen roughly span the spring and summer of two years, namely 1996–97 and 1997–98. The majority of cases are summertime, being from the months of December and January. The points of verification are subject to availability of observational data and also the simulation's resolution of the change. Bearing this in mind, there were over 190 opportunities for a direct comparison between the observed data and sim-

TABLE 7. As in Table 6 but with event 2, 6 Oct 1996, and simulations C and D.

Place	Prior	After	Mean (m s⁻¹)	Gust (m s⁻¹)	Obs time	C Timing	C Skill	C m s⁻¹	D Timing	D Skill	D m s⁻¹
Canberra	WNW	S	7.7	8.2	1100	1000	EX	8.3	0.900	F	7.1
Bellambi	W	S	7.7	10.9	0400	0800	F	15.0	0600	VG	13.0
Fort Denison	NW	SSW	7.7	7.8	0710	1100	F	15.1	0700	EX	12.8
Norah Head	W	SSW	15.3	16.6	1030	1400	F	13.5	1000	EX	12.0
Williamtown	W	SSW	7.7	11.4	1220	1600	F	12.5	1300	EX	10.1
Coffs Harbour	NNW	SW	10.2	11.4	2310	0200	G	10.1	0000	EX	8.0
Speed of propagation							Good			Good	

TABLE 8. As in Table 6 but with event 3, 25–26 Oct 1996, and simulations E and F.

Place	Prior	After	Mean (m s^{-1})	Gust (m s^{-1})	Obs time	E Timing	E Skill	E m s^{-1}	F Timing	F Skill	F m s^{-1}
Canberra	N	E	5.1	9.2	2020	2100	EX	6.3	2200	VG	7.1
Bellambi	WNW	SSE	10.2	14.0	2100	0500	P	11.8	0100	F	9.1
Fort Denison	ENE	SSW	12.8	14.0	2230	0900	P	7.8	0400	P	3.8
Norah Head	N	SSW	10.2	14.5	0030	1000	P	6.7	0800	P	3.3
Williamtown	ENE	SSW	10.2	11.4	0140	1100	P	5.3	1000	P	2.3
Coffs Harbour	—	—	—	—	—	—	—	—	—	—	—
Speed of propagation							Slow			Very slow	

ulated results. Table 11 combines the error rating from both the simulations associated with each southerly buster event. As such, the results are very encouraging with over 40% of the verification points falling inside the suggested 2-h range. It should be noted that only one-third were classified as poor and that these poor ratings are primarily restricted to just four events: 26 October 1996, 7 January 1997, 3 December 1997, and 15 January 1998. This would indicate that one (or both) of the entire simulation(s) was unable to capture the southerly buster time. In contrast, there is a fairly even spread through the rest of the cases as to the excellent and very good ratings, showing the generally very good capacity of the model to simulate the arrival time of a southerly buster. The implication clearly is that the model physics are more than adequate in the simulation of southerly busters and the isolated cases where the model did not perform well is a result of poor initial analyses.

The consideration of the speed of propagation of the front was also addressed and once again there are very encouraging results, as outlined in Table 12. Nearly 60% of the 40 simulations were able to consistently simulate the speed of the southerly buster as it moved up the coast of NSW. There is a slight tendency for the model to provide more slower than faster simulations of southerly busters.

It is concluded that while the numerical model simulated either timing or the speed of propagation well for most events, simulating *both* very well was achieved for 16 (40%) of the simulations. On the other hand, only 4 (10%) simulated both poor timing and speed. Half of the simulations had well-placed timings of the surges at specific stations and half the simulations were able to predict the speed of the southerly buster as it moved northward along the NSW coast. It is noted that while the second of the pair of simulations was twice as often the better at placing the time of arrival, both simulations of the pair were just as able to simulate the propagation speed.

A limited comparison of the above results with the local operational model was carried out with the available archives from the National Meteorological Operations Centre of the Bureau of Meteorology. The SLP contour that marks the leading edge of the southerly buster was compared and there was a significant (several hours) lag in the operational model. It should be noted that both HIRES and the operational model employ exactly the same initial data so that such a direct comparison is valid.

6. Discussion and conclusions

The results presented in section 5 deal with 20 case studies of southerly busters, which were all very different in nature, and with 40 corresponding simulations at 0000 and 1200 UTC. The time of occurrence of the southerly buster and the speed at which the surge propagates along the NSW coast vary markedly for each case. Of primary consideration was an assessment of the ability of a current real-time NWP model to simulate the timing and relative speed of the southerly buster as it moved northward along the east coast of NSW. A measure has been suggested that quantifies the error in absolute terms, with a view to direct application to real-time forecasting. Overall the NWP model was good to very good in simulating the time of arrival of the southerly buster and the speed of the

TABLE 9. As in Table 6 but with event 4, 26 Dec 1996, and simulations G and H.

Place	Prior	After	Mean (m s^{-1})	Gust (m s^{-1})	Obs time	G Timing	G Skill	G m s^{-1}	H Timing	H Skill	H m s^{-1}
Canberra	WNW	E	12.8	13.5	1800	1400	F	13.1	1200	P	12.5
Bellambi	N	SSE	15.3	21.8	1450	1300	VG	17.4	1300	VG	17.7
Fort Denison	E	S	17.9	24.4	1600	1600	EX	17.1	1400	VG	18.2
Norah Head	N	SSE	20.4	27.5	1720	1800	EX	18.0	1600	VG	18.7
Williamtown	ESE	S	15.3	18.7	1820	1900	EX	17.5	1700	VG	16.8
Coffs Harbour	NNW	SW	7.7	10.4	0150	0400	G	8.0	0200	EX	6.3
Speed of propagation							Slow			Good	

TABLE 10. As in Table 6 but with event 5, 7 Jan 1997 and simulations I and J.

Place	Prior	After	Mean (m s^{-1})	Gust (m s^{-1})	Obs time	I			J		
						Timing	Skill	m s^{-1}	Timing	Skill	m s^{-1}
Canberra	WNW	SSE	7.7	8.3	2030	1500	P	2.1	1200	P	7.3
Bellambi	WNW	SW	15.3	18.1	1310	0700	P	12.2	1000	F	16.0
Fort Denison	WNW	S	12.8	18.7	1430	0800	P	11.8	1200	G	17.1
Norah Head	W	S	17.9	23.8	1600	1000	P	10.4	1400	VG	16.6
Williamtown	WNW	SSW	12.8	18.7	1740	1200	P	9.0	1500	G	15.9
Coffs Harbour	ENE	SW	10.2	5.5	2040	0800	P	6.5	0000	F	11.2
Speed of propagation							Good			Very slow	

surge also was good. This has positive implications as a tool for forecasters in assisting the prediction of southerly buster passages. The intensities of the five cases covered in more detail provide an indication that the NWP is also able to simulate wind speeds of a similar nature to those observed.

Of note is the general improvement in model performance with respect to the timing for the later simulation of the pair of forecasts for each case study. Another aspect of note is the seasonal difference in the arrival of the southerly buster and the skill with which the NWP model simulated it. Of these 20 case studies, 5 events were in spring and showed overnight and morning changes. The majority of cases studied occurred during the summer months and these were predominantly afternoon events. The simulations that were during the spring had only 20% predict the time and speed well as opposed to 40% of the summer events. (The small sample for spring is noted.) With such differences in both the observations and simulations from spring to summer, questions can be asked about the different nature of a southerly buster in the spring and summer. The study of seasonal effects on southerly buster development and propagation could also be extended into the wide range of southerly wind changes that affect southeastern Australia.

Event 5 provides a starting point for further work in resolving the thunderstorm outflow. This could be achieved through higher-resolution studies. With these results, further work could cover southerly buster cases that contain prefrontal troughs, to explore the development and propagation of these cases. (A planned study, Part II, will cover these and associated aspects.) Other more complex aspects of the dynamics of a southerly buster and its propagation can then be studied to determine whether the surge travels at a constant speed or acceleration, which would have bearing on real-time forecasting.

As mentioned earlier, further work could cover the consideration of seasonal differences of southerly changes. Various factors have been suggested as influences on the development of southerly wind changes affecting the east coast of NSW. Among the suggestions are the location and strength of the forcing high pressure system over the bight, the föhn effect and the influence it has on the frontal passage and squall line activity (Egger and Hoinka 1992), the existence of an inversion layer and height thereof for possible vertical trapping of the surge, and diurnal effects.

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TABLE 11. Summary of all 20 cases and the corresponding 40 simulations indicating the spread of error between observation and simulation for the time of arrival of the southerly wind. It should be noted that the direct verification is subject to both the availability of observations and also the simulation's resolution of the change.

Absolute timing	EX	VG	G	F	P
1 Dec 1995	3	3			5
6 Oct 1996	5	1	1	5	
26 Oct 1996	1	1		1	7
7 Dec 1996	4	1	1	3	3
23 Dec 1996	2	4	1		1
26 Dec 1996	4	5	1	1	1
7 Jan 1997		1	2	2	7
16 Jan 1997	1	6	1	1	2
11 Nov 1997	4		2	1	1
28 Nov 1997	3	1	4	3	1
30 Nov 1997	1	2	2	3	2
3 Dec 1997					10
22 Dec 1997	2	1	1	1	4
27 Dec 1997	3	3	1		
5 Jan 1998	3	1			4
15 Jan 1998		1		1	8
18 Jan 1998	3		1	1	3
28 Jan 1998		2	2	2	
13 Feb 1998	3	2	3		
27 Feb 1998	4	2	1		
Total obs = 191	46	37	24	25	59
Percentage	24%	19%	13%	13%	31%

TABLE 12. Summary of propagation speed over the distance from Bellambi to Coffs Harbour, subject to the same constraints as Table 11.

Propagation speed	VS	Slow	Good	Fast	VF
Total = 40 runs	4	6	23	6	1
Percentage	10%	15%	57%	15%	2%

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