Numerical Prediction of the Summertime Ridge–Trough System over Northeastern Australia

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ABSTRACT

The synoptic pattern over northeastern Australia is dominated in the warmer months by a ridge–trough system. Accurate prediction of the location of the system is a significant forecasting problem for regional and global operational models. The regional model that was operational at the time of this study exhibited two significant weaknesses characteristic of many current operational global models, a westward bias in the location of the east coast ridge and errors in the location and strength of the inland trough. The present investigation had three aims: to compute model location errors of the ridge–trough system from a large (6 month, twice daily) dataset of operational forecasts, to explain these errors by evaluating a new regional model, and to confirm the diagnosis using a series of case studies and sensitivity studies. The operational model had a marked mean westward bias of about 2° longitude in the location of both the trough and the ridge. There was a noticeable latitudinal distribution in trough errors with the greatest errors in the north. Ridge location errors were much larger in the south. Overall, almost 60% of errors were 2° longitude or greater. The new model was far more skillful in forecasting the ridge–trough system with predicted locations of both ridges and troughs being superior at greater than the 99% confidence level. In the new model a mean westward error remained in the location of the ridges and troughs but was less than 1°. The percentage of errors greater than 2° longitude dropped to about 20% for ridges and 35% for troughs. The decreased location errors in the new model are attributed to improved representation of the steep coastal orography and of the simulations of both the heat low and inland trough to the west of the coastal ranges. This was confirmed in three case studies at very high resolution (15 km) using the new model but with operational data and also in two sensitivity studies with the new model using the operational model forecast surface temperatures. The forecasts showed similar trough location problems to the operational model.

1. Introduction

The heat trough that forms over the interior of northeast Australia and the associated east coast ridge are significant features of the surface circulation patterns during the warmer months of the year. An example is given in Fig. 1 and it shows a well-defined coastal ridge and inland trough extending from 35°S into Tropics. The coastal ranges, known as the Great Dividing Range, extend from north Queensland to south of New South Wales (NSW) in a zone approximately 140–400 km wide and act as virtually a continuous barrier of between 200- and 500-m elevation with higher peaks over 1000 m. The coastal ranges have many abrupt escarpments on the eastern (coastal) side, and on the western slopes there is a gradual descent to the inland plains, as can be seen in the location map of Fig. 2.

During the warmer months, from November to March, inland maximum screen temperatures are around 40°C with ground temperatures over 70°C. These contrast strongly with ocean surface temperatures in the Coral Sea, which are in the mid- to high 20°Cs. The location and strength of the near-coastal ridge, location and depth of the inland trough, as well as local effects, determine the strength and nature of the prevailing winds and the precipitation patterns. This pronounced variation in spatial and temporal distribution of rainfall, which is highly dependent on orography and wind direction, has been studied elsewhere (Sumner and Bonell 1986, 1988; Lyons and Bonell 1992). For example, on the north Queensland coast between Cairns and Cardwell the annual median rainfall is over 3000 mm. The nearby steep coastal ranges provide strong uplift for onshore moisture-laden winds resulting in substantial rainfall on this part of the coast. There is a rapid decrease

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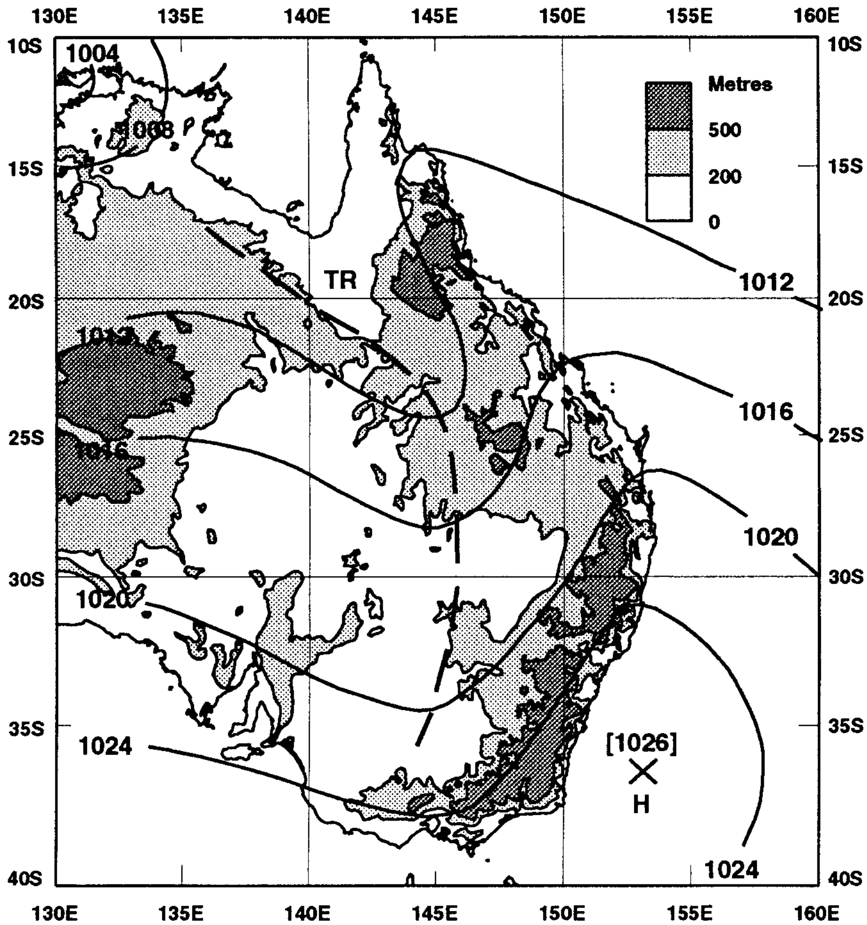

FIG. 1. Mean sea level pressure analysis 0000 UTC 2 Jan 1997. The inland trough line is dashed. The low-pressure system near Darwin developed into Tropical Cyclone Rachel.

of rainfall inland so that 150 km west of this region the median annual rainfall drops to about 800 mm. The inland trough is a semipermanent feature of summer and often is associated with a dryline, which separates the moist flow of the trade wind easterlies from the much drier continental air masses (Adams 1986). Dewpoint contrasts in summer across the dryline can on occasions exceed 20°C. On most days the trough, which shows a diurnal variation in location and strength, is a region of thunderstorm activity on its eastern side. These storms are either confined to a narrow region relatively close to the trough or can be scattered over a much larger area between the trough and the coast (Adams 1990). The dryline of northeast Australia, which is shallow and has a relatively sharp transition in moisture content, is analogous to the extensively investigated dryline of the United States. For an excellent summary of U.S. drylines see Ziegler et al. (1995)

The Australian region operational model, known as RA75, had a horizontal resolution of 75 km and 17 vertical levels. The RA75 model evaluation revealed a consistent and large westward bias in predictions of the coastal ridge and the inland trough. Although this model has now been replaced, it was operational during the time of the study and was superseded only recently, in July 1996. However, from a limited study over a 1-month period and from detailed subjective assessment over a much longer period, the current operational model known as LAPS (Limited Area Prediction System; Puri et al. 1996, 1998), which has replaced RA75, shows the same location problems as RA75. Both of these features are poorly forecast on many occasions. In this study a comprehensive comparison is made between RA75 and HLAM (an acronym for the High resolution Limited Area Model), a relatively new model that has numerics that were the forerunner of the current Australian regional operational model, LAPS. Both HLAM and LAPS have higher-order numerics than RA75 and an improved treatment of physical processes. The RA75 and HLAM models are described briefly in section 2. Following some definitions in section 3, section 4 is devoted to a quantitative assessment of the performance of RA75 and HLAM over the 6-month period from 1 November 1993 to 30 April 1994 using a number of indicators introduced in section 3. Emphasis was placed on calculating the errors in the location of the troughs

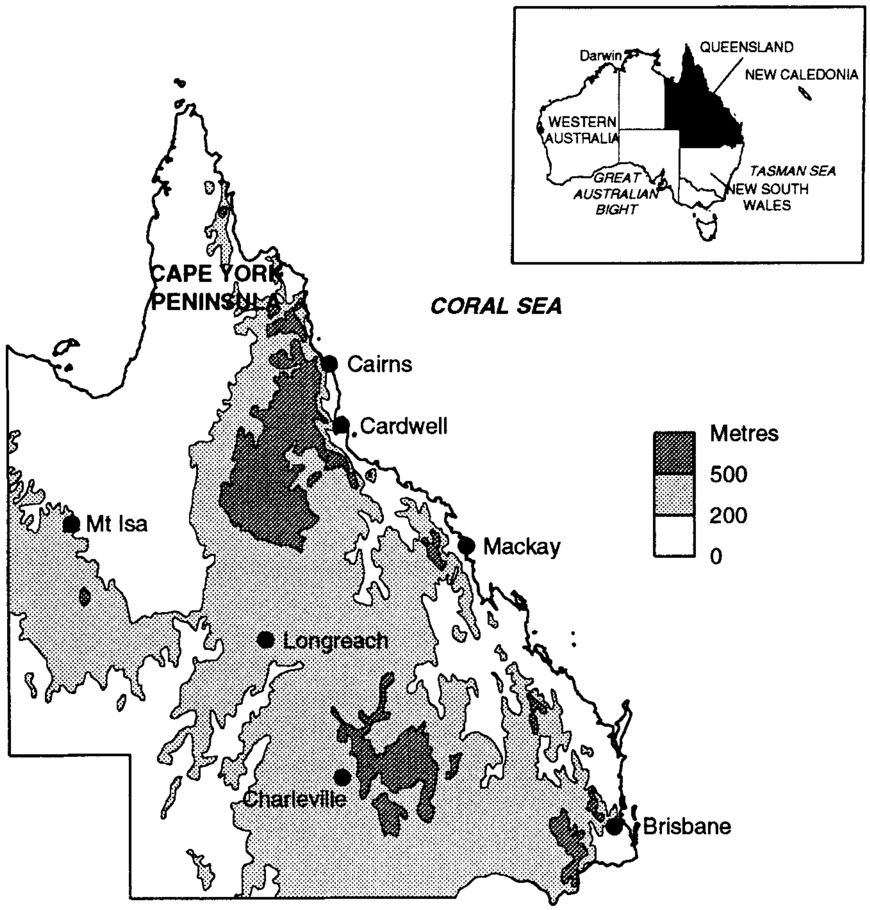

FIG. 2. The Queensland region with topography above 200 and 500 m indicated.

and ridges at three different latitudes in the Queensland region. In section 4 the RA75 performance was compared with that of HLAM. In section 5 three very different case studies were performed at 75-km resolution and also HLAM was run at 15-km resolution to confirm the judgement reached in section 4, that improvements in model performance are closely related to model resolution, realistic orography, and improved representation of surface heating. Additionally in section 5 sensitivity experiments were carried out on two of the case studies at 75-km resolution to confirm the impact of the surface heating and the orography. Finally, section 6 is a summary and discussion of the study.

2. The models

A very brief description of the models used in this study will now be presented as they differ considerably in both their numerics and their representation of physical processes.

a. *The operational model (RA75)*

The Australian Bureau of Meteorology's operational model was until recently the Regional Assimilation and Prognosis system (RASP) and was run, as all of the operational models, at the National Meteorological Operations Centre (NMOC) in Melbourne. A 75-km horizontal resolution version of RASP known as RA75 was operational until July 1996. The model numerics are second order, centered, and energy conserving for the advection terms. They are semi-implicit for the adjustment terms and the physics is carried out at a specified multiple of the semi-implicit time step. The model physics is virtually identical to that described in Leslie et al. (1985) and is relatively crude by present standards. The physics time step is set at 15 min in order to capture the details of the physical processes and yet not to be so small that computational efficiency becomes a problem. The model is described in Leslie et al. (1985) and Mills and Seaman (1990). For a summary of the details of the RA75 model see Table 1.

b. *The new real-time model (HLAM)*

HLAM, a new research model, is currently being run twice daily in real time at the Sydney Regional Forecast Centre of the Australian Bureau of Meteorology, details of which are given in Table 1. It has a very different

TABLE 1. Features of the RA75 and the HLAM models.

	RA75	HLAM
Horizontal resolution	75 km	75–15 km
Numerical scheme	Semi-implicit (second order)	Split semi-implicit (high order)
Vertical levels	17	17–31
Assimilation scheme	6-h cycling	6-h cycling
Initialization	Vertical normal mode	Dynamic (diabatic)
Orography	6 min	2 min
Boundary layer scheme	Simple K theory	Mellor–Yamada level 2.25
Radiation scheme	Surface energy balance	Fels–Schwarzkopf
Convection scheme	Kuo	Kuo
Shallow convection	None	Tiedke
Sea surface temperature	Climatology	7-day mean
Initial boundary conditions	Global model	Global model

formulation from RA75 but has similar numerics to the Bureau of Meteorology's LAPS, which is described in detail in the Australian Bureau of Meteorology NMC report of February 1997 and also in Puri et al. (1996, 1998). The model described in Leslie and Skinner (1994) is an early version of HLAM. The present version of HLAM uses numerics that are third-order upwinding for the advection terms, fourth-order semi-implicit in the treatment of the adjustment terms, and has a much more sophisticated physics package than RA75. All the model runs in section 4 were carried out with the same 75-km horizontal resolution as RA75 and with the same number of levels (17) in the vertical. The RA75 model physics employed simple K theory in the boundary layer and a surface energy balance scheme that had no radiation in the body of the atmosphere (Leslie et al. 1985). The deep convection scheme was a slight variant of the Kuo (1974) formulation but there was no parameterization of shallow convection. The HLAM scheme used a Mellor–Yamada (1974) high-order closure scheme (level 2.25) for the surface layer, the Fels–Schwarzkopf (1975) radiation package, and essentially the same deep convection scheme as RA75 but with a simple representation of downdrafts. However, shallow convection is included in HLAM and is based on that of Tiedke (1988).

c. Data and initial fields

The initial fields for the numerical experiments were obtained from the Australian Bureau of Meteorology's operational archives. The initial numerical analyses were the RA75 fields and were used for both models. The models were run from initial fields spanning the 6-month period from November 1993 to April 1994 inclusive and were produced twice daily, at 0000 and 1200 UTC. The verifying fields were the very detailed manual analyses, which also were obtained from the Bureau of Meteorology's archives.

d. Initialization procedure

The RA75 and HLAM models both have initialization procedures to reduce model shock and spinup from the initial analyses. The RA75 model uses the vertical mode initialization scheme of Bourke and McGregor (1983), which is somewhat problematic for the shorter horizontal modes and does not treat the diabatic terms, while the HLAM uses the nonlinear diabatic dynamic initialization scheme of Sugi (1986). However, in a test with a sample of 20 forecasts there was little difference between the 24-h forecasts for HLAM when a vertical mode initialization scheme was used in place of the Sugi scheme.

e. Lateral boundary conditions

Both the RA75 and HLAM models are nested in the Bureau of Meteorology's operational global spectral NWP model (GASP), using the same ''blending'' procedure in which a linear weighted average of the global and limited area models is applied over a small number (usually six) of grid points near the boundary. Experiments with HLAM, using a variety of weighting function forms other than linear, showed little sensitivity. The linear weighting used dropped from full weighting at the boundary of the global model to zero in the interior of the domain.

3. The ridge–trough system over northeastern Australia

During the warmer months of the year, November–April inclusive, the ridge–trough system often is evident over northeastern Australia. The coastal ridge is a semipermanent feature of the sea level pressure (SLP) charts and results from the prevailing onshore easterly wind stream to the north of the subtropical ridge. The circulation pattern is interrupted in the summer months by monsoonal lows and tropical cyclones moving over the area. The near-coastal ridge and the inland trough are readily explained in simple terms by conservation of potential vorticity as the southeasterly trade winds approach and pass over the coastal ranges (see, e.g., Holton 1992; Leslie and Fandry 1984). On the western side of the ranges the summer screen temperature maxima regularly are around 40°C or higher (ground temperatures

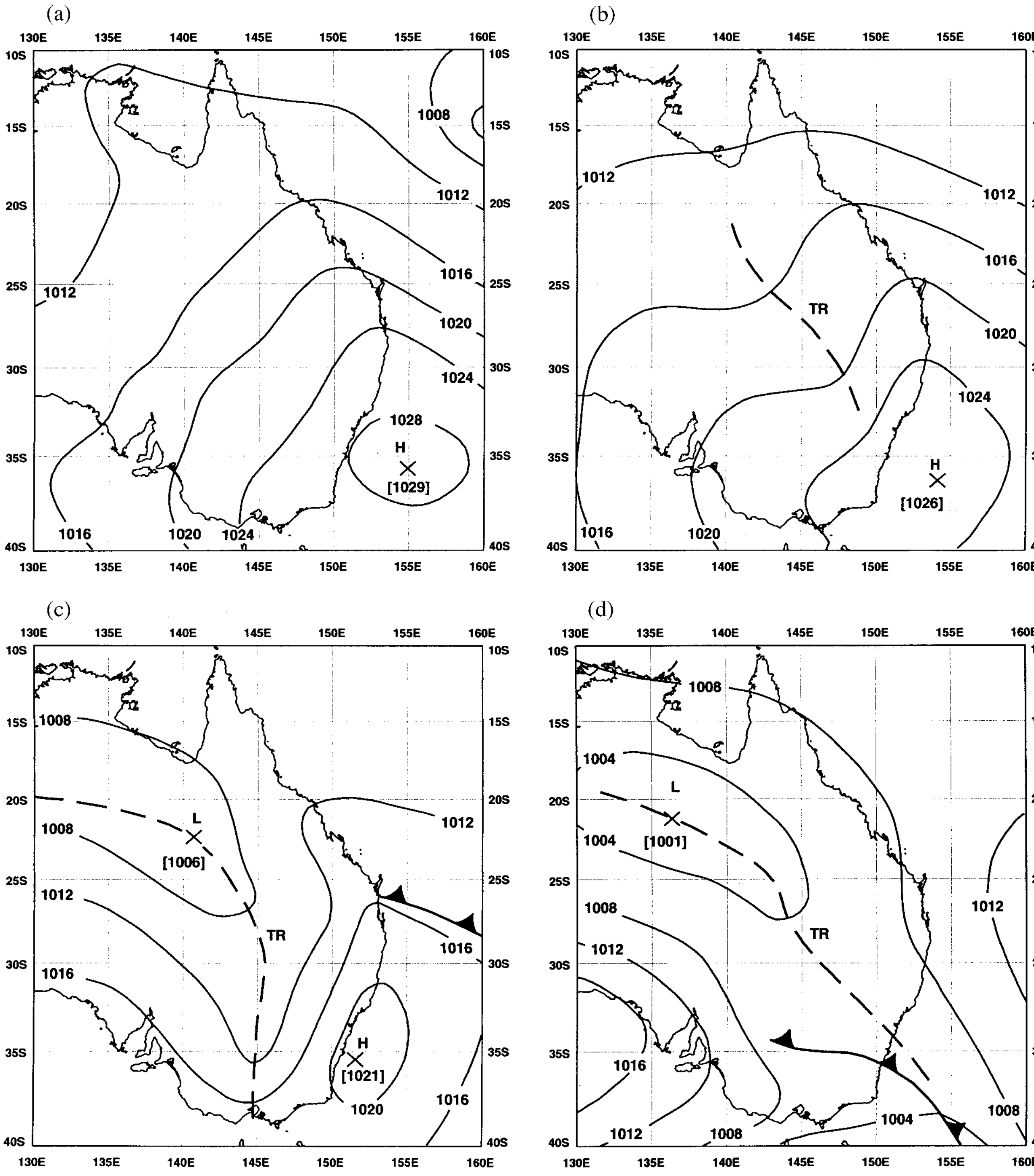

FIG. 3. SLP analysis illustrating the four main categories of warm season circulation patterns. (a) SLP analysis at 0000 UTC 4 Jan 1997 with marked coastal ridge linked to a strong anticyclone in the Tasman Sea. The inland trough is weak or nonexistent. (b) SLP analysis at 0000 UTC 23 Mar 1996 illustrating a marked coastal ridge and an inland trough with no heat low present. (c) SLP analysis at 0000 UTC 5 Jan 1990 with a dominant trough including a heat low and a relatively weak coastal ridge. (d) SLP analysis at 1200 UTC 22 Feb 1992 with an active monsoon low over northern Australia and a trough extending southeastward into NSW ahead of a weak front moving into the Tasman Sea.

TABLE 2. Percentage frequency of ridge and trough occurrences from November 1993 to April 1994 in the Queensland region at the three verifying latitudes. Total number of cases is in brackets.

	Trough		Ridge	
Nov 1993	59%	(106)	50%	(90)
Dec	65%	(121)	49%	(91)
Jan 1994	65%	(121)	72%	(133)
Feb	76%	(127)	70%	(117)
Mar	63%	(118)	52%	(96)
Apr	72%	(130)	58%	(105)

can reach over 70°C) and enhance the effect of the descent over the ranges, producing a quasi-permanent heat trough in those months (Leighton 1993). A closed circulation heat low is often present over northern Queensland but is very shallow, rarely extending above 1500 m.

a. Some definitions

The *near-coastal ridge* is defined, in this study, as an extension of the high-pressure area that stretches along or near the Queensland coast and is linked to an anticyclone, which is part of the subtropical ridge to the south. The coastal ridge on many occasions can develop initially in response to cold air advection into the Tasman Sea from the southwest with subsequent development of an anticyclone off the east coast of Australia. During the summer months the ridge might not always be in evidence or is very weak, particularly if a monsoon depression or tropical cyclone is in the Queensland region.

The *inland trough* is generally oriented parallel to the Queensland coast and ranges and, on occasion, is linked to a heat low over north Queensland. The Queensland heat low is part of the heat trough extending from Queensland to Western Australia and results from the intense heating that occurs over northern Australia prior to the onset of the wet northwest monsoon. Figure 3 illustrates the four main warm season circulation patterns associated with the coastal ridge and inland trough, and has been adapted from Sumner and Bonell (1986). Figure 3a is the case of a pronounced ridge on the east coast, with a weak or nonexistent inland trough. Figure 3b illustrates the case of a pronounced ridge on the east coast with an inland trough and with no heat low present; Fig. 3c shows a marked summer inland trough with an associated heat low. A coastal ridge is present but is weak in the Tropics; and, finally, Fig. 3d indicates a combined monsoon trough active over northern Australia and a summer inland trough linked to a prefrontal system in the south.

b. Statistics

The RA75 24-h forecasts of the ridge and trough locations were verified against the manual NMOC Melbourne analyses twice daily at 0000 and 1200 UTC during the period from 1 November 1993 to 30 April 1994. Verification of the longitudinal errors of the ridge whenever it was present were calculated at the latitudes of the following stations: Cairns (17°S, 146°E), Mackay (21.5°S, 149°E), and Brisbane (27.5°S, 153°E). These stations are part of the Australian Bureau of Meteorology's observing network with 3-h surface observations and 12-h upper-air wind and temperature observations. Trough verification points were at 20°S, 25°S, and 30°S, respectively, with these latitudes being located close to meteorological observing stations at Mount Isa (20.5°S, 139°E), Longreach (23.5°S, 144°E), Charleville (26.5°S, 146°E), and Moree (29.5°S, 149.5°E).

c. Statistical characteristics of the ridge–trough system

It is vital to obtain statistical information to help gain an understanding of the behavior of the ridge–trough system under investigation in this study. The tables below summarize the statistical properties of the ridge and the trough in relation to their occurrence and movement during the period 1 November 1993–30 April 1994 based on twice daily analyses at 0000 and 1200 UTC. Table 2 shows the monthly percentage frequency of occurrence of both the ridges and the troughs over the Queensland region at the three combined latitudes. The frequencies represented in this table imply that one feature (ridge or trough) evident at both 0000 and 1200 UTC and identified at all three locations is registered as six counts. In November, for example, there were 106 out of a possible 180 cases in which a ridge was evident at least at one of the three verifying latitudes on the Queensland coast. Similarly, there were 90 cases out of a possible 180 in which the inland trough was present.

As can be seen from Table 2 the frequency of ridges along the coast from Cairns to Brisbane is greater during the latter half of the study period. The inland trough reaches its peak frequency in January with minima in November and December. In the south of the region there was a rapid decrease in trough occurrence during April. In Table 3 a breakdown of the frequencies of each type of movement of the ridge and the trough over a 24-h period is made into the three categories of progression, retrogression, and quasi-stationary. A ridge or trough is defined as progressive if its movement over a 24-h period is eastward by greater than 1° of longitude and conversely if the movement is westward by greater than 1° of longitude, it is then retrogressive. There are several features of note. Approximately half of the ridge movements are in the quasi-stationary category (within 1° long of the previous 24-h analyzed location), particularly on the north and central coasts of Queensland. The ridge in the south is more likely to be progressive than retrogressive, being closer to the mobile cells of high pressure. During the period from 1 November 1993 to 28 February 1994 the southern part of the ridge tends to progress into the Tasman Sea while the northern por-

TABLE 3a. The 24-h movement statistics of the near-coastal ridge from November 1993 to April 1994 at Cairns, Mackay, and Brisbane.

Ridge	Progression	Retrogression	Quasi-stationary
1994 Nov 17°S	2	5	15
21°S	8	7	8
28°S	12	3	7
Dec 17°S	10	8	18
21°S	12	14	11
28°S	16	7	10
1994 Jan 17°S	11	8	14
21°S	7	6	21
28°S	12	11	16
Feb 17°S	5	6	19
21°S	7	9	23
28°S	19	13	10
Mar 17°S	6	6	25
21°S	6	9	23
28°S	9	8	22
21°S	10	14	19
Apr 17°S	4	7	33
21°S	10	14	19
28°S	9	8	16
Total 17°S	38 19%	40 20%	124 61%
21°S	50 23%	59 28%	105 49%
28°S	77 37%	50 24%	81 39%

TABLE 3b. The 24-h movement statistics of the inland trough from November 1993 to April 1994 at 20°, 25°, and 30°S.

Trough	Progression	Retrogression	Quasi-stationary
1993 Nov 20°S	4	9	4
25°S	6	9	2
30°S	7	6	1
Dec 20°S	5	8	2
25°S	6	8	4
30°S	8	4	3
1994 Jan 20°S	11	12	9
25°S	20	17	8
30°S	14	14	9
Feb 20°S	11	4	8
25°S	17	10	6
30°S	17	9	4
Mar 20°S	6	9	9
25°S	12	14	3
30°S	4	14	2
Apr 20°S	10	12	5
25°S	8	15	3
30°S	3	7	1
Total 20°S	47 34%	54 39%	37 27%
25°S	69 41%	73 43%	26 16%
30°S	53 42%	54 43%	20 15%

tion, over central and north Queensland tends to show little movement on or near the coast. During March and April 1994 the ridge tended to remain quasi-stationary along the entire Queensland coast. The trough system shows much greater mobility than the ridge with over 80% of cases showing either progression or retrogression. Progression of the trough dominates in the south from November to February due to the influence of southern frontal systems but during March and April retrogression is predominant at all latitudes.

We note in passing that these statistics were taken during a relatively inactive phase of the protracted El Niño event of 1991–95 (Trenberth 1997). There is no evidence to suggest that they are not representative of the ‘‘normal’’ synoptic patterns over northeastern Aus-

TABLE 4a. The 24-h prediction errors in long (°) of the near-coastal ridge in RA75 and HLAM at Cairns, Mackay, and Brisbane.

	Table of ridge errors RA75 and HLAM			
	RA75 errors (°)		HLAM errors (°)	
	Avg	Std dev	Avg	Std dev
1993 Nov 17°S	−1.2	1.5	0.2	0.9
21°S	−1.7	1.5	−0.1	1.2
28°S	−1.4	1.3	−0.5	1.6
Dec 17°S	−1.2	0.8	0.3	1.2
21°S	−2.4	1.7	0.4	1.2
28°S	−2.8	1.7	−0.3	1.2
1994 Jan 17°S	−2.4	2.1	0.3	1.2
21°S	−2.3	1.9	0.2	1.0
28°S	−1.8	1.0	−0.2	1.0
Feb 17°S	−1.8	1.8	−0.6	1.0
21°S	−2.4	1.3	−0.4	1.0
28°S	−2.6	1.4	−0.7	1.0
Mar 17°S	−0.6	1.4	0.2	0.6
21°S	−2.0	1.5	0	1.0
28°S	−3.3	1.8	−0.9	1.0
Apr 17°S	−0.7	1.2	0.3	0.9
21°S	−1.6	1.1	0	1.1
28°S	−2.2	1.4	−0.4	1.0
Mean 17°S	−1.3	0.62	0.1	0.32
21°S	−2.1	0.32	0	0.25
28°S	−2.4	0.63	−0.5	0.24

TABLE 4b. The 24-h prediction errors in long (°) of the inland trough in RA75 and HLAM at 20°, 25°, and 30°S.

	Table of trough errors RA75 and HLAM			
	RA75 errors (°)		HLAM errors (°)	
	Avg	Std dev	Avg	Std dev
1993 Nov 20°S	−2.3	1.9	−0.9	0.9
25°S	−1.8	3.0	−1.0	1.1
30°S	−1.7	2.0	−0.8	1.2
Dec 20°S	−3.5	3.0	−1.2	1.4
25°S	−2.8	3.2	−1.0	1.5
30°S	−0.7	2.2	−1.4	1.5
1994 Jan 20°S	−2.0	3.0	−0.3	1.2
25°S	−1.0	1.7	−0.4	1.3
30°S	−1.3	1.9	−0.5	1.2
Feb 20°S	−3.0	2.8	−0.4	1.3
25°S	−3.2	3.0	−0.9	1.9
30°S	−1.8	2.8	−1.0	1.5
Mar 20°S	−1.0	1.9	−0.2	1.4
25°S	−2.1	2.6	−1.2	1.7
30°S	−1.6	2.1	−1.3	1.0
Apr 20°S	−1.3	1.7	−0.8	1.5
25°S	−2.1	2.1	−1.0	1.6
30°S	−0.8	1.7	−1.0	1.6
Mean 20°S	−2.2	0.88	−0.6	0.34
25°S	−2.2	0.70	−0.9	0.25
30°S	−1.3	0.43	−1.0	0.30

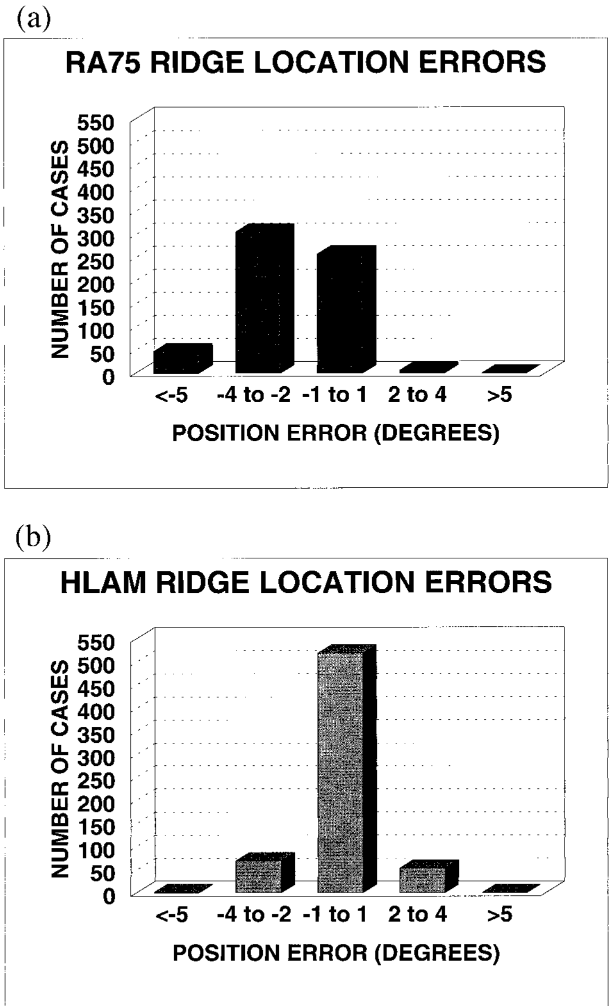

FIG. 4. (a) Distribution of the 24-h forecast errors in long (°) of the near-coastal ridge in RA75 at the combined three verifying locations during the period November 1993–April 1994. (b) Distribution of the 24-h forecast errors in long (°) of the near-coastal ridge in HLAM (75-km resolution) at the combined three verifying locations during the period November 1993–April 1994.

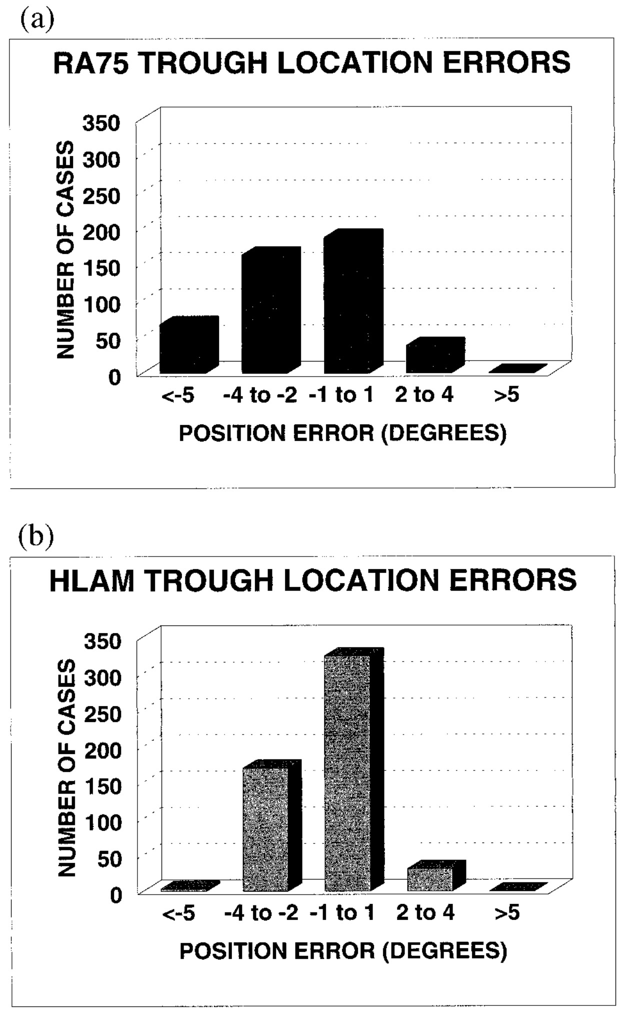

FIG. 5. (a) Distribution of the 24-h forecast errors in long (°) of the inland trough in RA75 at the combined three verifying locations during the period November 1993–April 1994. (b) Distribution of the 24-h forecast errors in long (°) of the inland trough in HLAM (75-km resolution) at the combined three verifying locations during the period November 1993–April 1994.

tralia during the warm season. While the ridge–trough system might vary in strength, it is a quasi-permanent feature of the surface circulation during the warmer months.

4. Results

The RA75 model was run operationally twice daily as the Australian Bureau of Meteorology's regional model. The HLAM also was run twice daily on the same datasets, which were extracted from the bureau's archives. The model comparison therefore is ‘‘clean'' in that identical initial and boundary conditions were used by RA75 and HLAM. During the test period from 1 November 1993 to 30 April 1994, out of a total of more than 360 forecasts, the coastal ridging was identifiable on over 200 cases and the inland trough on over 120 cases.

a. Verification of the forecasts

The SLP charts used to verify both RA75 and HLAM forecasts, which were the Australian region manual analyses from the National Meteorological Operations Centre in Melbourne, were carefully scrutinized to determine the ridge and trough locations. The analyses were available every 3 h, thereby allowing time continuity in the estimates of the positions and the calculation of the errors. RA75 and HLAM were compared by evaluating the longitudinal errors in the location of the coastal ridge and the inland trough, whenever they were present. Troughs were identified as the line of pres-

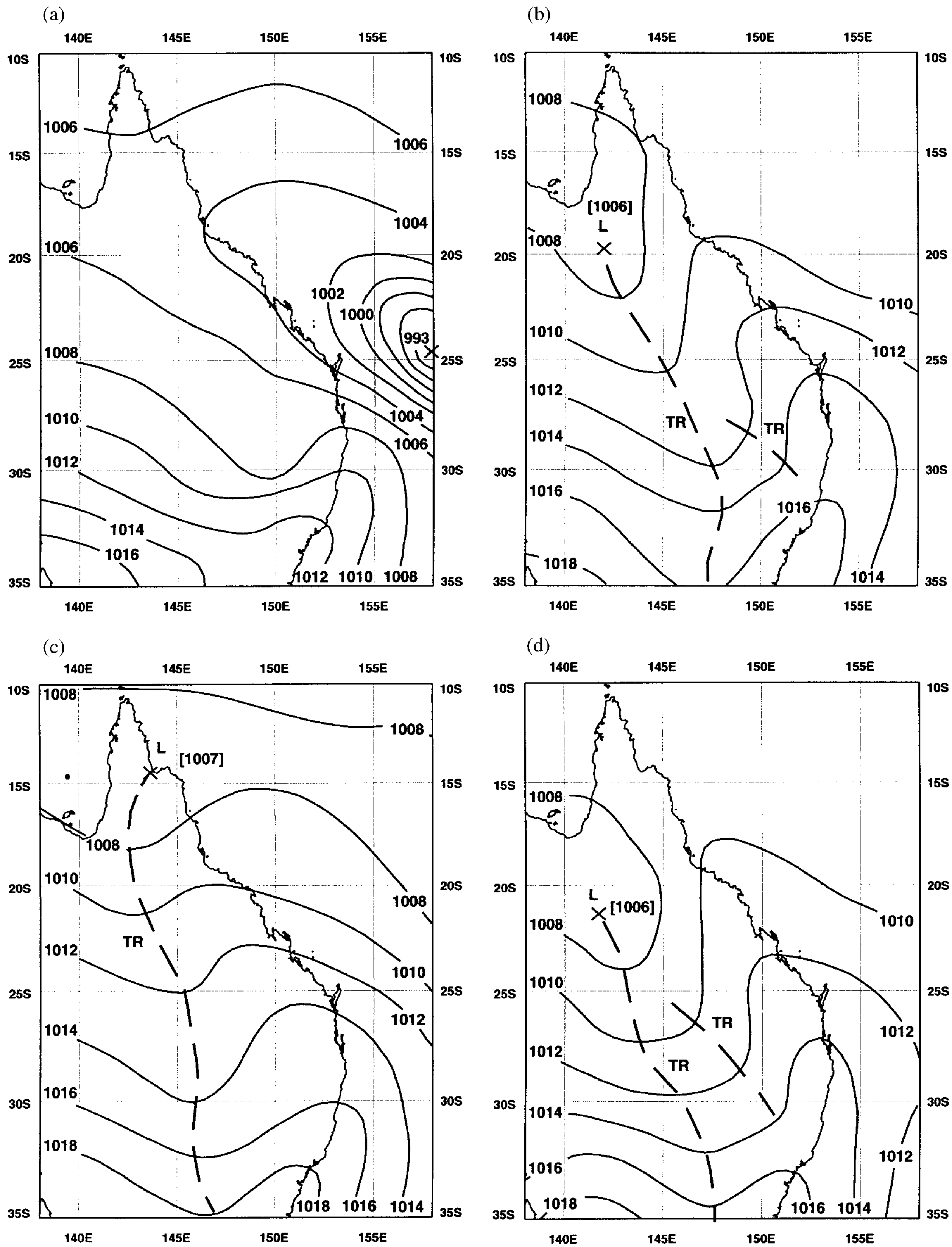

FIG. 6. (a) Initial (numerical NMOC) SLP analysis 0000 UTC 24 Dec 1995. Note the deep low east of the Queensland coast with only a weak coastal ridge in the south of the domain and no evidence of an inland trough. (b) Verifying (numerical NMOC) SLP analysis 0000

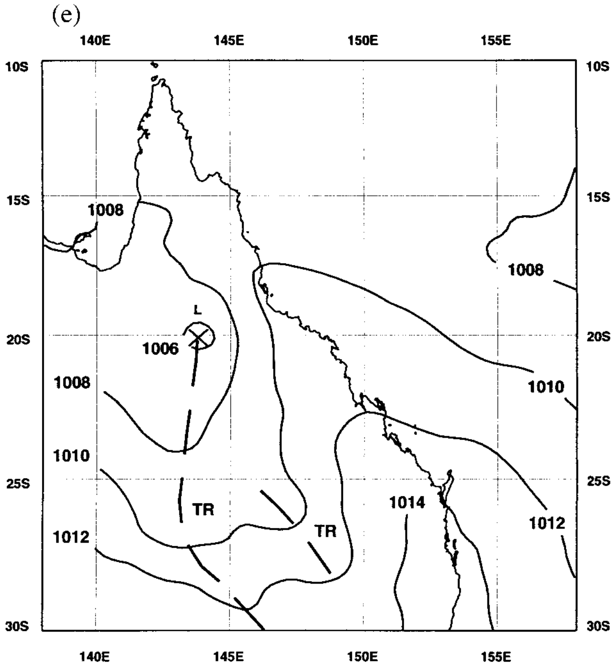

FIG. 6. (*Continued*) UTC 25 Dec 1995. The near-coastal ridge has now become well developed and the inland trough and heat low are clearly evident. (c) The RA75 SLP 24-h forecast for 0000 UTC 25 Dec 1995. (d) The HLAM (75-km resolution) SLP 24-h forecast for 0000 UTC 25 Dec 1995. (e) The HLAM (15-km high resolution) SLP 24-h forecast for 0000 UTC 25 Dec 1995.

sure minima combined with surface and gradient wind data whenever possible. On occasions the trough was very broad in anticyclonically dominated flow as shown in Fig. 3a, with relatively low daytime temperatures as in early autumn. Consequently, trough locations could not be specified and therefore were not included in the statistics. Ridge locations were based also on the SLP pressure fields combined with surface and gradient wind directions.

b. Ridge locations

Table 4a shows the monthly distribution of the longitudinal errors of RA75 and HLAM at Cairns, Mackay, and Brisbane. Forecasts are regarded as being in error if the forecast error is greater than 1° long.

In Tables 4a and 4b the following points should be noted. There is a westward bias in the location of the coastal ridge especially in RA75. This bias is generally larger in the south than in the north; over 30% of RA75 errors are 2° long or greater. HLAM errors are clearly smaller than those of RA75, with a predominance of small westward errors. The variability in the RA75 forecasts is much greater than the HLAM forecasts.

Figures 4a and 4b show the distribution of ridge errors in RA75 and HLAM. The distribution of ridge errors in RA75 is skewed to the west with over 50% of cases showing a westward bias. Approximately 40% of the RA75 forecasts can be considered as ''correct.'' In contrast, HLAM has a much smaller westward bias in approximately 10% of the cases, with some eastward biases as well. Over 80% of HLAM forecasts can be considered as correct. A chi-squared test of statistical significance was applied to the success rate of both models in predicting correctly the ridge locations at the three coastal stations. It was found that the HLAM forecasts were superior to RA75 at the 99.9% confidence level.

c. Trough locations

Table 4b shows the monthly distribution of the longitudinal errors of RA75 and HLAM at latitudes 20°, 25°, and 30°S. Forecasts are regarded as being in error if the trough location error is greater than plus or minus 1° long. Table 4b indicates the following: westward errors predominate at all three latitudes of the inland trough forecasts of RA75 with the greatest errors generally in the north; on average, HLAM errors are clearly smaller but there is still a westward bias evident, as in December and April in the south, when the mean errors were greater in HLAM than in RA75. Nevertheless, there was a greater variability of errors in the RA75 forecasts throughout the period. Figures 5a and 5b show the distribution of trough errors in RA75 and HLAM. Over 50% of cases in RA75 have a westward error and 40% of forecasts can be considered to be correct. Approximately 60% of HLAM forecasts can be considered to be correct and the westward error percentage is about 30%. A chi-squared test of statistical significance was again applied to the success rate of both models and the HLAM predictions were superior to the RA75 predictions at the 99.9% confidence level.

5. Case studies and sensitivity studies

It was found in section 4 that the HLAM run at 75-km resolution, despite being significantly superior to the RA75 model, still retains a westward bias in the forecast location of the coastal ridge and even more so in the inland trough. It was hypothesised that the improvement of HLAM over RA75 was due to enhanced orography and surface heating in the physics of HLAM. The obvious further test of the hypothesis is to assess whether the HLAM errors are further diminished by increasing the HLAM resolution from the modest 75 km, 17 levels to 15 km and 31 levels. The model was run on three very different cases to test our hypothesis as fully as possible.

The cases chosen for investigation all had clear errors in the depiction of the ridge–trough system in the operational 24-h forecasts. These three case studies included one in which RA75 and two in which LAPS were the operational models. This arose from the fact that the operational initial and forecast fields are now available only from 1995 onward. Also of great im-

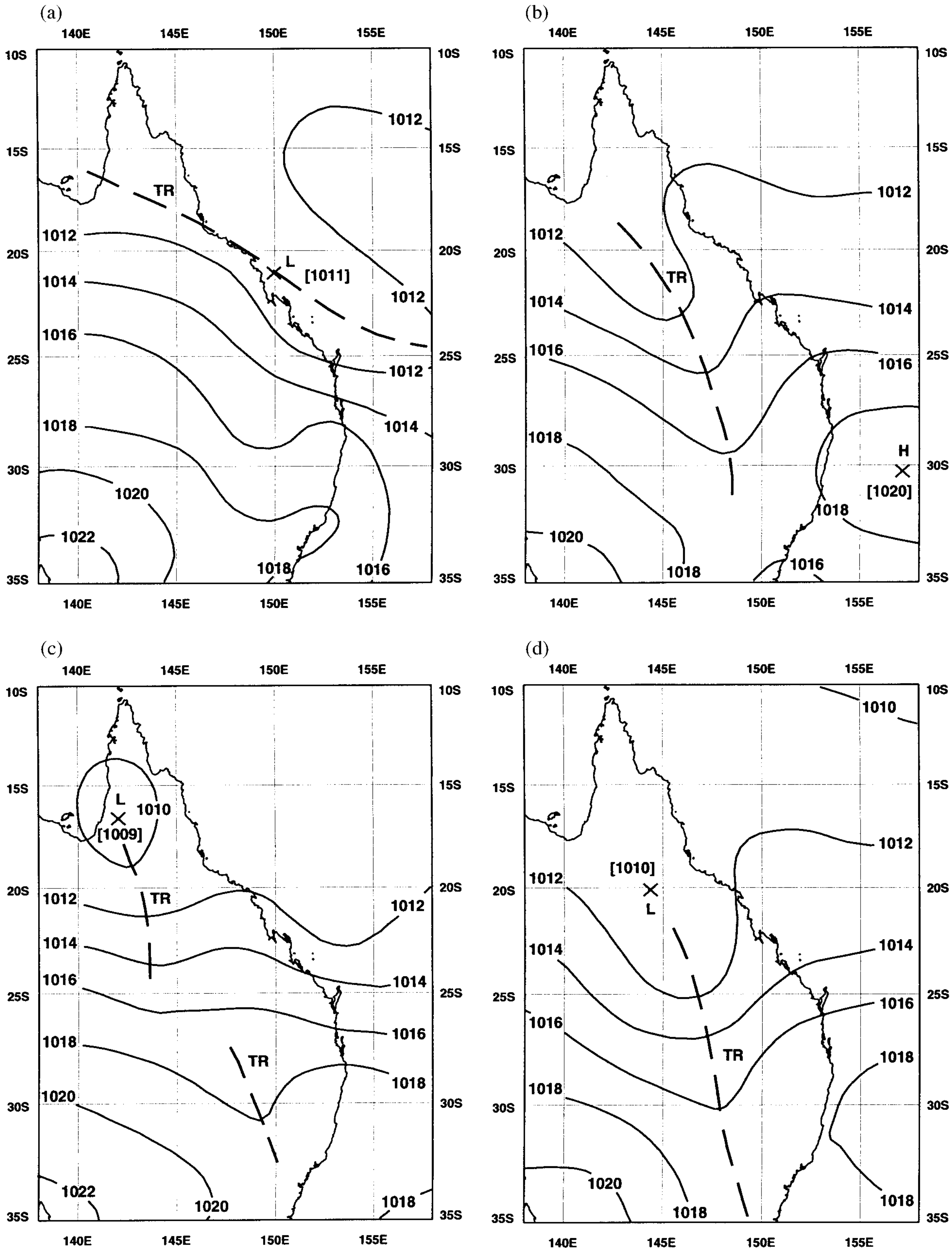

FIG. 7. (a) Initial (numerical NMOC) SLP analysis 0000 UTC 19 Nov 1996. The coastal ridge and inland trough are only weakly evident in the south of the domain. (b) Verifying (numerical NMOC) SLP analysis 0000 UTC 20 Nov 1996. The ridge while not strong is evident

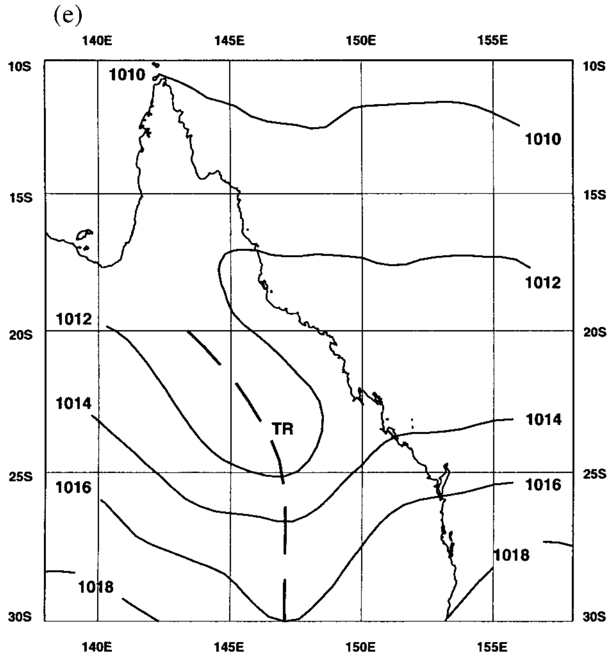

FIG. 7. (*Continued*) along the entire old coast and a weak high has become established off the NSW coast. (c) The LAPS (75-km resolution)SLP 24-h forecast for 0000 UTC 20 Nov 1996. (d) The HLAM (75-km resolution) 24-h forecast for 0000 UTC 20 Nov 1996. (e) The HLAM (15-km high resolution) SLP 24-h forecast for 0000 UTC 20 Nov 1996.

portance was that the synoptic situation was mobile rather than static. That is, the pressure fields over eastern Australia and the Tasman Sea changed markedly during the 24-h forecast period. This is seen as a test of the ability of the analysis–prognosis system to forecast correctly a rapidly developing ridge–trough situation where there is little evidence of these features in the initial fields. The manual analyses at NMOC, Melbourne, were used for verification.

a. *Case 1: 0000 UTC 24 December 1995*

This situation as shown in Fig. 6a reveals a deep mobile low-pressure system with a central pressure of 993 hPa in the Coral Sea. There is a ridge pushing northward along the coast of New South Wales into southern Queensland extending from a large anticyclone south of Western Australia. The low-pressure system over the Coral Sea is the remnants of Tropical Cyclone Gertie, which traversed the Australian continent as a monsoon depression having crossed the northwest coast of Western Australia on 20 December 1995. During the forecast period from 0000 UTC 24 December to 0000 UTC 25 December the Coral Sea low continued to progress rapidly eastward at over 25 kt (about 13 m s^{-1}) toward New Caledonia thereby allowing the coastal ridging to penetrate farther north into the Tropics. At the same time the inland heat trough with its associated heat low formed very rapidly, as shown in Fig. 6b. Daytime maximum screen temperatures in the region of the trough were in the mid- to high 30°Cs, with strong dewpoint discontinuities across the trough.

1) THE 24-H RA75 FORECAST VALID AT 0000 UTC 25 DECEMBER 1995

As can be seen in Fig. 6c, the RA75 prediction of the coastal ridge is far too broad and is several degrees out to sea, north of latitude 20°S. On the central Queensland coast between 20° and about 25°S, the ridge has a westward bias compared to the verifying analysis. Only in the south at Brisbane's latitude is the ridge location correctly forecast. RA75, although giving reasonable guidance in location of the inland trough, gives a poor representation of its amplitude. Moreover, the heat low is incorrectly forecast to be located over the east coast of Cape York Peninsula instead of being positioned some 600 km southwest over the interior.

2) THE 24-H HLAM FORECASTS FOR 0000 UTC 25 DECEMBER 1995

(i) The 75-km resolution HLAM prediction

As is shown in Fig. 6d the 75-km resolution HLAM correctly forecasts the near-coastal ridge to be much sharper than the RA75 prediction. However, it also locates the ridge too far to the east in the northern part of the domain. The inland trough is well forecast and also has good amplitude when compared with the verifying analysis. The associated heat low is far more realistically positioned over the interior and its strength also is well predicted. Note that there is a hint of a double-trough structure that is evident in the verifying analysis.

(ii) The 15-km resolution HLAM prediction

As can be seen in Fig. 6e the 15-km resolution HLAM forecast, which for computational reasons is displayed over the Queensland region only, is a notable improvement on the 75-km forecast. The near-coastal ridge is now very well located, with good amplitude and with almost no error at the three latitudes at which forecast verifications were carried out. Moreover, the double-trough structure that was suggested in the 75-km HLAM forecast is now clearly present and of good location and amplitude although there is a small eastward error in the position of the heat low.

b. *Case 2: 0000 UTC 19 November 1996*

In Fig. 7a the SLP analysis for 0000 UTC 19 November 1996 shows a ridge across southeastern Australia extending from an anticyclone centered south of Western Australia. The Queensland Tropics are under

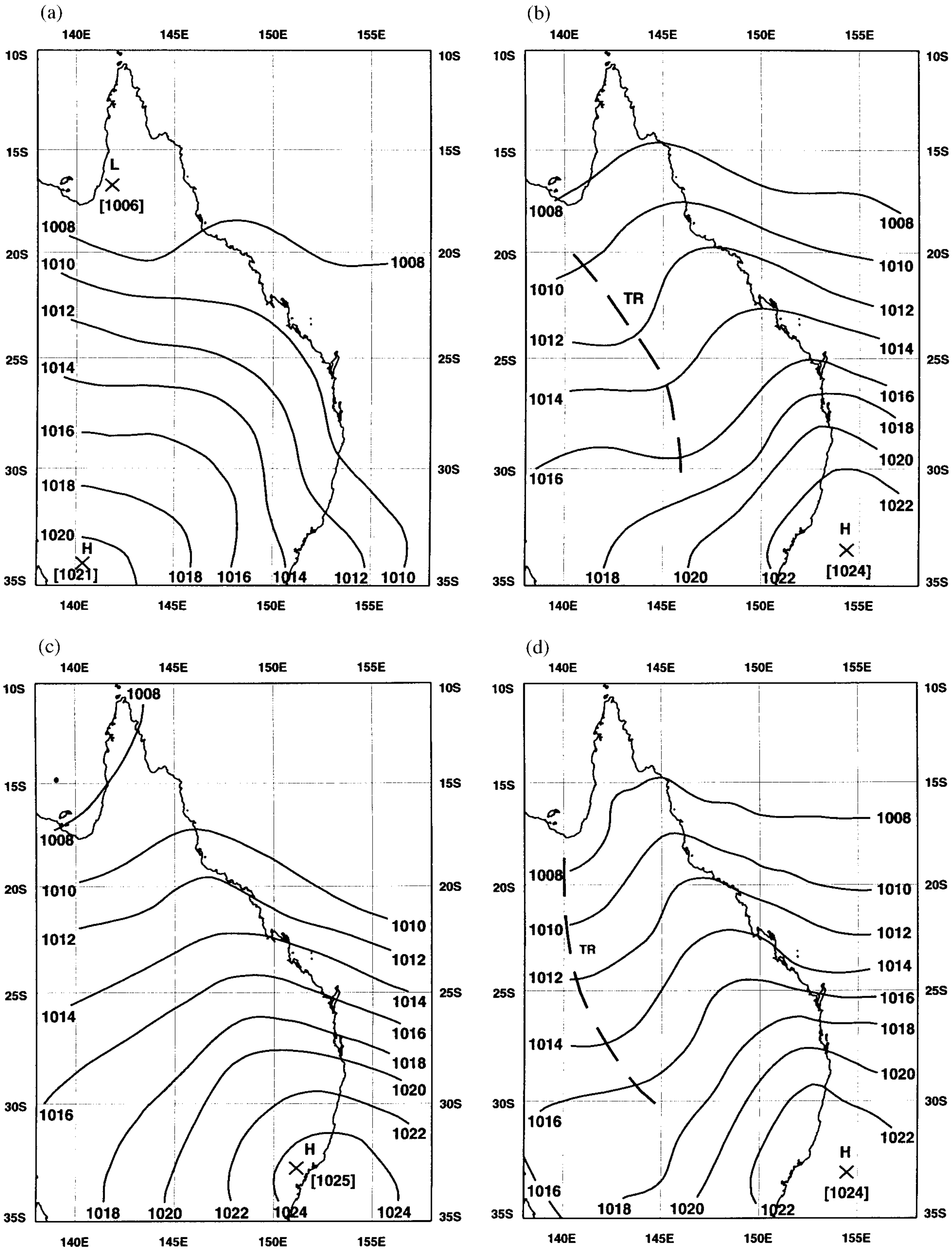

FIG. 8. (a) The initial (numerical NMOC) SLP analysis for 0000 UTC 20 Dec 1996. Broad anticyclonic flow is evident over Queensland with a weak heat low over the southern Cape York Peninsula. The coastal ridge is present only near Cairns. (b) Verifying (numerical NMOC)

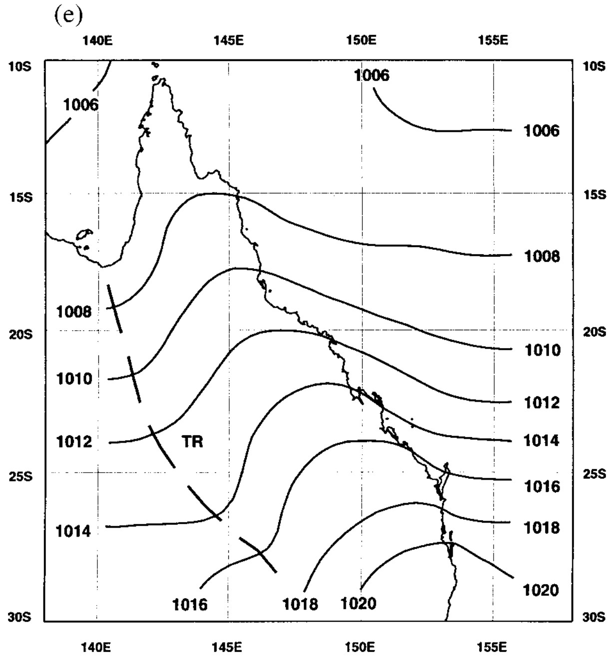

FIG. 8. (*Continued*) SLP analysis for 0000 UTC 21 Dec 1996. The coastal ridge is now clearly evident and a high cell has formed off the east coast. A broad inland trough extends from 20° to south of 30°S. (c) The LAPS (75-km resolution) SLP 24-h forecast valid 0000 UTC 21 Dec 1996. (d) The HLAM (75-km resolution) SLP 24-h forecast valid 0000 UTC 21 Dec 1996. (e) The HLAM (15-km high resolution) SLP 24-h forecast valid 0000 UTC 21 Dec 1996.

the influence of a southeast–northwest-oriented trough in the easterlies, which is the northern extension of a frontal system associated with a deep low (975 hPa) over New Zealand. Once again the situation is not static over the eastern half of the continent, so that by 0000 UTC 20 November, as shown in Fig 7b, the trough over the Coral Sea has weakened considerably and the inland trough has developed rapidly. The ridge along the Queensland coast is evident particularly in the north extending from a weak high-pressure cell of 1021 hPa in the Tasman Sea.

1) THE 24-H LAPS FORECAST VALID AT 0000 UTC 20 NOVEMBER 1996

The LAPS forecast as shown in Fig. 7c fails in several ways to match the verifying analysis of Fig. 7b. The tropical dip, which is the remnants of the trough over the Coral Sea, has been overemphasized off the central coast. Consequently, the near-coastal ridge is poorly represented south of 20°S with a westward bias of about 2° long. Additionally, the inland trough has poor amplitude so that at 25°S its location is indeterminate. The strength of the 1020-hPa cell off the NSW coast is slightly underestimated.

2) THE 24-H HLAM FORECASTS VALID AT 0000 UTC 20 NOVEMBER 1996

(i) The 75-km HLAM forecast

The HLAM forecast at 75 km (Fig. 7d) locates the coastal ridge well although there is a slight eastward error in the north. The inland trough is correctly depicted with very good amplitude but there is a westward bias in the south. Weak anticyclonic curvature is shown in the Coral Sea, which does not verify well with the NMOC analysis of Fig. 7b. Overall, the HLAM forecast at 75 km is superior to the LAPS forecast in its depiction of the near-coastal ridge and the rapid development of the inland trough.

(ii) The 15-km HLAM forecast

The positive features of the 15 km-resolution HLAM forecast are that errors in the ridge–trough pattern have been greatly reduced and are very small as in Fig. 7e. For example, the near-coastal ridge is well placed with very good amplitude at all latitudes sampled. The heat trough location and amplitude also are very well predicted, being within 1° long of the analyzed position shown in Fig. 7b. Also there is no indication of the spurious remnant trough over the north Tasman Sea at 24°S as in the LAPS forecast. However, the unsmoothed forecast does show some sign of grid-scale noise, as no attempt has been made to filter the HLAM forecasts.

c. Case study 3: 0000 UTC 20 December 1996

The main features in this case are the broad southeast trades over Queensland equatorward of an anticyclone centered near Adelaide (Fig. 8a). A weak inland trough has formed at 142°E and is associated with a weak (1006 hPa) heat low over southern Cape York Peninsula. As seen in Fig. 8b, by 0000 UTC 21 December the high-pressure cell near Adelaide had intensified rapidly as it moved off the NSW coast, resulting in rapid ridge formation along the entire Queensland coast. By this time the inland trough had become broad and well developed as inland daytime screen temperatures rose to the mid- to high 30°Cs.

1) THE 24-H LAPS FORECAST VALID AT 0000 UTC 21 DECEMBER 1996

The features of the LAPS forecast as depicted in Fig. 8c are as follows: the amplitude of the near-coastal ridging is good but the location is too far inland with the greatest westward bias being in the south, the inland trough is virtually nonexistent with a very pronounced westward bias of approximately 5° of longitude in the north, the high-pressure cell is overestimated by 2 hPa and is incorrectly located inland instead of about 5° farther east over the Tasman Sea, the cyclonic curvature over the north Tasman Sea is well captured, and the location of both the coastal ridge and the inland trough are too far inland.

2) THE 24-H HLAM FORECASTS VALID AT 0000 UTC 21 DECEMBER 1996

(i) The 75-km HLAM forecast

The rapid coastal ridging has been captured very well by the 75-km HLAM model, with small location and amplitude errors (Fig. 8d). The broad inland trough has a westward bias but is well defined and is a superior forecast to the operational model. Weak cyclonic curvature over the north Tasman Sea is predicted quite well, as is the anticyclone off the NSW coast.

(ii) The 15-km HLAM forecast

The very high-resolution HLAM forecast is an excellent 24-h prediction, correctly showing the near-coastal ridge along the entire Queensland coast, with cyclonic curvature in the onshore flow (Fig. 8e). The inland trough also is well predicted, being within 1° of longitude from the analyzed position.

d. Sensitivity studies

To confirm further the key role of adequate representation of orography and surface heating in the models, two of the case studies above were run with the HLAM model (at 75-km resolution) using the surface temperature predictions from LAPS. The initial surface temperature in HLAM, as a lower boundary condition, was held the same as in the LAPS forecasts in both of the sensitivity studies. The HLAM model showed no apparent problems with this approach, possibly because the temperatures were applied every hour and smoothed in time to be inserted at each time step. The cases are presented in turn below, but first it is essential to show the different orography and surface temperatures in the two models run at the same nominal resolution of approximately 75 km.

1) THE ROLE OF OROGRAPHY AND SURFACE TEMPERATURE

Figures 9a and 9b show the orography for HLAM and LAPS, respectively, and it is immediately obvious how much additional detail is present in the HLAM orography. The difference can only result from far less smoothing being applied to the HLAM orography as both orography datasets come from high-resolution basic datasets. It is clear from simple dynamical arguments (see, e.g., Holton 1992, 98–102) that the prevailing easterly flow will be affected more by the HLAM orography. In addition, the LAPS orography will produce a ridge that is of smaller amplitude and is shifted westward as the maximum orographic height is considerably lower, and farther west, and the coastal gradient is weaker than in the more realistic HLAM orography. In Fig. 10 the corresponding surface temperatures are shown from the two forecasts in cases 2 and 3 above. Figure 10a shows the HLAM surface temperature forecast at 0500 UTC 19 November 1996 and Fig. 10b is the corresponding LAPS forecast at the same time, which is approximately the time of maximum insolation over eastern and central Australia. There is a striking difference in the two surface temperature fields. The HLAM surface temperature fields are realistic with maxima in the northeast and northwest of the Australian continent, the location of the heat lows. The actual values of mid-50°Cs are also close to the known values at this time of the year. In contrast, the LAPS forecast surface temperatures are only in the mid-30°Cs and are approximately 20°C too low in the region of interest. In fact they are very similar to the maximum *screen* temperatures recorded in the region that day. The HLAM surface temperatures also show strong coastal gradients at 0500 UTC whereas the LAPS surface temperatures exhibit almost no contrast. Figures 10c and 10d are the forecast surface temperatures at 0500 UTC 21 December 1996 and again the HLAM values are realistic whereas the LAPS forecast surface temperatures are again far too low and consequently unrealistic.

2) THE SENSITIVITY STUDIES

As mentioned previously, two experiments were carried out using the HLAM orography described above, but with HLAM surface temperatures being replaced by those in LAPS for cases 2 and 3 in sections 5b and 5c above.

(i) Sensitivity study 1: 0000 UTC 19 November 1996

Results from a 24-h forecast are shown below. The field of major interest here is the SLP chart at 24 h (Fig. 11a), which shows the impact of the altered surface temperatures on the ridge–trough forecasts. The important comparisons to be made are the SLP fields in Figs. 7c, 7d, and 11a. These forecasts are, respectively, the standard 75-km LAPS forecast, the standard 75-km HLAM forecast, and the HLAM forecast with the LAPS surface temperature field but retaining the HLAM orography. The results are quite conclusive in their support of the argument that realistic surface temperature forecasts and the use of more detailed orography are critical to the accurate forecasting of the ridge–trough system. The pressures along the coast in the easterly flow in HLAM are barely affected in Fig. 11a and are close to that of Fig. 7d, although there are slight changes in the anticyclonic curvature of the onshore flow. However, the trough has been weakened considerably and is not evident south of 25°S. It is also located westward of the HLAM forecast shown in Fig. 7d. Moreover, the heat

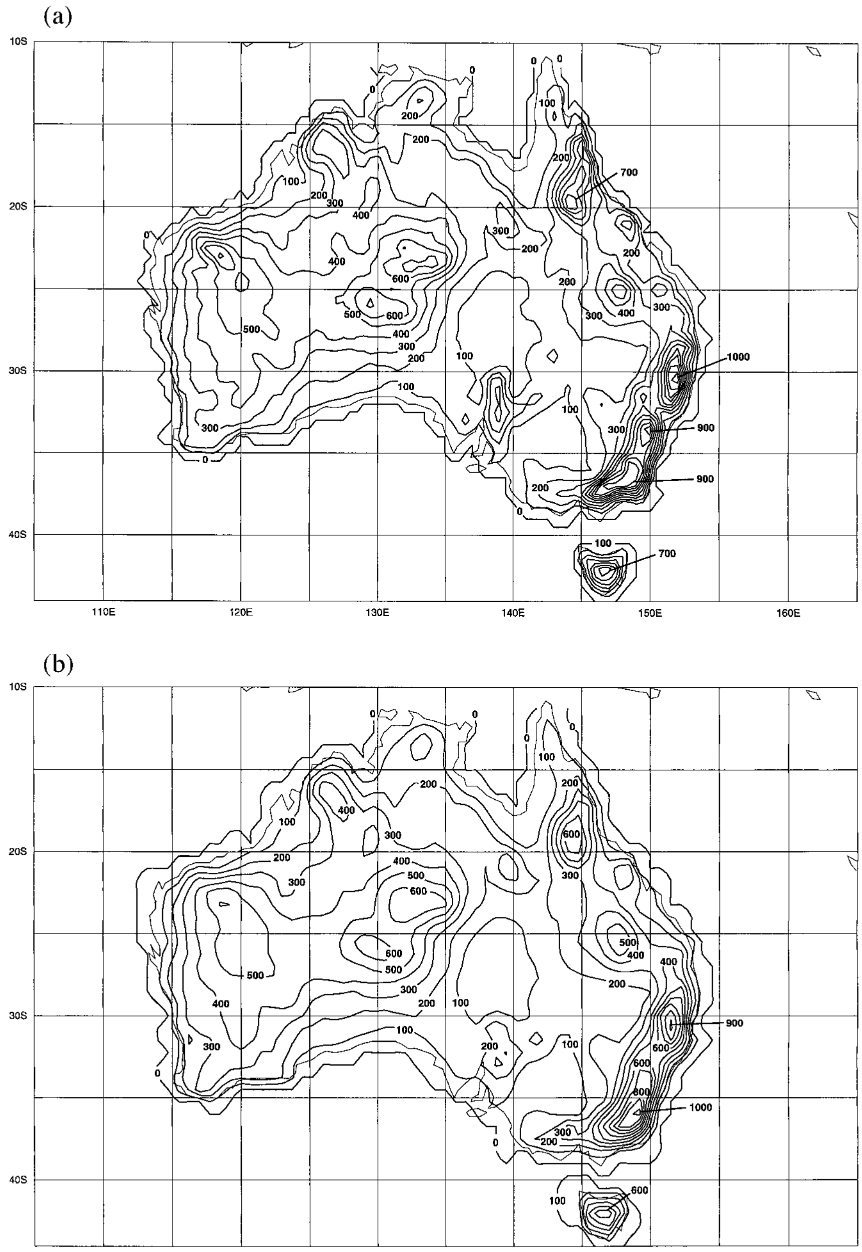

FIG. 9. (a) The HLAM orography at 100-m contour interval. (b) The LAPS orography at 100-m contour interval.

low in the northern end of the trough has shifted to Cape York Peninsula and is in a very similar location to the LAPS forecast of Fig. 7c.

(ii) Sensitivity study 2: 0000 UTC 20 December 1996

This is a repeat of sensitivity study 1 except that it is for another event, case study 3 of section 5c. The important figures to be compared here are Figs. 8c, 8d, and 11b, which show the same pattern as in the previous sensitivity experiment. Figure 11b shows the 24-h forecast of the SLP for HLAM valid at 0000 UTC 21 December 1996. The result is similar to sensitivity study 1. The ridge in Fig. 11b is little changed from the HLAM forecast shown in Fig. 8d, as the HLAM orography is used in both forecasts. However, there is a clear degradation in the definition of the trough, given the far lower forecast surface temperatures from LAPS.

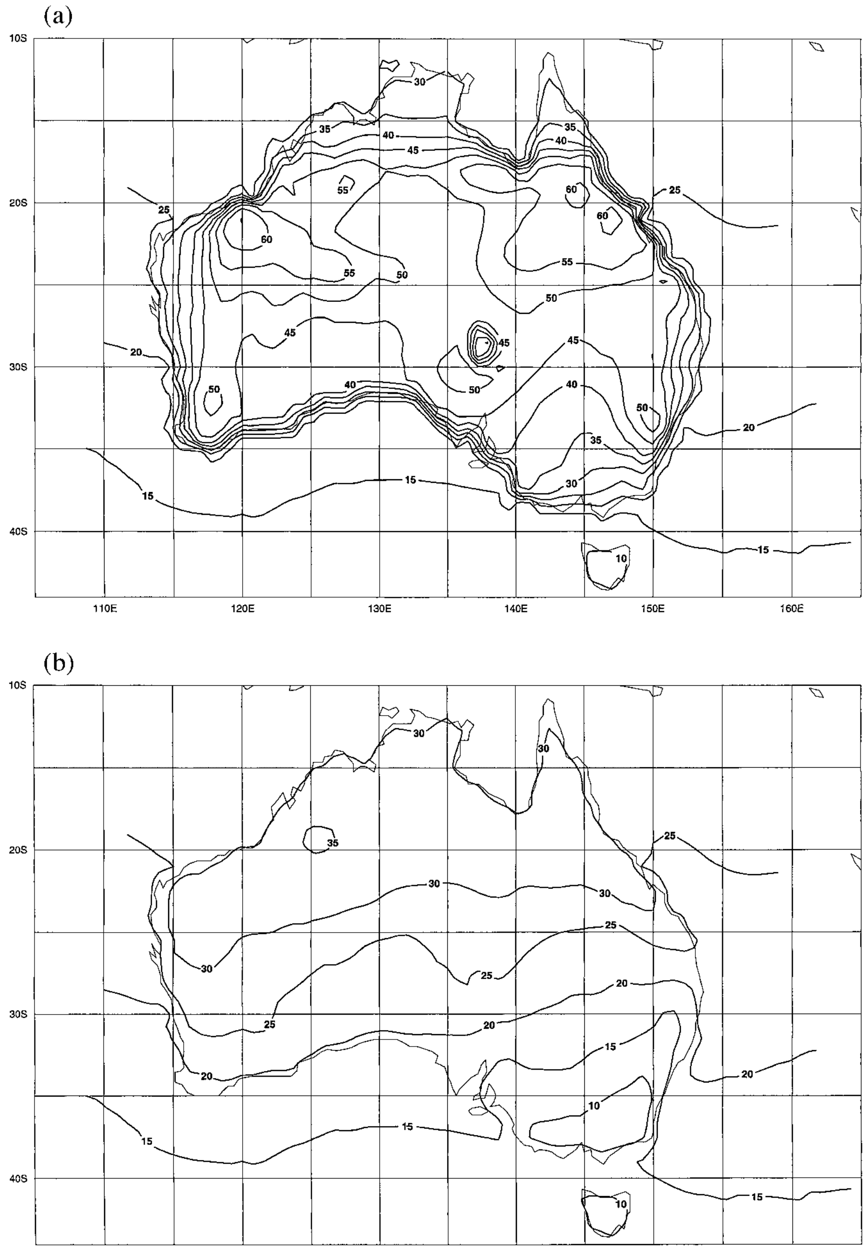

FIG. 10. (a) The forecast surface temperature at 0500 UTC from HLAM, for sensitivity case 1. (b) The forecast surface temperature at 0500 UTC from LAPS, for sensitivity case 1. (c) The forecast surface temperature at 0500 UTC from HLAM, for sensitivity case 2.

6. Discussion and conclusions

This study had as its focus a significant forecasting problem over northeastern Australia that has been identified throughout the history of operational NWP in Australia. Stated briefly, the problem is a significant westward displacement in the coastal ridge–inland trough system over eastern Queensland and a frequent underrepresentation of the inland trough. The aims of the study were threefold: first, to quantify the location errors in both the ridge and the trough; second, to identify the source or sources of the problem; and third, to confirm the diagnosis through both a long series of more advanced model runs and some carefully selected case and sensitivity studies. The first aim was achieved by evaluating the Australian Bureau of Meteorology's operational regional model over a total of more than 350 forecasts during the period 1 November 1993 to 30 April 1994. Although this model has since been replaced, it was operational up until July 1996 and the replacement model, which is run at the same horizontal

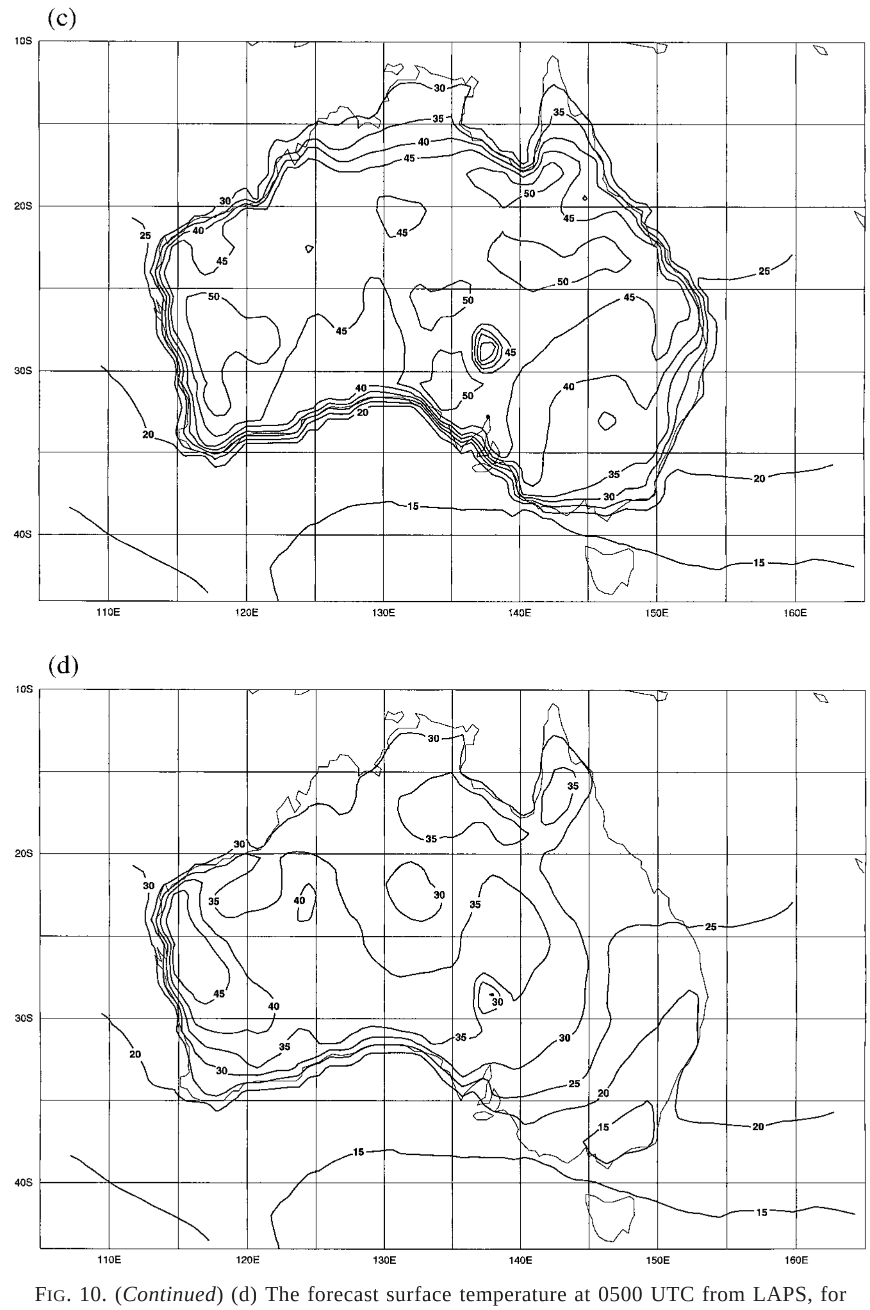

FIG. 10. (*Continued*) (d) The forecast surface temperature at 0500 UTC from LAPS, for sensitivity case 2.

resolution of 75 km, appears to have the same problem based on a limited study of its performance in the 1996 southern summer over the month of February. In this single month numerous examples of the ridge–trough system problem were evident with a mean-systematic westward bias of about 2.5° averaged over three latitudes in both ridge and trough forecasts. Turning to the second aim, the authors had suspected for some time that lack of resolution of the steep coastal orography and underestimation of the inland surface heating had been responsible for the westward error bias. This theory was confirmed by the results of parallel runs of a new real-time model also at 75-km horizontal resolution, with better representation of the coastal orography, which in northern Queensland is quite precipitous and a superior representation of the surface and boundary layer fluxes. Finally, the third part of the study was to confirm the hypothesis in two ways. First the new model was run at the very high resolution of 15 km and 31 levels in the vertical on three selected case studies. The case studies produced further significant improvement over the 75-km resolution pre-

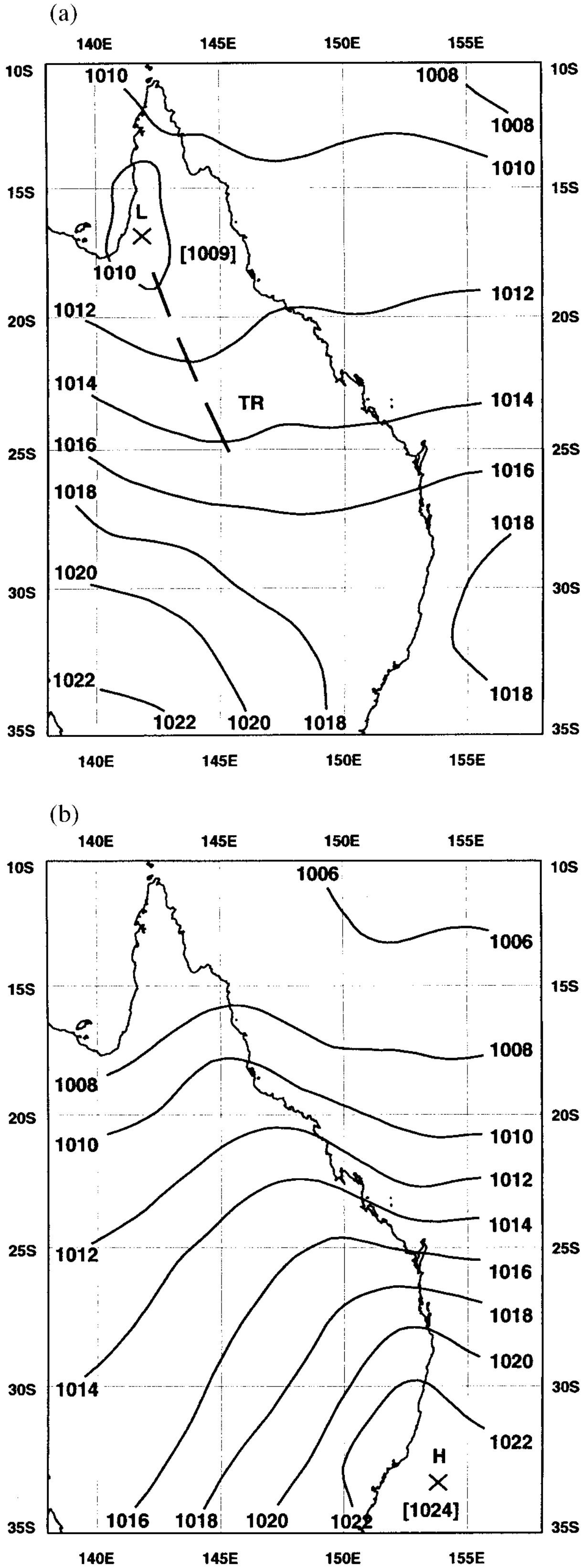

FIG. 11. (a) The 24-h HLAM forecast of SLP valid at 0000 UTC 20 Nov 1996. (b) The 24-h HLAM forecast of SLP valid at 0000 UTC 21 Dec 1996.

dictions and the small remaining westward biases had been reduced to near zero. Second the HLAM model was run on two of the case studies using the LAPS surface temperatures. This resulted in a degraded representation of the trough in both cases, very similar to those produced in the LAPS forecasts.

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