BUREAU OF METEOROLOGY

150 Lonsdale Street Melbourne Victoria Australia. Tel: (03) 9669 4000 Telex: AA 30434 Fax: (03) 9669 4548
ADDRESS CORRESPONDENCE TO: Director of Meteorology GPO Box 1289K Melbourne Victoria 3001 Australia

In reply please quote
70/714

Detective Senior Constable Stewart Gray
NSW Water Police
Wharf 25, Harris Street
PYRMONT NSW 2009

Dear Detective Senior Constable Gray,

On 18 June 1999 Mr Bruce Neal, the Bureau's Assistant Director (Services), wrote to you regarding further projects being undertaken by the Bureau as input to our final report on the meteorological aspects of the race, and also in response to questions you asked at the meeting in April with Mr Pat Sullivan, the Bureau's Regional Director for NSW. I am now able to submit this additional information for use by the Coroner in his inquiry into the 1998 Sydney to Hobart Yacht Race.

I also feel that it may be of some use to you if I also provide comment regarding the CYCA's Report of the 1998 Sydney Hobart Race Review Committee as it makes some important recommendations concerning weather related matters.

As you are aware, the Bureau's view is that in issuing its first "Storm Warning" at 2pm on Saturday 26 December 1998, the fleet, Race organisers and the media were given unambiguous warning that the Bureau's expectations were for dangerous wind and sea conditions to develop over the Race area the following day. This warning, the most severe possible for these latitudes, gave the fleet at least 18 hours notice before the storm occurred.

Since the event there has been considerable public discussion about how the sailors interpreted the forecasts and warnings and about the adequacy of the service provided by the Bureau. This has caused the Bureau much concern as the forecasts and services we have provided in the past have been based on strict adherence to international standards and conventions in the use of terms to describe weather conditions at sea. In the light of this experience we have approached the CYCA directly with a view to our working closely together to improve the communication and understanding of meteorological information by the yachting community. We also recognise that we will need to work closely with the media on this issue.

Report of the 1998 Sydney Hobart Race Review Committee

On 2 June 1999 the CYCA released the Report by the Race Review Committee into the running of the 1998 Sydney to Hobart yacht race. Several findings and recommendations were related to weather services, and the Bureau's attitude to these is at Attachment A.

Definitions and Terminology

Wind speeds at sea are measured (or forecast) as the average wind over10 minutes, and given in nautical miles per hour (knots). Over open waters, wind gusts can be expected to be up to 40% greater than the 10-minute average speed.

Shelter is often sought in the lee of an island or other landfall. Inshore, the average wind speed is substantially reduced on a lee shore. However, in the lee of a very rugged coast wind gusts and squalls can in the extreme reach twice the 10-minute average wind speed.

Sea and swell wave heights are measured as the vertical distance between a trough and the following crest. By international convention, the measure of sea state is the *significant wave height*, defined as the average height of the highest one third of all the waves past a point over a given time interval. It includes the combined effect of the swell and wind driven sea waves. This is close to the average height of the waves as estimated by an experienced observer.

The relationship between the significant wave height and the maximum wave height will depend on the time interval of the wave-measuring period. The most likely maximum wave height is about 1.7 times the significant wave height as measured over a half hour interval and almost twice the significant wave height when measured over a three hour interval.

In the analysis of the raw data from a Waverider buoy, a 30 minute interval will estimate adequately the significant wave height, but if the maximum wave height measured is also to be quoted in a collective of coastal reports broadcast to mariners, wave measurements over a three hour interval is preferred.

Separate Studies

As detailed in Mr Neal's letter of 18 June 1999, the Bureau has undertaken further studies in the following areas:

(a) A study of wind observations from Wilsons Promontory lighthouse

The Bureau has investigated the effect of the topography of Wilsons Promontory, how representative the Bureau's observing station at the Promontory is of wind flow in nearby areas of Bass Strait, and the role it plays in forecasting weather in the Strait.

It has found that the disruption to the airflow caused by the irregular shape of the Promontory should extend at the most, to the order of 40 to 50 km beyond the Promontory. At the present time this "area of influence" around the Promontory can only be estimated using physically based mathematical scaling techniques. A more detailed analysis would require that fluid dynamic modelling be undertaken, either of a theoretical nature using complex numerical simulations, or physical nature using scale models in a fluid dynamic laboratory. Such a study is outside the current expertise and scope of the Bureau's research centre and, if considered necessary, will need to be carried out by another research group.

To confirm that the winds measured at Wilsons Promontory are unrepresentative of the winds over the nearby areas of Bass Strait, the Bureau performed a study which compared wind observations from Wilsons Promontory with other coastal sites in the Bass Strait region. Details of this study are discussed at Attachment B. The study examined the hypothesis that Wilsons Promontory is no different to other coastal observing sites in the vicinity of Bass strait.

The outcome of the study was that Wilsons Promontory observations are statistically speaking quite different from other observations in the area. It showed that for the long term records for the Bass Strait area, Wilsons Promontory has reported the highest incidence of winds above 30 knots, with 16.4% of all its observations over 30 knots. Cape Grim located on top of a 93m bluff on the northwestern tip of Tasmania was second ranked with 9.1% and Kingfish B third with 7.9%. Wilsons Promontory reported winds over 40 knots on 5% of occasions, which is about five times as frequently as the next windiest location, Cape Grim. For winds over 50 knots this ratio increased to more than 6 times. Most of the Bureau stations have not reported winds in excess of 60 knots. Moreover, on occasions when wind speeds of more than 40 knots were reported at the Promontory, a significantly large proportion of stations elsewhere in the Strait reported wind speeds less than 35 knots. The Bureau's scientists are of the view that the high incidence of strong winds at Wilsons Promontory is directly attributable to orographic forcing of the wind field at that location.

(b) An evaluation of anemometers used to measure winds from yachts

In order to be able to utilise the observations from yachts which competed in the 1998 race (in the re-analysis of the event and modelling studies), the Bureau needed to ascertain the accuracy of masthead anemometers of the type typically used by racing yachts. To this end, a report on the calibration and behaviour of masthead anemometers was undertaken by the Australian Regional Instrument Centre, Observations and Engineering Branch, of the Bureau. A copy of *Instrument Report 653* is at Attachment C.

The study tested 3 masthead anemometers, from different manufacturers, and found that there was a high *uncertainty of measurement* with only one sample conforming to the Australian Standard (AS 2923) and Bureau specifications for a robust anemometer suitable for network use under controlled conditions. One of the samples did not satisfy threshold start speed of accuracy specifications. Other findings include:

- A data logger that could not record wind observations above 50 knots;
- An anemometer that could not withstand wind speeds beyond 80 knots;
- Problems with smoothing and filtering of data by the data loggers and control units;
- The anemometers are largely unaffected by roll position, but each has a unique response to pitch angle that increases the uncertainty in the wind speed measurement; and
- The accuracy may be affected by the vertical orientation of the rotor, by about 14% of the true wind speed and as much as 100% for low wind speeds (under 10 knots).

Given these findings, the uncertainty in any wind measurement on a boat under any wind conditions is likely to be greater than 10% of the true wind. The study also indicates that observations in wind conditions like those of the 1998 Race, even from well maintained anemometers, could be highly unreliable.

(c) Estimates of wave heights from the police helicopter

This study was not progressed largely as a result of the use by the Bureau of alternative reports of sea state from a wide range of sources including yachts competing in the Race, other shipping in the area, and satellite observations.

(d) An explanation of numerical prediction and the numerical models used by the Bureau

This explanation, supplied in full at Attachment D:

- includes a schematic description of how computer forecasting models operate;
- explains some of their limitations and capabilities; and
- provides charts from the various models which were available to the forecasters through to Boxing Day (26 December 1998).

To further illustrate the limitations and capabilities of numerical simulation of atmospheric and oceanic phenomena I have also included as Attachment E, part of a draft post-race research study performed by the Bureau of Meteorology Research Centre using high resolution weather and surface wave prediction models which are currently being developed by the Bureau. To assist in understanding of how numerical models were used to simulate the development of the storm, I have also organised for an animated presentation of the modelled event to be provided to you.

The following main points result from the post-event diagnostic study:

- The broadscale meteorological environment prior to the development of the intense but small scale low pressure system could be well-explained by classic mid-latitude meteorological theory relating to amplifying low pressure trough concepts;

- The secondary cyclogenesis (formation and intensification of the small, intense low pressure system) was extremely unusual, but could be explained using diagnostic techniques applied to very high resolution numerical forecast fields. The exact forcing mechanism for such cyclogenesis has not been described for Australian storms before;

- The pre-existing low in the Tasman Sea provided a source of warm, moist air which preconditioned the atmosphere over Bass Strait to enable the rapid development of the small, intense low pressure system;

- The high winds experienced were generated as a result of a narrow (approximately 50 km wide) band of winds up to 60 knots about 500m above the sea (called a *low-level jet* by meteorologists), which was oriented west-east across Bass Strait and to the east of longitude 148°E. This band of winds developed during the early hours of 27 December, strengthened and progressed rapidly eastwards to impact directly on the main body of the fleet as it tracked into waters south of latitude 37°S during the day;

- As the surface wind field responded to the intense, short-lived low level jet, waves of 5 m to 6 m significant wave height developed off Gabo Island during the early afternoon of 27 December. During the afternoon and evening of 27 December, waves of between 7 m and 8m significant wave height were generated in a band running north-east from about

100km east of Gabo Island. This band persisted into the morning of 28 December, as it moved eastwards into the Tasman Sea and began to dissipate;

- Only with very high resolution numerical models running in real time, coupled with an accurate starting analysis of the surface wind and pressure fields, could the detailed development of such a low pressure system and its associated sea wave field be forecast.

Most Likely Wind and Sea Conditions Experienced

To provide an assessment of the most likely conditions experienced by the fleet during the critical period on Sunday 27 December 1998, the Bureau has obtained as many observations as possible from yachts, the race Relay Vessel *Young Endeavour* and merchant shipping in the area at the time. This information has been used in the detailed manual re-analyses as well as the computer model studies of both the atmospheric and oceanographic conditions.

A study of wind and wave conditions at the Kingfish B platform during the storm was commissioned to provide insight on how unusual the conditions experienced in Bass Strait were. On the basis of study of wave conditions at the Kingfish B platform, the storm (as experienced at Kingfish B) can be characterised as a one in eight to ten years event. This infers that the storm was of a relatively unusual, but not highly unusual, intensity for that part of Bass Strait.

Crews who competed in the 1998 Race were surveyed by the CYCA on a range of areas related to the Race and their participation in it, including their observations or impressions of wind and wave conditions encountered at the height of the storm. The Bureau has analysed the responses to these questions which were provided by the CYCA. On the question of the wind speed encountered during the storm, the mean response for average speed[1] reported (from the 94 yachts that responded) was 56.4 knots, and the mean of maximum gusts[2] reported (from the 88 yachts that responded) was 67.8 knots. On the question of the wave heights encountered during the storm, the mean response for average wave height[3] reported (from the 99 yachts that responded) was 9.4 m, and the mean of maximum wave height[4] reported (from the 96 yachts that responded) was 13.9 m.

Taking into account all known and inferred environmental data to hand, the Bureau estimates that the most likely highest winds experienced by the competing yachts at the height of the storm were in the range from 50 to 60 knots. In particular, on the basis of the modelling studies, and taking into account the well known gustiness of winds, it was likely that gusts and squalls of around 70 to 80 knots would have been experienced in the band of high winds extending eastwards out of mid-Bass Strait, east of Kingfish B, as the storm developed during the afternoon of 27 December and the rain squalls mixed winds from the low-level jet down to the surface.

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[1] CYCA Survey Q.33 "During the storm what was the average wind speed and direction recorded on your yacht?"

[2] CYCA Survey Q.34 "What was the strongest wind gust and direction recorded on your yacht?"

[3] CYCA Survey Q.35 "In your opinion what was the average height of waves during the Storm?"

[4] CYCA Survey Q.36 "In your opinion what was the biggest wave you encountered?"

Taking into account observations from yachts, merchant ships, satellites and the results of the post-event modelling study, the highest significant wave heights generated by the storm would have developed in response to the development, intensification and movement of the narrow west-east oriented jet of surface winds during the second half of 27 December. The highest significant wave heights experienced would have been in the range 7 m to 8 m, in a band oriented south-west to north-east off Gabo Island which developed during the second half of 27 December. On the basis that peak wave heights would have been around 1.9 times the significant wave heights achieved during the storm, extreme wave heights (heights for one-in-1000 waves) were most likely to have been in the range 13 m to 15 m.

Yours sincerely,

G. B Love

G. Love
Deputy Director (Services)

8 December 1999

Attachment A

BUREAU OF METEOROLOGY COMMENT ON METEOROLOGICAL MATTERS COVERED IN THE CYCA'S REPORT OF THE 1998 SYDNEY-HOBART YACHT RACE REVIEW COMMITTEE

This Attachment provides comment on a number of weather related matters raised in the Cruising Yacht Club of Australia's (CYCA's) Report of the 1998 Sydney Hobart Race Review Committee, May 1999, and sets out the Bureau's attitude to the Weather Recommendations section of that Report.

CYCA Report Section 4: Weather (pages 29-52)

2. On pages 35-36 there is comment on the pre-Race meteorological briefing which was provided by the Bureau with possibly negative comment in relation to the Bureau staff member outlining a number of alternate scenarios for the possible weather pattern development. We would note that with regard to weather briefings, each meteorologist will have his/her preferred style of presentation. With the benefit of hindsight, it is clear that it was appropriate for the Bureau's representative to stress the uncertainty caused by the very divergent solutions presented by the models and encourage the competitors to reassess the weather on Race-morning.

3. At page 37 of the CYCA Report there is speculation concerning the appropriateness of the times the Bureau forecasts were issued. The service provided by the Bureau for the Race was developed in consultation with the CYCA and issue times for the special forecasts were determined to coincide with the official race schedule (skeds) times. The Bureau can, and does, issue warnings and updated special race forecasts whenever the need arises.

4. On page 41 there is speculation concerning the performance of Bureau numerical forecasting models with a particular focus on their resolution (or spacing of the grid points at which the atmosphere's governing equations are solved). Certainly global models, with an effective grid spacing of 75 km or greater, would not accurately resolve gradients in the wind fields of the type observed with the low in Bass Strait on 27 December. However, high resolution models such as the Bureau's meso-LAPS model (25 km resolution) do so adequately. An explanation of how numerical models differ and the effects of increased model resolution can be found in the companion Attachments D and E.

5. Further research into this event by modellers in the Bureau's research centre using a higher resolution model, which is currently being developed for eventual operational implementation by the Bureau, showed that increasing the resolution of the models increased the definition of the structure of the surface wind and pressure fields generated by the model and also improved the positioning of the low that developed in eastern Bass Strait at the time of the Race. However, given the lack of reliable observations from the race area, it is difficult to verify the model guidance and forecast performance with any certainty.

6. On page 42 there is a statement to the effect that; "*at all times, the official race forecast was for 40 to 50 knots*". This is only partly correct as the special race forecast issued at 2.50pm on Boxing Day referred to storm force winds developing the next day. While no specific wind speeds were referred to in the outlook, the definition of storm force winds implies that 10-minute mean wind speeds of between 48 and 63 knots were expected to develop. Also, this forecast was supplemented by the official Storm Warnings (which are themselves an integral part of the forecast), broadcast every two hours on the coastal radio network, which warned of winds to 55 knots. The first Storm Warning issued at about 2pm Boxing Day was for winds in the range 45/55 knots (see Appendix 2 to the Bureau's Preliminary Report). Many of the subsequent Storm Warnings specified winds to 55 knots.

7. On pages 51 and 52 there is the assertion that there was a qualitative difference in the forecasts prepared by the Victorian Regional Forecasting Centre (RFC) for eastern Bass Strait compared with those prepared for the Race by the RFC in Sydney. It is suggested that the RFC in Melbourne should originate the Bass Strait forecasts for future races.

8. The Bureau agrees that the Victorian RFC staff have greater experience in forecasting for the area east of Bass Strait than the Sydney RFC staff. Under the Bureau's integrated mode of operation there is strong operational coordination between adjoining Forecasting Centres and there was a considerable exchange of information between the Sydney, Melbourne and Hobart RFCs during the Race. In fact the arrangement has always been for the Victorian RFC to prepare the forecasts for Bass Strait but that during the Race, that information is copied into the special race forecast by the issuing forecasting centre, in this case Hobart.

9. The Bureau proposes that to simplify the liaison arrangements between the Race organisers and the forecasters during future races, only one regional office will collate and issue the special race forecasts. This will be done using the usual coordination arrangements between the various offices.

CYCA Report Findings: 9.3 Weather (pages 137-139)

10. The first weather related finding of the CYCA's Report states that "*...the speed with which the depression developed caught most, even forecasters, by surprise*". The Bureau disagrees strongly with this finding, at least as it relates to its forecasters, given that the models predicted the development and intensification of the low around 13 hours before it even appeared on the chart and about 18 hours before the storm force winds reached the Race area. The forecasters then immediately issued a Storm Warning. Given the meteorological circumstances that had prevailed up to the time, this turned out to be an excellently judged professional decision which produced what was, by international standards, a very accurate and skillful forecast. Further, Storm Warnings are rarely issued anywhere in the world in advance of the development of a surface low pressure system. The usual situation is to provide warning of the movement of a pre-existing system into a forecast area and/or the system's subsequent intensification.

11. The next finding refers to the Bureau's assumption that the "*forecasts would be interpreted differently to what they were*". Nowhere in the CYCA Report is there any acknowledgement that the Bureau's two page brochure on its Marine Weather Services highlights the definition of mean winds and gusts, or that this "assumption" has been accepted national and

international practice for many decades. This brochure, also available on the Bureau's Web Site, was placed next to the navigator's kits at the CYCA prior to the pre-Race briefing and was available at the Bureau's briefing stand, at the CYCA, on race day. A Bureau staff member, Mr Kenn Batt, in addition to conducting regular weather courses for yachtsmen and yachtswomen, has written several articles explaining aspects of meteorology which have been published in various magazines. One particular article, which explained how to interpret weather forecasts, was featured in the December 1997/January 1998 issue of the CYCA's own publication, *Offshore Yachting*. It is the Bureau's understanding that this was the official issue of the magazine for the 1997 Race and contained all the sailing instructions, etc, required by competitors. The article was not repeated in the official race issue of the magazine for last year's (1998) race, but an article about how and where to get weather information, in addition to the special race forecast, was included.

CYCA Recommendations (Pages 151-153)

12. The recommendations in Section A1-Weather (pg 152) commence with a Compulsory component followed by a Recommended component.

13. The first Compulsory component recommends:

- *The CYCA needs to develop a weather strategy, which includes working with its nominated race forecaster to:*
- *generate (close to) real-time forecasting,*
- *educate yachtsmen on the forecasting/interpretation,*
- *provide easily understood/laymen forecasts, and*
- *develop forecasting assets in Eastern Bass Strait, including accessing information from the Bass Strait Oil Rigs.*

14. The Bureau agrees that the CYCA needs to develop a weather strategy (or plan for accessing and using weather data and information) for the planning and management of the Race.

15. The Bureau has traditionally supplied specialised services to the CYCA for the Race on a cost recovered basis and is prepared to continue in this role, recognising that it is clearly in the public interest that the best possible weather information be available in support of the safety of the competitors and others associated with the race. Should the CYCA prefer to use a commercial forecaster the Bureau would make available to the CYCA and its nominated forecaster the routine marine forecast service for coastal waters and the high seas plus any ancillary information and data which the CYCA considered useful. This would be done under the normal arrangements for accessing such information (generally those accessing the information must meet the incremental costs the Bureau incurs in making such access available).

16. In relation to real-time forecasting for the Race, the Bureau considers that a continuous weather watch should be maintained over the race area, and that forecasts and warnings should be issued/amended as required.

17. In relation to the education of yachtsmen, the Bureau recognises that surveys conducted after the 1998 Race show considerable confusion in the participants interpretation of the

terminology used in marine forecasts, and agrees that further education is required. The Bureau has already initiated such education in respect of standard Bureau products.

18. With regard to the part of the recommendation relating to easily understood/laymen forecasts, the Bureau has strong reservations. The Race is conducted, at least in part, in international waters. The Bureau uses international standards and practices and would be reluctant to change from these. Furthermore many of the international competitors are familiar with these standards. This said, the Bureau recognises that a case can be made for forecasts and warnings to contain additional information where the available communication channels allow such information to be carried effectively. However, to employ lengthy plain language descriptions of the possible evolution of weather patterns, to use units not traditionally used off-shore (for example wind speed in km/hr rather than knots), may confuse rather than clarify, and may overload communication channels. Changes along the lines suggested in this part of the recommendation need to be carefully worked through. One alternative would be for the Bureau to work with the Race participants to develop a range of graphical and pictorial products and seek to establish on-board systems on every yacht for accessing them.

19. With regard to the recommendation relating to "forecasting assets in Eastern Bass Strait", the Bureau assumes that this relates to the implementation of one or more moored buoys which would provide meteorological (air pressure, air temperature, wind speed and direction) and oceanographic data (wave spectra information and sea surface temperature). The Bureau would strongly support such an initiative. The Bureau has, or is entering into, consortium arrangements in Tasmania, New South Wales, South Australia and Western Australia to establish, operate and collect data from wave rider buoys. We would be pleased to contribute resources to a consortium establishing such a facility in Eastern Bass Strait. We note that the buoy off the west coast of Tasmania cost around $50,000 to establish and currently costs around $35,000 per annum to maintain (this includes buying a new buoy every second year). We would also note that the depth of the sea to the east of Bass Strait may preclude the implementation of a moored buoy, or alternatively make the cost of a mooring prohibitively expensive.

20. In relation to access to weather observations from the Bass Strait oil rigs, it should be noted that the Bureau makes these observations accessible in a number of ways. As explained in an article "Finding that Weather Information", which was authored by Mr. Batt and included in last year's official race issue of *Offshore Yachting*, the observations from, and forecast for, the Bass Strait oil rigs is available to the competitors via the Coastguard at Lochsport, Victoria. We have recently learned that the Coastal Patrol Eden broadcasts these forecasts and observations 6 times per day. The regular coastal waters forecasts which cover the oil rigs area were also available via a number of means, including coastal radio. Further discussions will be conducted with the CYCA to determine what other modes of access they envisage.

21. The second part of the Compulsory Recommendation is that:

- *The CYCA must provide yachts with a practical interpretation of the weather forecast. This should include:*
- *indication of maximum wind speeds and wave heights expected,*
- *duration of bad weather/storms,*
- *indication of the movement/direction/pattern the centre of the storm will most*

> *likely take, and*
>
> - *inclusion in the Race Management team of a full-time adviser from its nominated forecaster.*

22. The Bureau agrees with the intent of this recommendation, that is, to ensure that forecasts of weather hazardous to Race participants describe as accurately as possible, and as fully as necessary, those conditions. This said, the Bureau has some reservations about the detail of this recommendation.

23. We note that the Race fleet is often spread out over the course, and that specifying the duration of bad weather is location specific, leading possibly to quite complicated, and lengthy, forecasts. We also note that at times there may be more than one weather system affecting the course. For example there may be an active cold front associated with one or more lows, and a band of maximum winds displaced from the centre of any of these (in fact many of these circumstances were present during the 1998 Race). Having the Race participants conditioned to avoid the centre of a single low pressure system may be not as helpful as the recommendation would suggest.

24. The Bureau agrees that the Race Management should have good access to meteorological expertise, and that close involvement with one or more professional meteorologists over time would build both their understanding of the value, and limitations, of meteorological forecasts, and of the ability of the individuals advising them.

25. The third part of the Compulsory Recommendation section states that:

> - *In winds of 40 knots (true) or more, yachts will be required to report wind strength, direction and wave height at Radio Skeds if asked to do so by RRV. Yachts should be encouraged to report wind strengths in excess of 40 knots (true) at any time and should not be penalised under RRS Rule 41 for doing so. The RRV should relay weather reports received at the next Sked.*

26. The Bureau agrees with the general thrust of this Recommendation but considers that it does not go far enough. One of the great difficulties for the Bureau during the 1998 Race was that it received no weather reports from Race participants.

27. Weather forecasting commences with building an accurate picture of the weather and sea conditions at some initial time and then projecting forward. If no observations are provided to the RRV until the winds reach 40 knots then the task of forecasting those conditions (and giving advance warning) is made more difficult. Furthermore, the way the Recommendation is framed, yachts will only provide observations when the winds are above 40 knots (true) <u>if asked to do so by the RRV.</u> Even if the winds are above 40 knots, if the RRV does not know this to be the case, it may fail to ask for such observations.

28. Additionally, the Recommendation does not indicate that the observations would be provided either to the Race meteorologist or the Bureau of Meteorology.

29. The Bureau would prefer to reach an agreement with the CYCA that put in place arrangements for around 20 or so boats from the fleet to provide to the Bureau of Meteorology and to the Race Management up to 8 observations per day for the duration of their participation in the Race, regardless of weather conditions. The 20 boats to range in capability, from some of the fastest to some of the slowest in the fleet, so that a geographical spread of data would be available. The Bureau would offer to inspect the meteorological instrumentation on these yachts and make available training for the crews on the taking, and coding of weather observations for transmission to the Bureau.

30. The Recommended Recommendation states that:

- *Barometer as a part of the yacht's equipment, and*
- *Sailing Instructions should include an Addendum detailing all stations and times weather forecasts are available for the Race area.*

31. The Bureau supports this Recommendation. We would note that the Bureau provided the 1998 fleet with details of all coastal weather observations, and the times which observations and forecasts for the Race area were to be broadcast, in its pre-Race package of information.

Attachment B

COMPARISON OF WIND OBSERVATIONS FROM WILSONS PROMONTORY WITH OTHER SITES: A STATISTICAL STUDY

Introduction

A comparison of the frequency and strength of winds at Wilsons Promontory and other coastal locations has been prepared by the National Climate Centre. The results from this study highlight how the particular geography and topography of the Promontory site has a major influence on the characteristics of the wind observations taken there, and sets them apart from wind observations taken at other weather observing sites in Bass Strait.

2. This study examines the statistics of wind observations for a number of sites around Bass Strait. If the local geography of a site plays no role in changing the wind field it would be expected that the frequency of observations in given wind speed ranges would be the same for all sites. Conversely, where topography changes the local winds there will be variations in wind speed ranges between sites.

Analysis

3. Wind data have been extracted from the Bureau of Meteorology's climate archive and analysed to show how often winds of certain strengths occur, and how the winds experienced during the period of the 1998 Sydney to Hobart yacht race compared with other high wind events. A view of the Promontory, showing the lighthouse where the Bureau's observing site is co-located, is shown in Fig. 1.

Figure 1. Aerial view of Wilsons Promontory.

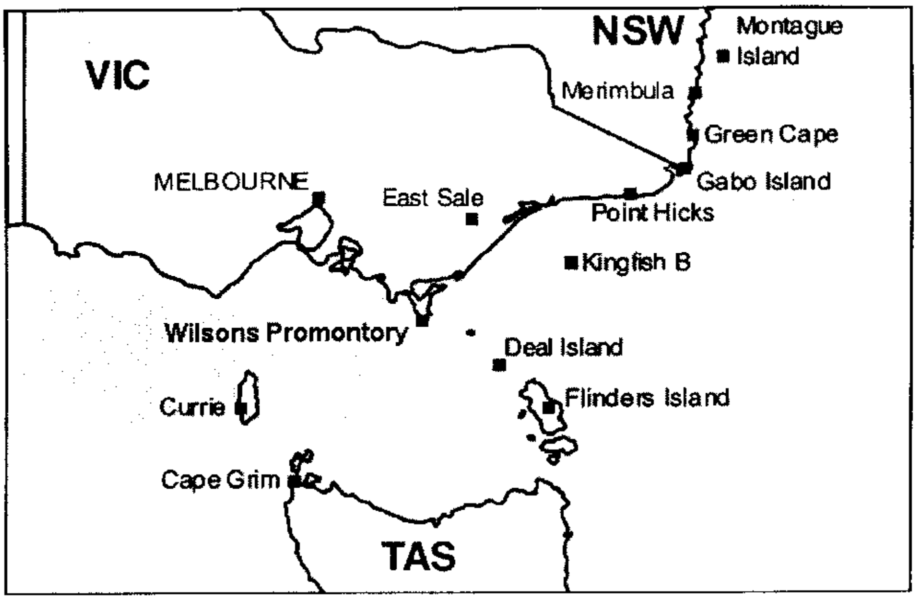

Figure 2. Map of the Bass Strait region showing Bureau of Meteorology observing sites for which data has been used in this study.

4. The Figs. 3-14 show the percentage of winds that exceed various thresholds of wind speed for a number of locations around Bass Strait as depicted in Fig. 2. The first column in these graphs gives the percentage of winds greater than or equal to zero knots (always 100%), the second for winds greater than or equal to 5 knots, the third for winds greater than or equal to 10 knots, and so in 5 knot increments. The final column shows the percentage of winds to have reached 75 knots. Wilsons Promontory has the highest incidence of winds above 30 knots (16.4% of winds are above 30 knots). After Wilsons Promontory, Cape Grim is the windiest reporting station, due primarily to its location atop a bluff 93m above sea level. It reported the next highest incidence of 9.1%, followed by Kingfish B with 7.9%. All three locations observed record or near record high winds during the December 1998 event. A summary of these results is shown in Table 1.

5. A comparison of high wind events shows how frequently winds at Wilsons Promontory are significantly higher than other Bass Strait locations. Table 2 shows an analysis of the occurrence of wind speeds under 30 knots, 35 knots and 40 knots in the Bass Strait area on days when winds reached 40 knots <u>or more</u> at Wilsons Promontory. These have been calculated using a 48 hour window, to allow for the movement of weather systems across Bass Strait. At Cape Grim, which is the next most windy location reporting from the Bass Strait area, winds less than 40 knots occurred on 66 per cent of occasions when the Promontory reported over 40 knots. Most of the other locations analysed reported winds of less than 35 knots on more than 80% of occasions when the Promontory reported more than 40 knots, and on more than 60% of occasions reported winds of less than 30 knots.

Location	**≥ 30kn**	**≥ 35kn**	**≥ 40kn**	**≥ 45kn**	**≥ 50kn**
Wilsons Promontory	16.4	8.3	5.0	2.0	0.6
Cape Grim	9.1	3.2	1.1	0.3	*
Kingfish B	7.9	1.7	0.7	0.2	*
Gabo Island	6.2	2.1	1.0	0.2	*
Point Hicks	3.6	1.4	0.7	0.1	*
Montague Island	2.9	1.2	0.6	0.2	*
Deal Island	2.6	1.0	0.6	0.2	*
Currie	2.5	1.2	0.6	0.2	*
Green Cape	1.7	0.6	0.4	0.1	*
Flinders I. Airport	0.7	0.1	*	*	0
East Sale	0.2	*	*	*	0
Merimbula	0.2	0.1	*	*	0

Location	**≥ 55kn**	**≥ 60kn**	**≥ 65kn**	**≥ 70kn**	**≥ 75kn**
Wilsons Promontory	0.3	0.1	*	*	*
Cape Grim	*	0	0	0	0
Kingfish B	0	0	0	0	0
Gabo Island	*	*	0	0	0
Point Hicks	*	*	*	0	0
Montague Island	*	*	*	0	0
Deal Island	*	0	0	0	0
Currie	*	*	*	*	0
Green Cape	*	*	0	0	0
Flinders I. Airport	0	0	0	0	0
East Sale	0	0	0	0	0
Merimbula	0	0	0	0	0

Table 1. Frequency (per cent) of wind speeds observed at locations around Bass Strait, for speeds above 30 knots, 35 knots, etc., for all years of records. An asterisk (*) indicates a value under 0.1 %.

Location	**Less than 30 knots**	**Less than 35 knots**	**Less than 40 knots**
Cape Grim	9	33	66
Kingfish B	24	68	87
Gabo Island	34	64	78
Point Hicks	62	80	88
Montague Island	74	87	91
Currie	60	79	86
Flinders I. Airport	69	90	98
East Sale	94	99	100

Table 2. Frequency of occurrence (per cent) of wind speeds recorded around Bass Strait, on days when 40 knots or more were reported at Wilsons Promontory.

6. Of the stations in the Bass Strait area, Wilsons Promontory and East Sale have consistently measured, over a number of years, the daily maximum wind gust reported to the Bureau from the Bass strait area. Both stations set or equalled records for their highest wind gust on December 27 1998, when Wilsons Promontory recorded 92 knots and East Sale recorded 82 knots.

Attachment C

Summary of Bureau of Meteorology
INSTRUMENT TEST REPORT 653

Report on calibration and behaviour of three masthead anemometers

The measurement of wind speed on sea going vessels is problematic. The devices used for measuring wind speed (anemometers) are usually attached to a mast; the mast is moving with the boat, and the boat is moving relative to the wind and swell. As a result assessing the accuracy of shipboard measurements of wind in the open ocean is extremely difficult. However, one can test the performance of these masthead anemometers in control conditions to see if they can measure wind parameters on a land based towers, as used for climate and weather monitoring. The responses of these anemometers can then be assessed against well-defined Australian wind measurement standards and their accuracy determined. In addition, under control conditions the masthead anemometers can be tested to look at the impact of orientation to the wind to see if the anemometers respond, as the physics would dictate.

2. To that end, three masthead 3-cup anemometers (Raytheon [or Autohelm] ST60 and ST80, and Brooks and Gatehouse [B &G Hydra 2000]) were purchased and tested by:

(1) calibration at a National Association of Testing Authorities (NATA) registered wind tunnel (CSIRO Atmospheric Research) for wind speed less than 50 knots;

(2) calibration at the Monash University wind tunnel for wind speeds between 0 and 100 knots; and

(3) special tests to gauge anemometer and display responses.

3. Tests were performed by (a) measuring the output of the anemometers in steady wind speed conditions and comparing them with the true wind speed measured with very accurate anemometers, and (b) by examining the way they responded to rapid changes in wind speed. The NATA tests provided an independent assessment of the anemometers accuracy, and these results were used to indicate how well the instruments would perform in conditions specified by the Australian Standard 2923-1987 for wind speed measurement (AS2923). Also, the NATA testing enabled linking the low wind speed tests to those performed in the high wind speed facility at Monash University.

4. The results of the tests are shown in Figure 1 where the difference between the true wind speed and the measured wind speed are plotted for the Raytheon anemometers, and Figure 1 for the B&G Hydra 2000. Figure 1 clearly shows that for the various wind speeds the Raytheon ST60 and ST80 always underestimated the wind speed and for wind speeds below 50 knots both theST80 and ST60 would require corrections of +14% to their readings to provide the true wind speed. In steady state constant wind conditions below 80 knots the B&G Hydra 2000 read within 1.8 knots of the true wind for all wind speeds.

5. An interesting feature of the Raytheon ST60 wind indicator was that is could not indicate wind speeds above 50 knots. In these conditions all wind speeds above 50 knots would register as 50 knots and go no higher. The Raytheon ST80 anemometer wind speed

sensor did not survive the high speed wind tunnel tests. The cups (and vane) blew off the transducer several times during these (50-80 knots) tests. During tests at 80 knots to assess how orientation of the cups changed the performance of the anemometer, the ST80 sensor came apart and further testing was impossible.

6. Each masthead anemometer produced unique results during tests designed to indicate the impact of the pitching of the boat in swell on wind speed measurement. In all cases of pitch testing the difference between the true and measured wind speed increased, and hence the accuracy decreased. There was little impact due to roll (side-side) position on wind speed measurement.

7. The display systems supplied with all the anemometers had various idiosyncrasies that complicated the measurement of wind speed. The main problem was the different averaging of wind values depending on wind speed and rates of change in wind speed. In some cases several minutes were required to be certain that the final value representing the measured wind speed had been reached. The likely reason is that these display units are usually linked with other sensors for boat speed to attempt to determine the 'true wind', hence the uncertainty of the ideal conditions in the wind tunnel tests is the best accuracy that one could expect with such transducer/display combinations.

8. The tests show that the B&G Hydra 2000 conformed to the Australian Standard 2923-1987 (AS2923) for a robust and low maintenance sensor and would be suitable for land based wind measurement, and could achieve accuracies of better than 10%. However, none of the Raytheon anemometers tested conformed to the Australian Standard 2923-1987 (AS2923) for robust and low maintenance sensors and would not be suitable anemometers for climate and weather measurements. The tests suggested that the accuracy of all the anemometer wind speed measurements would be poorer under the conditions of wind and swell expected in open ocean racing.

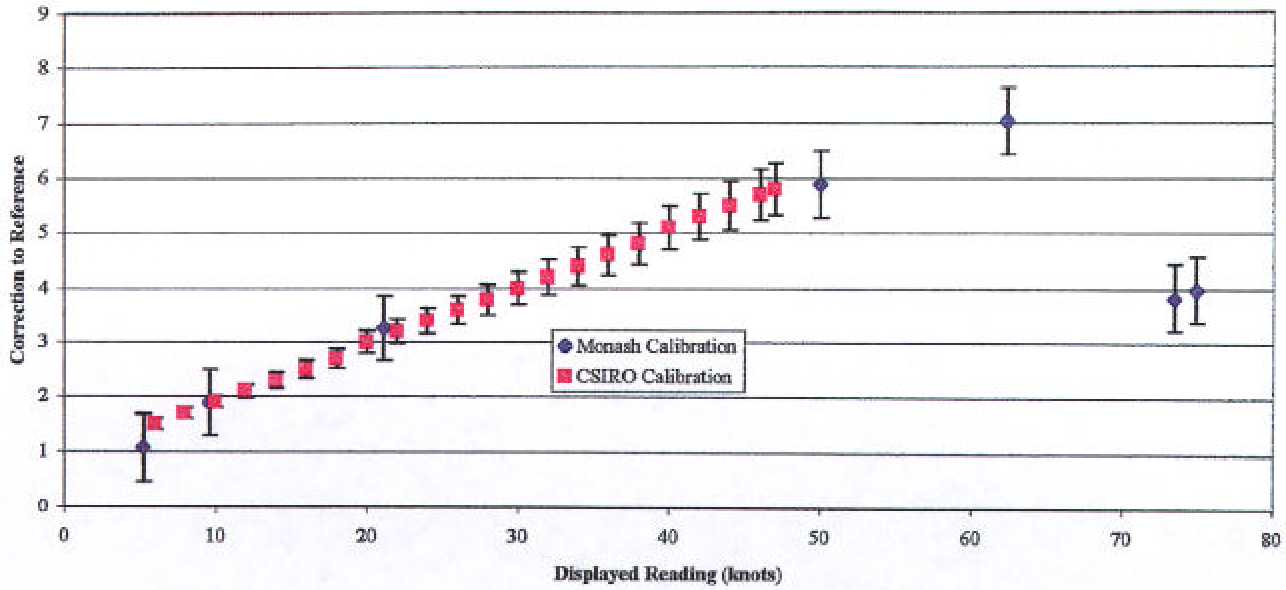

Figure 1: Corrections in knots to the Raytheon ST60 and ST 80 that need to be added to the measured value to provide the true wind speed. The vertical bars indicate the uncertainty of the correction at the 95% level of confidence.

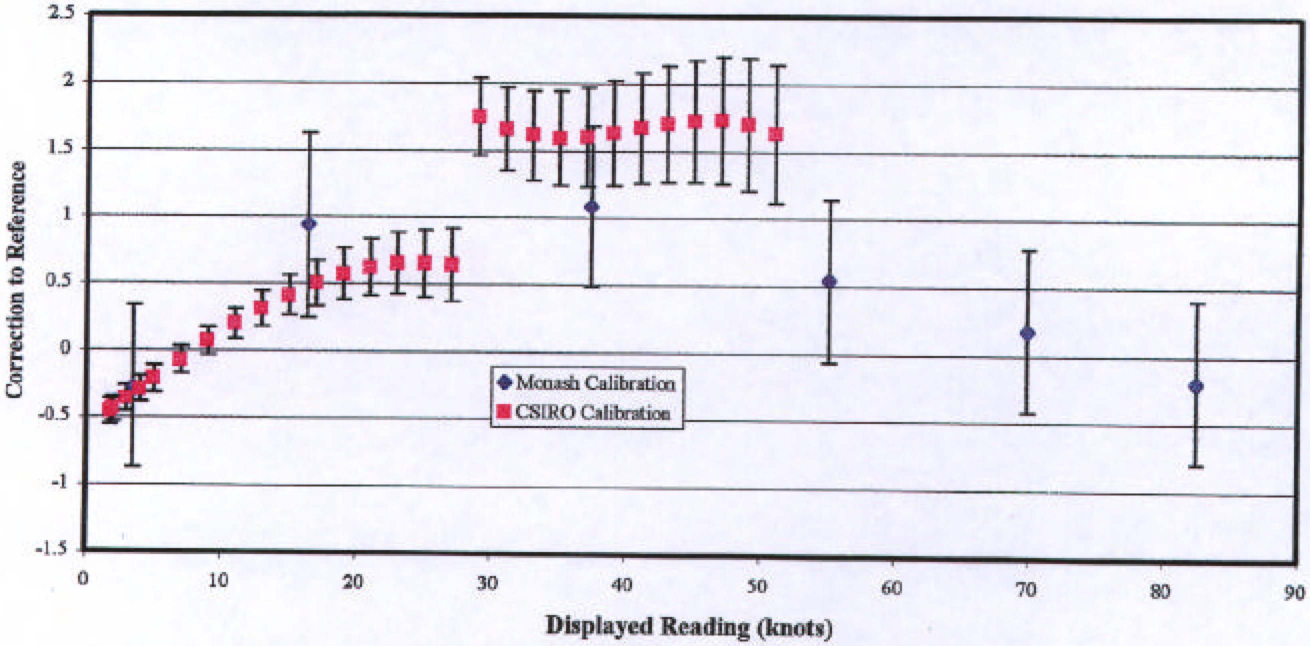

Figure 2: Corrections in knots to the B&G Hydra 2000 that need to be added to the measured value to provide the true wind speed. The vertical bars indicate the uncertainty of the correction at the 95% level of confidence.

WEATHER PREDICTION USING COMPUTER SIMULATIONS

Numerical Weather Prediction (NWP) is the process of forecasting the weather using computer-based simulations of the atmosphere. The behaviour of the atmosphere, and therefore the weather, is governed by a set of physical laws which can be expressed as mathematical equations. These equations take into account how atmospheric quantities such as temperature, wind speed and direction, and humidity will change over time from some initial starting condition or value. The NWP systems used to simulate weather patterns are often referred to a "models".

2 There are two types of models generally used in meteorology for weather prediction: *grid point* and *spectral*. Grid point models represent the atmosphere using a mesh of points which may be between 10 and 200 km apart. The spectral models represent the physical properties of the atmosphere by trigonometric functions and solve the predictive equations governing the atmosphere's behaviour using these functions. However, in order to display the results from a spectral model the output is generally projected onto a grid display with a grid spacing approximating the system's capability of resolving features in the horizontal plane. The fineness of the horizontal spacing is called the *resolution* of the model. In the vertical, the models only have a limited number of levels which may be up to one kilometre apart. At the surface, mountain ranges or the details of the topography are only approximated, so that local features such as sea-breezes or funnelling of winds through valleys may be poorly represented. While the sophistication of treating these physical processes is increasing, due to research efforts from both the climate and NWP communities, they are still imperfect.

3 Global models analyse and predict the weather for the entire globe. Smaller regional- and meso-scale models analyse and predict for a sub-global area, using boundary conditions (data at the "edges" of the regional domain) from a global model. In general, the time saved by not having to solve all the equations over the full globe can be used to increase the horizontal and vertical resolution of these smaller scale NWP systems.

4 The skill of NWP systems forecasts deteriorates as they extend in time from the starting analysis. Currently NWP systems are considered to have some skill in forecasting out to between 5 and 7 days from the initial starting analysis. The skill is high for forecasts 12 hours beyond the starting analysis, dropping steadily until at about day 7 when there is little or no useful skill. The main measure of skill is usually whether, on average, the NWP system forecast turns out to be more accurate than a forecast based on persistence[1].

5 The errors which lead to decreasing skill with time derive from two main sources:

(1) errors in the starting analysis and approximations in the ways the governing mathematical equations are used to represent the atmosphere; and

(2) the approximations and assumptions used to solve the governing equations.

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[1] The persistence forecast is one which assumes that the atmosphere will not change over time, and so the forecast for tomorrow's conditions is the analysis of today's conditions.

6 The state of the atmosphere at any given time can only be partly known. Observations are only available at a finite number of points and, generally speaking, there are fewer observations over sea than land and fewer taken above the Earth's surface than at the surface. Surface observations from the southern hemisphere oceans are provided by the relatively few ships operating in the area and drifting buoys, augmented by estimates from human analysts based on satellite imagery. Observations from above the surface are quite sparse, originating from weather balloons, some commercial aircraft and meteorological satellite measurements. Even where there are dense observations, the limitations of numerical analysis techniques require them to make the "best fit" to the observations given the limitations associated with the approximations used in the models. Uncertainties in the starting analysis, due either to the limitations in observations or the models, can grow into large errors in the predictions and degrade the quality of the forecast as the prediction range increases. For example, a starting analysis which underestimates a low pressure system over a data sparse area may lead to a poor prediction of the low several days later as it reaches a populated area.

7 Secondly, the models themselves are not perfect and introduce errors which grow as the projection extends further into the future. Errors in the model may arise from errors in the translation of the mathematical equations into computer instructions or from the approximations required to simplify the complex equations that represent the state of the atmosphere.

8 Finally it must also be noted that because the atmosphere is essentially chaotic, small differences in initial conditions can cause NWP models to generate vastly different solutions in a matter of days or even hours. In some situations, where rapid development is occurring, errors can grow rapidly, in a non-linear fashion, quickly rendering the subsequent prognosis to be a very poor one.

Numerical Weather Prediction (NWP Output) Available During the 1998 Race

9 There were a number of NWP system outputs available for the 1998 Sydney-Hobart Yacht Race. The material could be sourced from the Bureau directly via the Internet or through the media, and additionally from overseas providers via the Internet.

10 The analysis here is not intended to comprehensively review the output available, but to use the analyses and prognoses valid at 11.00 pm EDST (12.00 UTC) on Sunday 27 December 1998 as illustrative of the strengths and weaknesses of NWP guidance for forecasters. Also, the discussion which follows is not intended to represent the thought processes of the forecasters during the days leading up to the Race.

11 Each NWP system providing analyses and prognoses will start with a slightly different initial database. Each system analyses the data in different ways and then generally uses different horizontal and vertical grid spacings, and different approximations to the atmospheric equations when projecting the data as a starting analysis and when integrating forward to produce prognoses valid for times in the future.

12 The Bureau's forecasters had access to the output from at least seven NWP systems:

- The US Aviation model (US).

- The Japanese Meteorological Agency (JMA) model;
- The European Centre for Medium-Range Weather Forecasting (EC);
- The United Kingdom (UK) Meteorological Office model;
- The Bureau of Meteorology's high resolution 'meso-LAPS' system;
- The Bureau of Meteorology's Limited Area Prediction system (LAPS);
- The Bureau of Meteorology's Global Assimilation and Prediction (GASP) system.

13 Figure 1 shows four analyses valid at 11.00 pm (12UTC) on Sunday 27 December, one from each of EC, US, UK and LAPS. These analyses correspond to the time at which many yachts in the 1998 Sydney to Hobart fleet was experiencing storm force conditions in eastern Bass Strait. While the analyses are broadly similar they are significantly different in detail. When considering the area around Bass Strait and to the east of Tasmania there are considerable differences in the positioning of the low pressure system as well as differences in the analysed central pressure of the low. This is not surprising as there would have been a paucity of observations available to the NWP systems to accurately depict the low pressure system's centre location, structure or intensity over the oceanic areas. In the remainder of this discussion the LAPS analysis will be used as some sort of reference analysis, even though subsequent detailed analysis in the Preliminary Report differs in some key detail (for example, the Bureau's Preliminary Report on the Meteorological Aspects of the 1998 Sydney to Hobart Yacht Race assigns a central pressure to the low, at 9 pm on 27 December, of 980hpa). Table 1 summarizes the features of these NWP systems.

Model	Domain	Type	Horizontal resolution	Number of vertical levels	Forecast range (hrs)
LAPS	16.75N - 65 S 65 - 184.25 E	Grid point	0.75° (~ 75 km)	19	48
Meso-LAPS	22.25 - 52 S 125 - 164.75 E	Grid point	0.25° (~ 25 km)	19	36
GASP	Global	Spectral	T239 (83 km)	29	192
EC	Global	Spectral	T319 (62 km)	31	168
US	Global	Spectral	T126 (157 km)	28	72
UK	Global	Grid point	60 km grid (approx.)	30	120
JMA	Global	Spectral	T213 (93 km)	30	168

Table 1: Summary of features of seven NWP models available to Bureau of Meteorology forecasters.

14 Three global forecast systems used by Bureau forecasters at the medium range (forecasts for days 5, 6 and 7 ahead) are the EC, the UK and GASP. The EC is, on average, the best performer

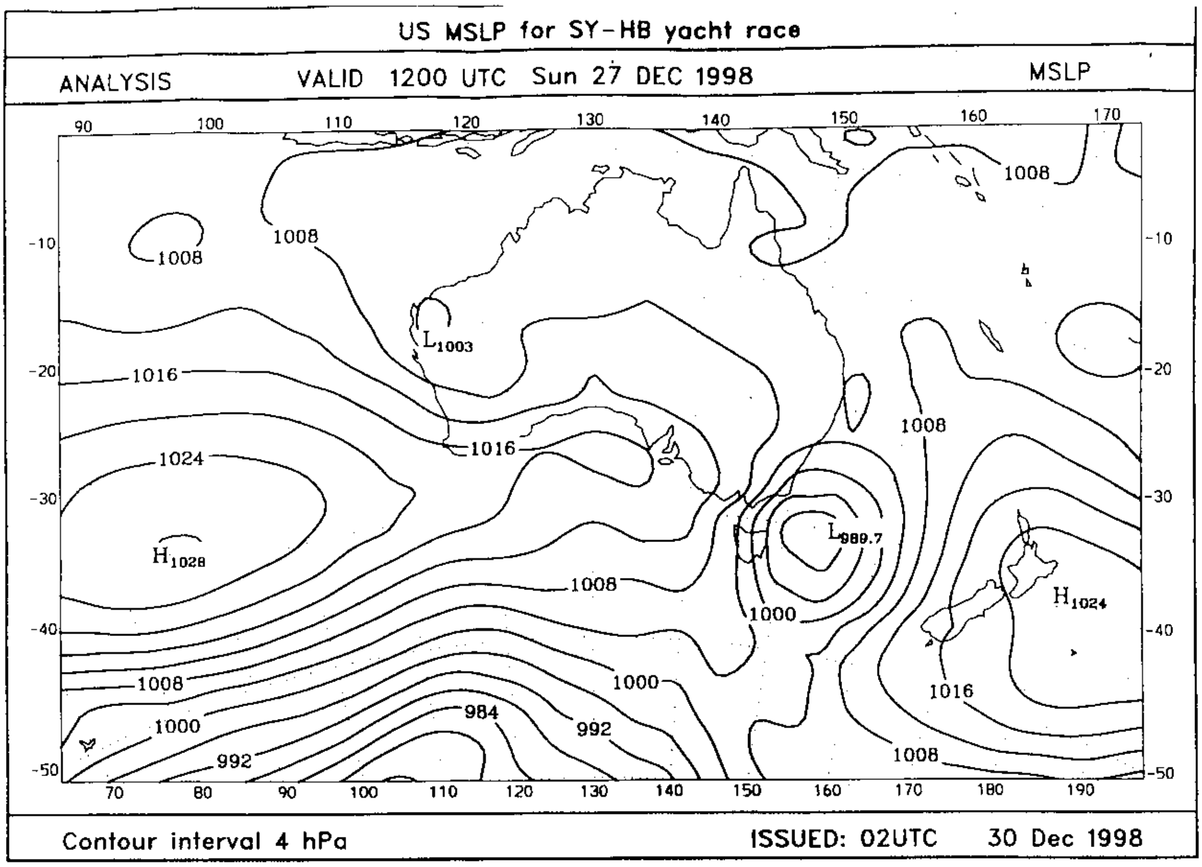

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Figure 1(a): Analysis from the US model, valid 11 pm EDST (12 UTC), Sunday 27 December 1998.

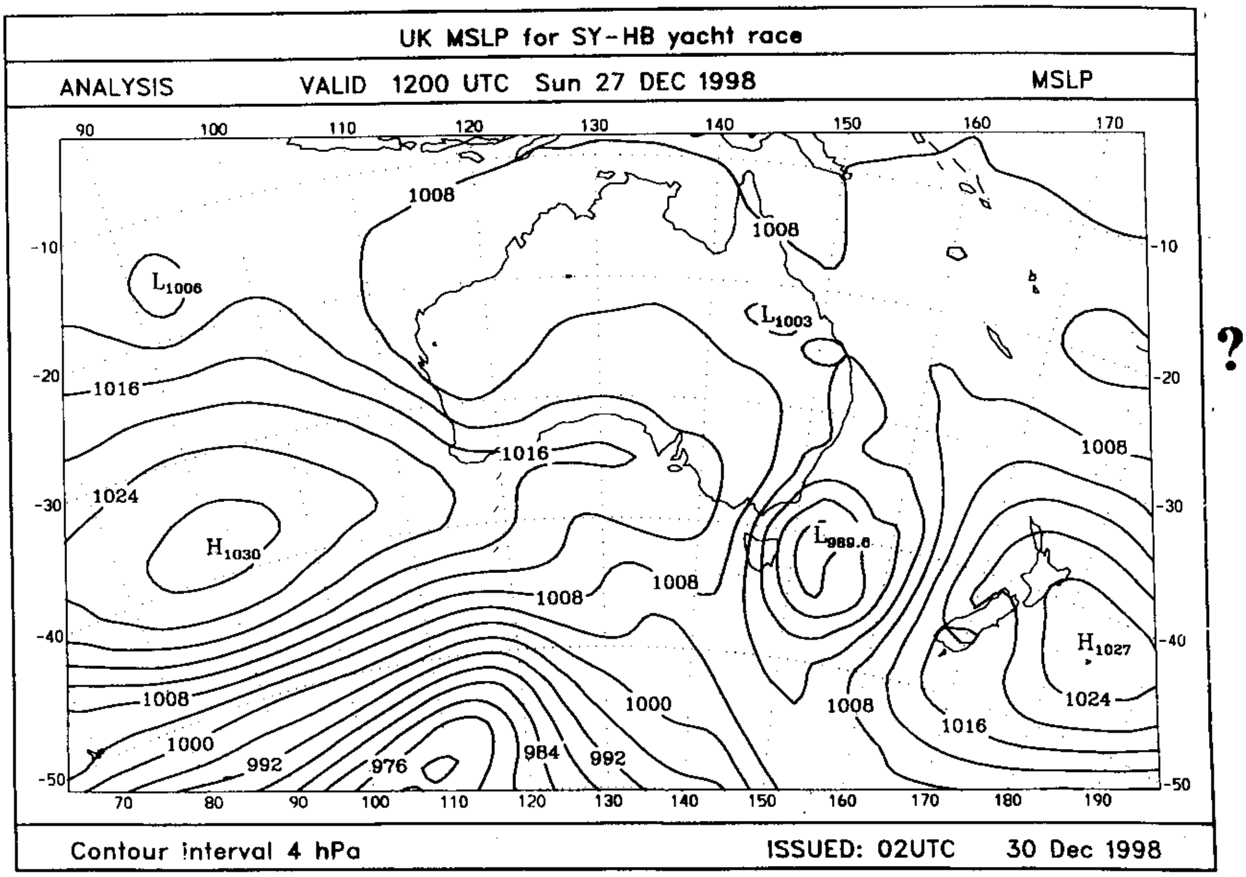

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Figure 1(c): Analysis from the UK model, valid 11 pm EDST (12 UTC), Sunday 27 December 1998.

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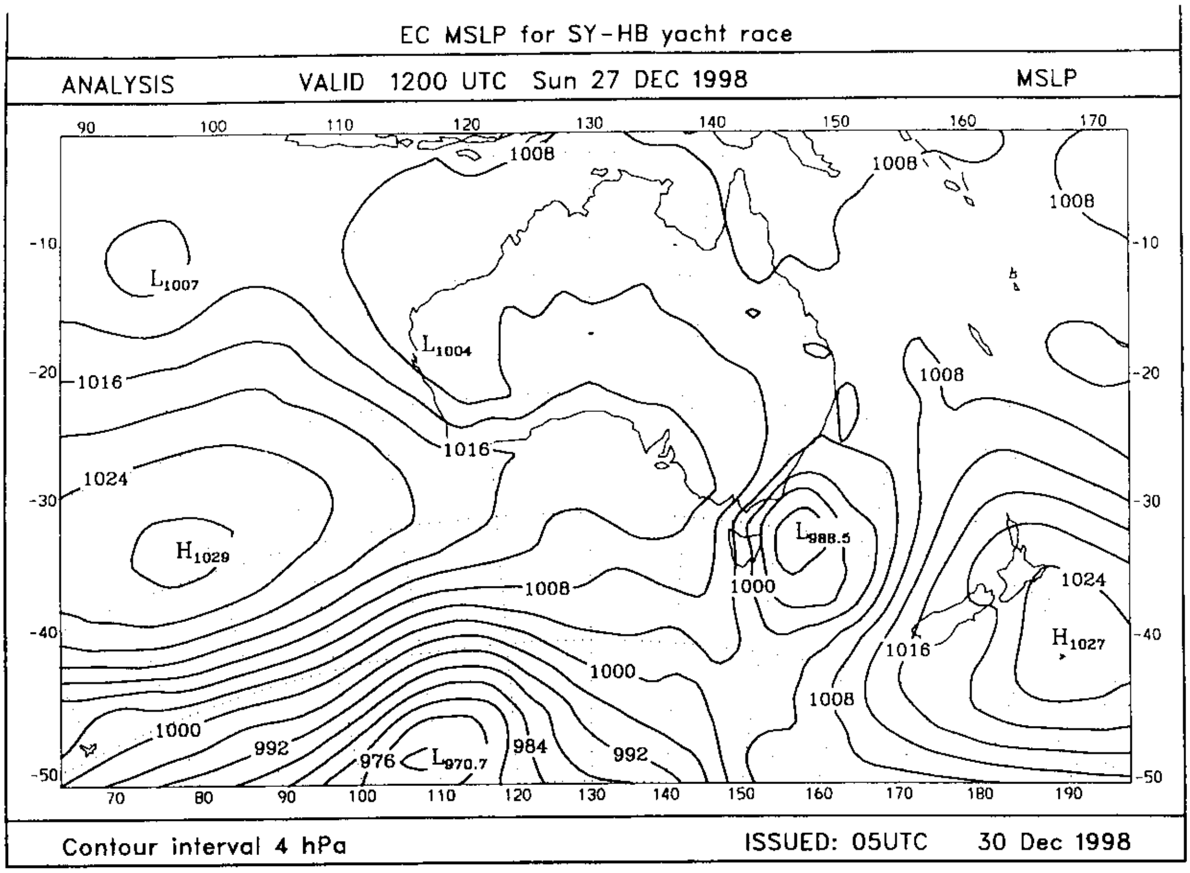

Figure 1(b): Analysis from the EC model, valid 11 pm EDST (12 UTC), Sunday 27 December 1998.

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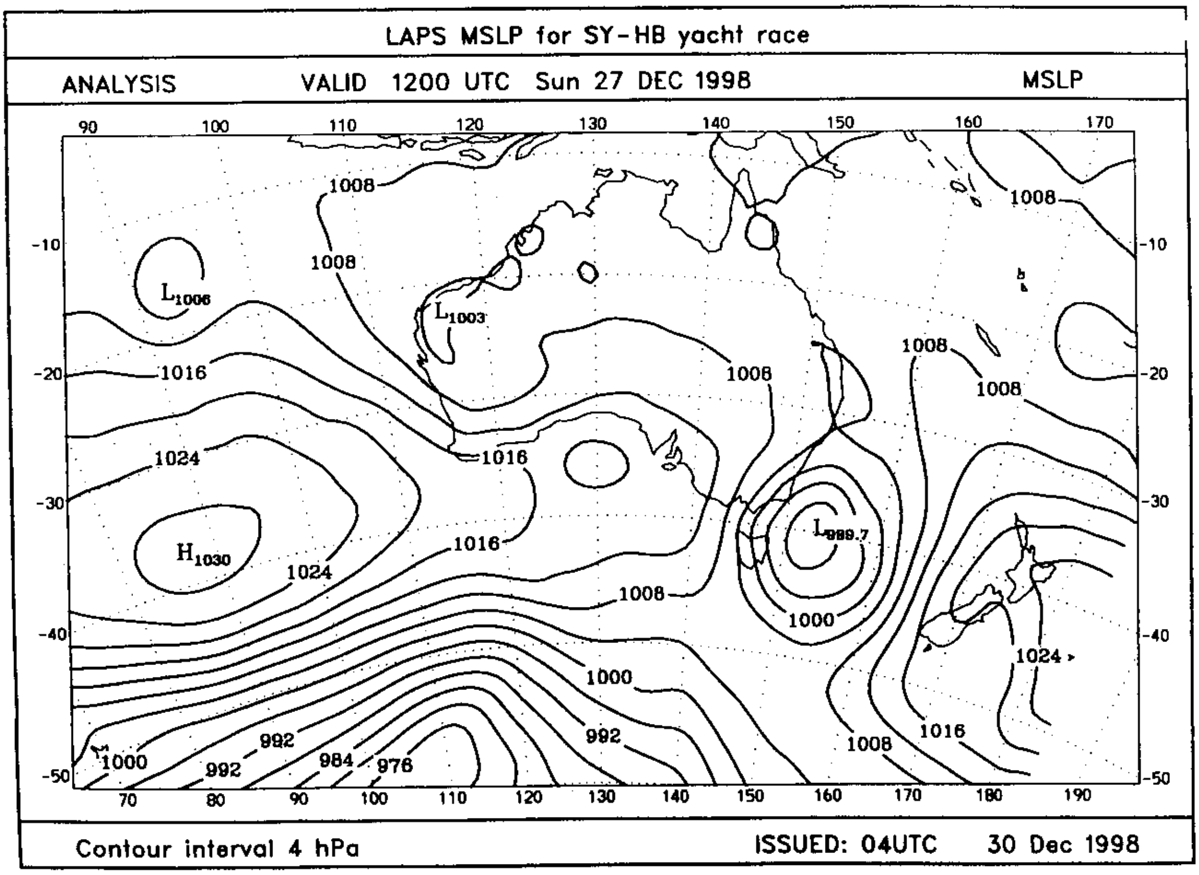

Figure 1(d): Analysis from LAPS, valid 11 pm EDST (12 UTC), Sunday 27 December 1998.

in the Australian area, but this does not necessarily mean that it is always used in preference to the other model output. Forecasters over time may form the view that certain models perform better in certain synoptic situations, and, furthermore, since all models are under constant development it is usual to monitor all of their predictions in case the most recent set of improvements have dramatically changed a model's performance.

Figure 2 is the 12-month running mean skill scores for each of these three systems; the lower the skill score the more accurate the prognoses over the Australian region. As can be seen, the EC system has, on average, outperformed US and GASP.

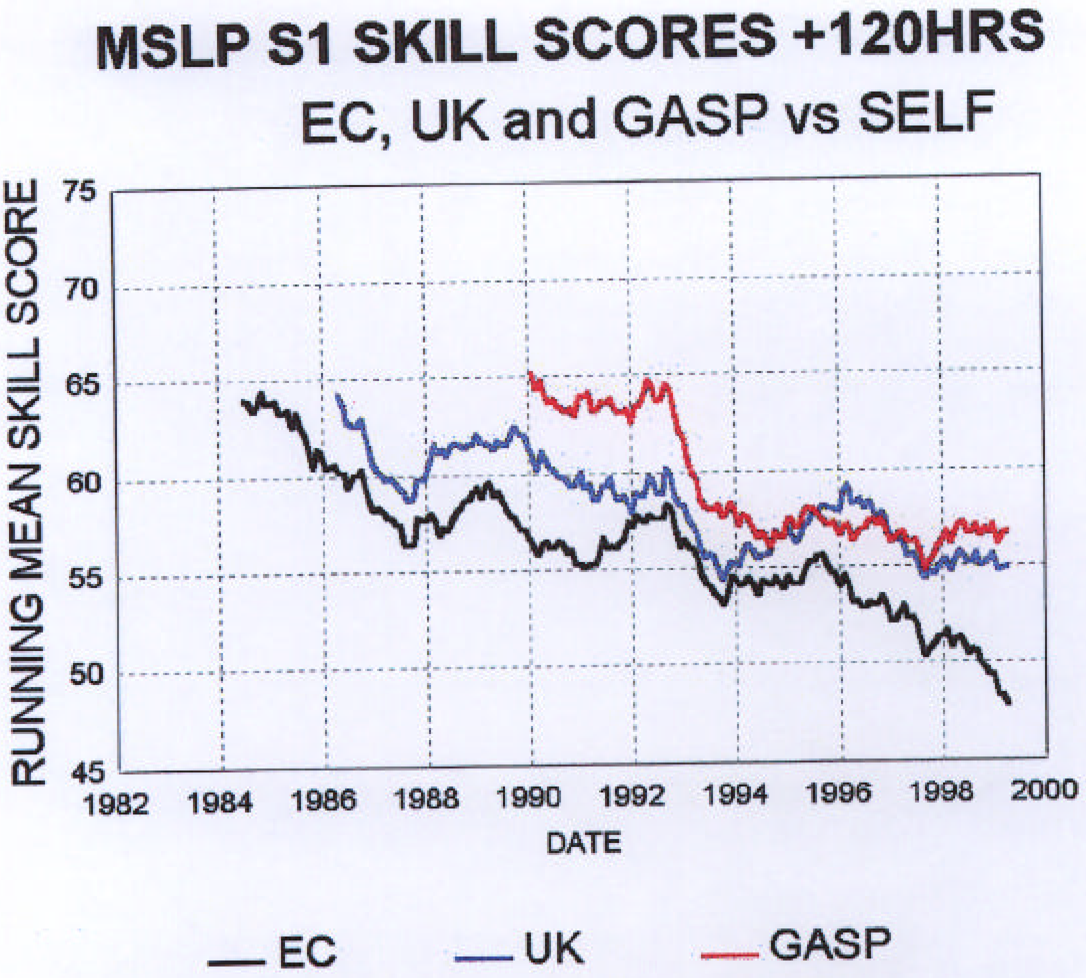

Figure 2: 12-month, running mean S1 skill scores for the 5 day (120 hour) predictions of the EC, UK and GASP models over the Australian region. The lower the S1 skill score, the more skilful the model's performance. SELF refers to the process whereby each 120 hour forecast is verified against an analysis produced by the forecast system being verified.

NWP output available on the morning of 23 December 1998

15 On Wednesday 23 December the EC, UK and GASP systems each provided a 120 hour/5day prognostic chart valid for 11pm (12 UTC) on Sunday 27 December, when the Sydney-Hobart storm was well developed. Figures 3(a), (b) and (c) show these prognoses and figure 3(d) the analysis at the time for which the forecasts are valid (the so-called verifying analysis). The EC forecast is for a weak anticyclone over the race area, the UK system for a low pressure trough in the easterly flow and the GASP system for a weak high pressure ridge moving in from the Great Australian Bight. As can be seen by comparing figures 3(a), (b) and (c) with figure 3(d), none is a particularly good forecast, and their divergence in solution would discourage a forecaster from being confident about any particular weather outcome for Sunday evening.

NWP output available on the morning of 26 December 1998

16 On the morning of Saturday 26 December Race forecasters would have had available the 2 Day (48 hour) forecasts from NWP systems to help them ascertain likely race conditions at 12Z on Sunday 27. At 6am (EDST) the GASP output would have been available (figure 4(c)) and, as events were to develop, it provided a relatively good forecast. This was followed by the US and the UK system output (figures 4(a) and 4(b) respectively) around 8.00am (EDST) with lows shown further southeast than on the GASP prognosis.

17 There is a global data collection at 11am EDST (OO UTC) and these data would have been used in another run of key forecast models later that day. The LAPS +36 hour forecast for Sun 11pm EDST (12 UTC) was available at around noon on Saturday 26, (figure 5(a)) followed one hour later by the meso-laps output (figure 5(b)). This LAPS run would have used the previous 12.00 UTC run of GASP for its outer boundary conditions. On LAPS and meso-laps for the first time the low pressure system is maintained north of 40°S at 11pm on Sunday 27. Furthermore meso-laps shows a deepening of some 10 hpa on earlier NWP runs (a lower central pressure than found in the verifying analysis at figure 5(d)). The feature of meso-LAPS which enabled the intensity of the low to be maintained close to the Australian coast was essentially its high spatial resolution. With a grid point spacing of some 25 Km it was able to show a much smaller, tighter circulation than the other models. It was this particular prognosis, and the accompanying charts of the associated wind and ocean wave fields, which led to the decision by the Bureau's forecasters to issue the first Storm Warning.

18 The remainder of the +36 hour forecast charts prepared from the OO UTC, 26 December data base arrived later that day (GASP at 6pm (figure 5(c))), and around 8.00pm the UK and UK (not shown). By the time the output from these last three global models had arrived the Bureau's forecasters were well committed to their forecasting strategy.

Summary

19 Forecasters have available to them a variety of NWP system output. Generally prognoses are available up to 7 days ahead from global models, but experience and objective verification have shown that significant skill, particularly in difficult situations such as with rapidly developing low pressure systems, is found at shorter lead times such as days 5 and less.

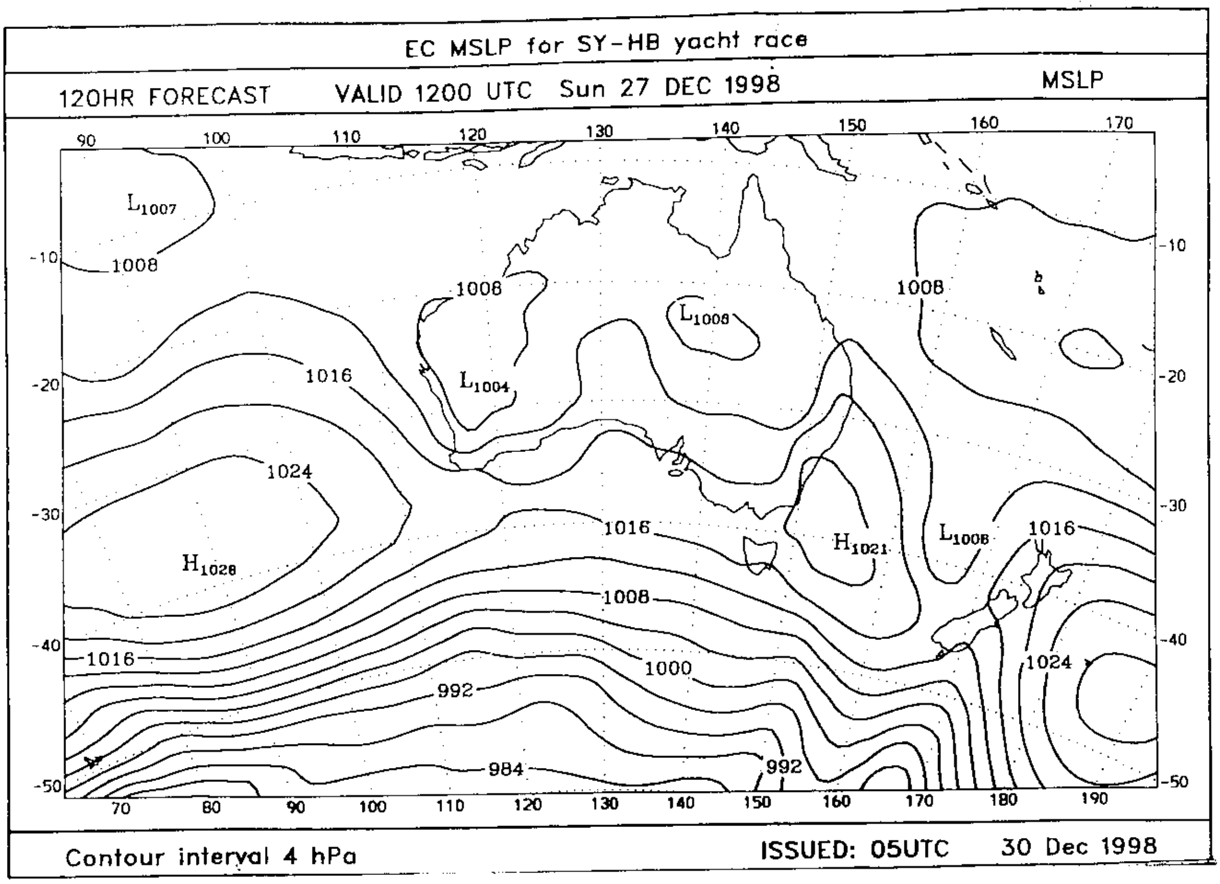

Figure 3(a): 5 Day (120 hour) prognosis from the EC model, valid 11 pm EDST (12 UTC), Sunday 27 December 1998. Available at around 11 am EDST on 23 December.

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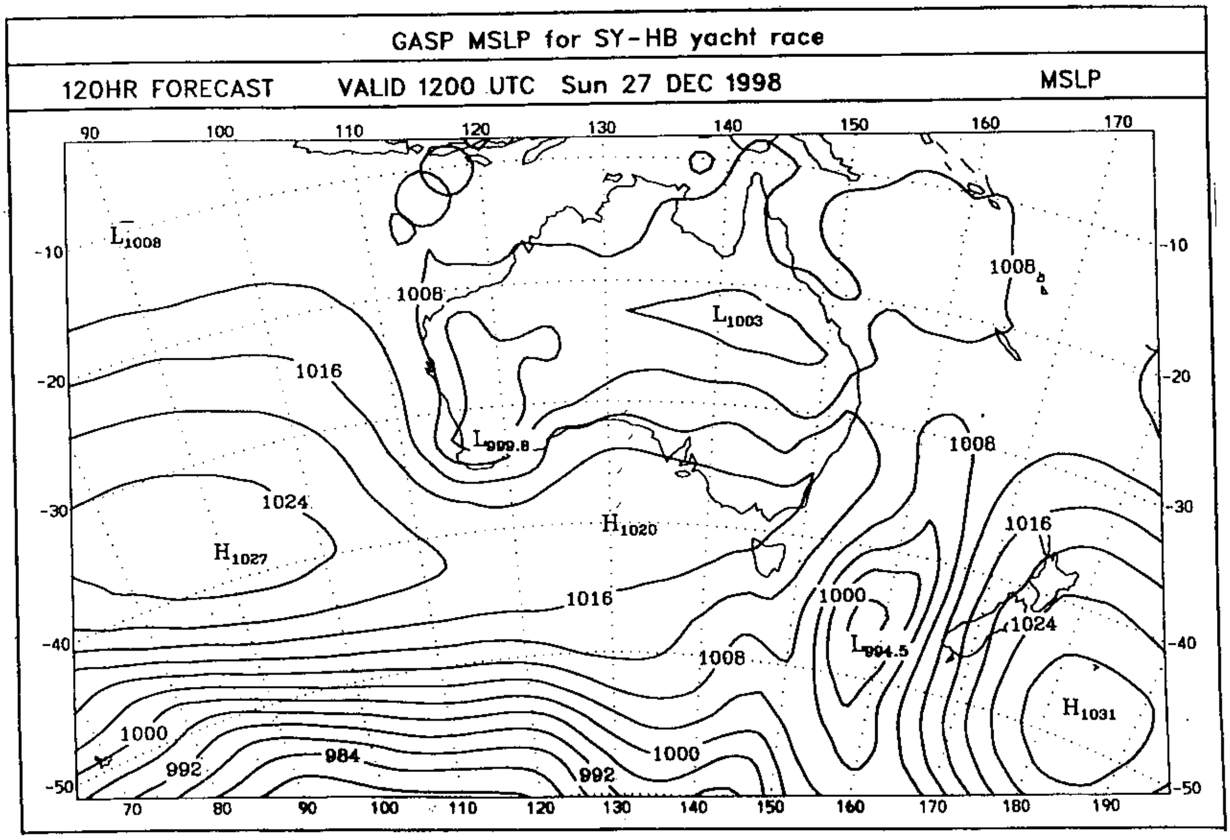

Figure 3(c): 5 Day (120 hour) prognosis from GASP, valid 11 pm EDST (12 UTC), Sunday 27 December 1998. Available at around 8 am EDST on 23 December.

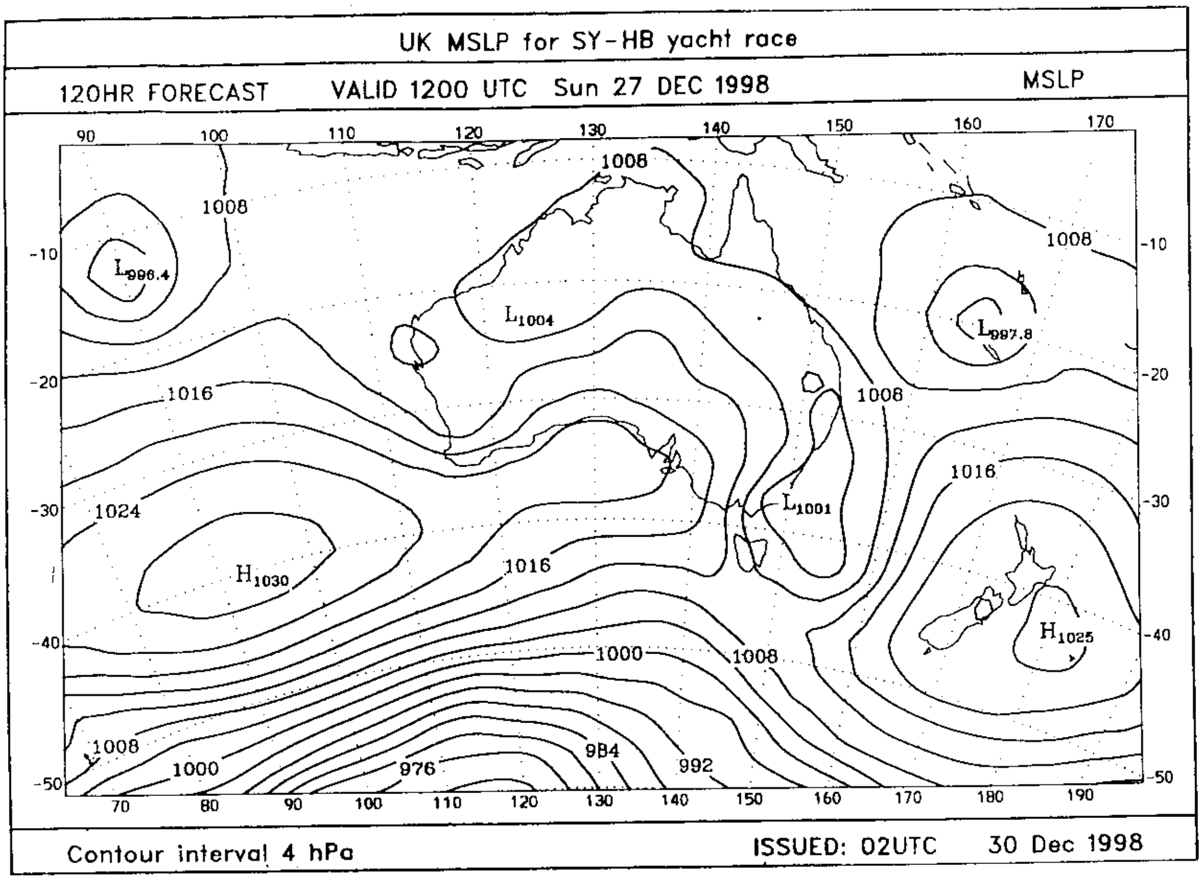

Figure 3(b): 5 Day (120 hour) prognosis from the UK model, valid 11 pm EDST (12 UTC), Sunday 27 December 1998. Available at around 8 am EDST on 23 December.

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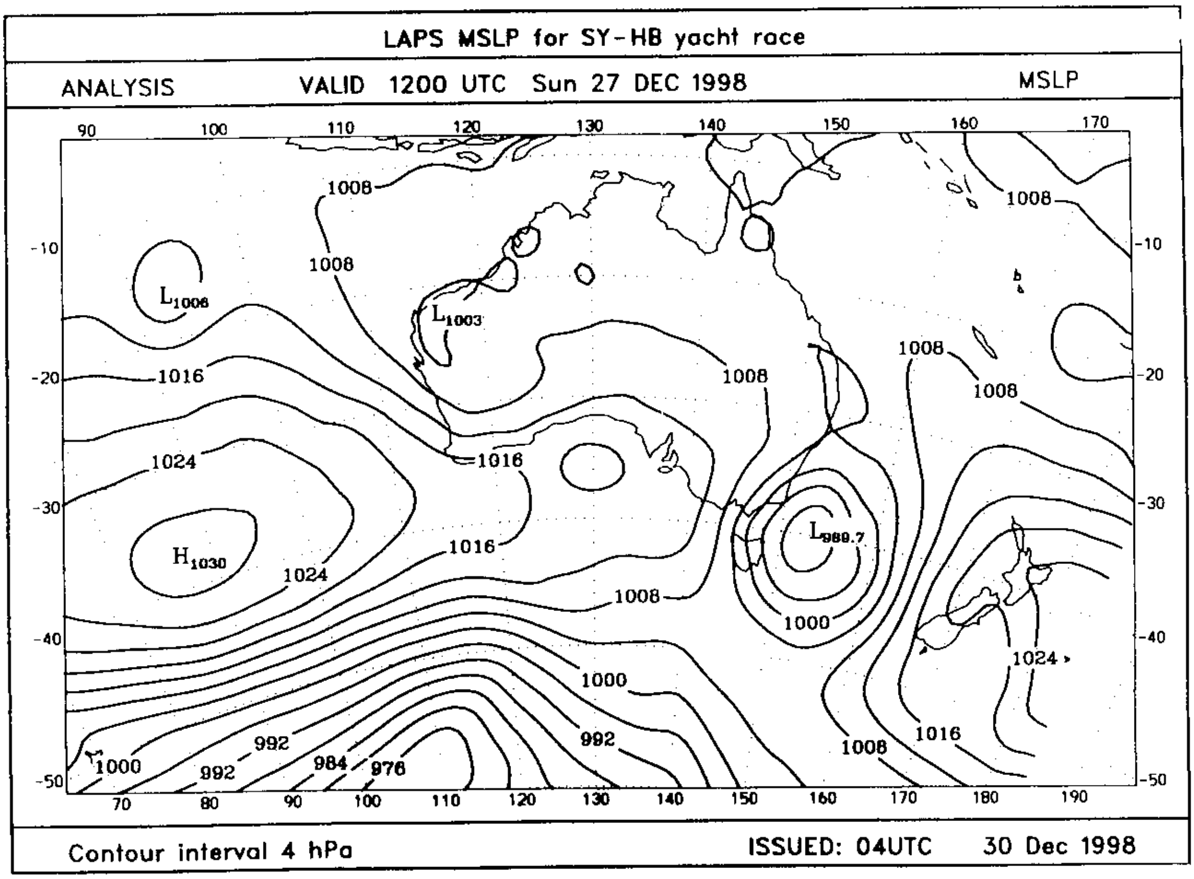

Figure 3(d): Verifying analysis from LAPS, valid 11 pm EDST (12 UTC), Sunday 27 December 1998.

20 Of the models available the EC prognosis are on average the best, but for any given situation any of a variety of models may outperform it. For lead times of 48 hours and less, regional- and meso-scale models become available. By not having to analyse and forecast for the full globe they can have increased horizontal resolution over local areas of interest. To define the weather conditions at the boundaries of the regional- and meso-scale models, data from the global models is utilised, and so these smaller scale models are dependent upon the skill of the larger scale systems they are "nested" within.

21 With hindsight it is easy to identify the NWP system which provided the best guidance for the storm affecting the 1998 Sydney to Hobart Yacht Race. During a significant weather event, however, it requires experience, good judgement and a cool head to accept model output which has extreme consequences and to develop a forecast strategy consistent with that output.

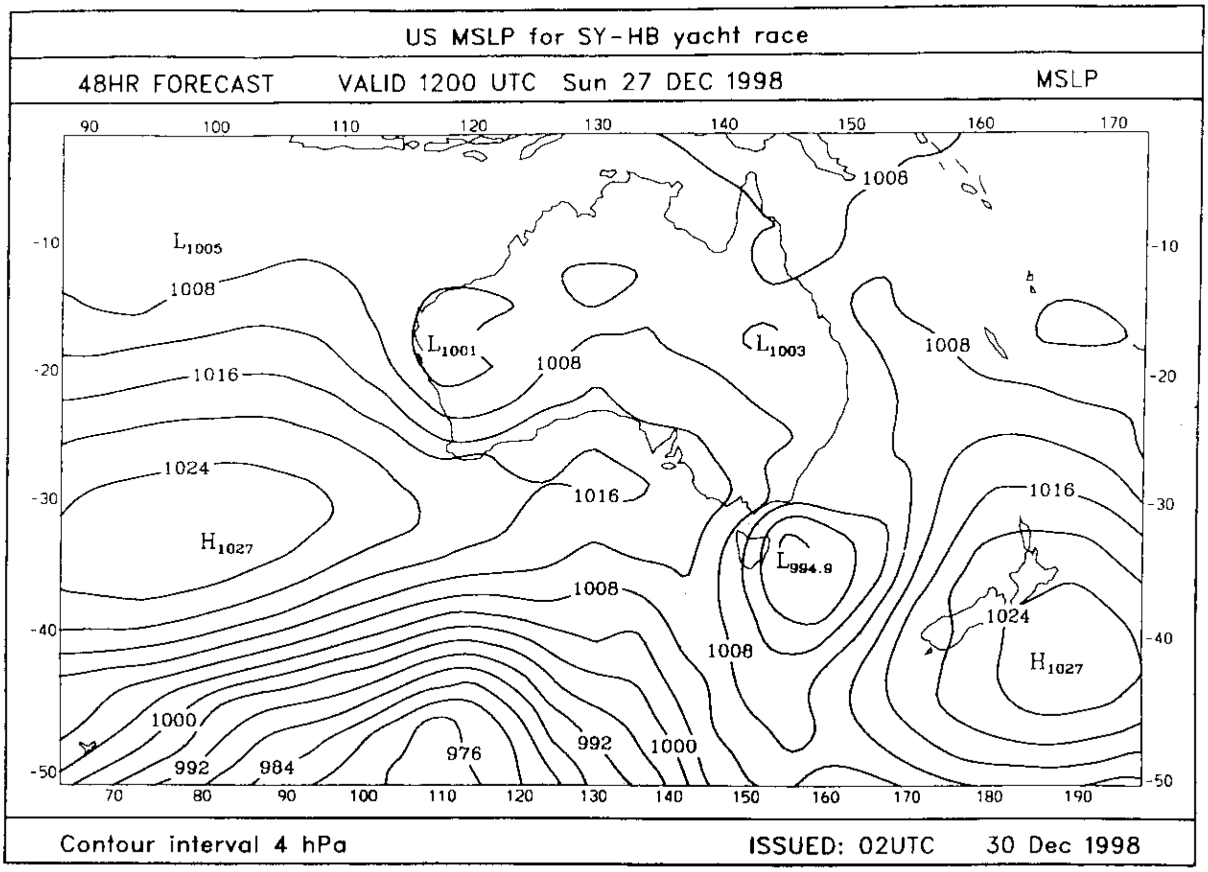

Figure 4(a): **2 Day (48 hour) prognosis from the US model, valid 11 pm EDST (12 UTC), Sunday 27 December 1998. Available at around 8 am EDST on 26 December.**

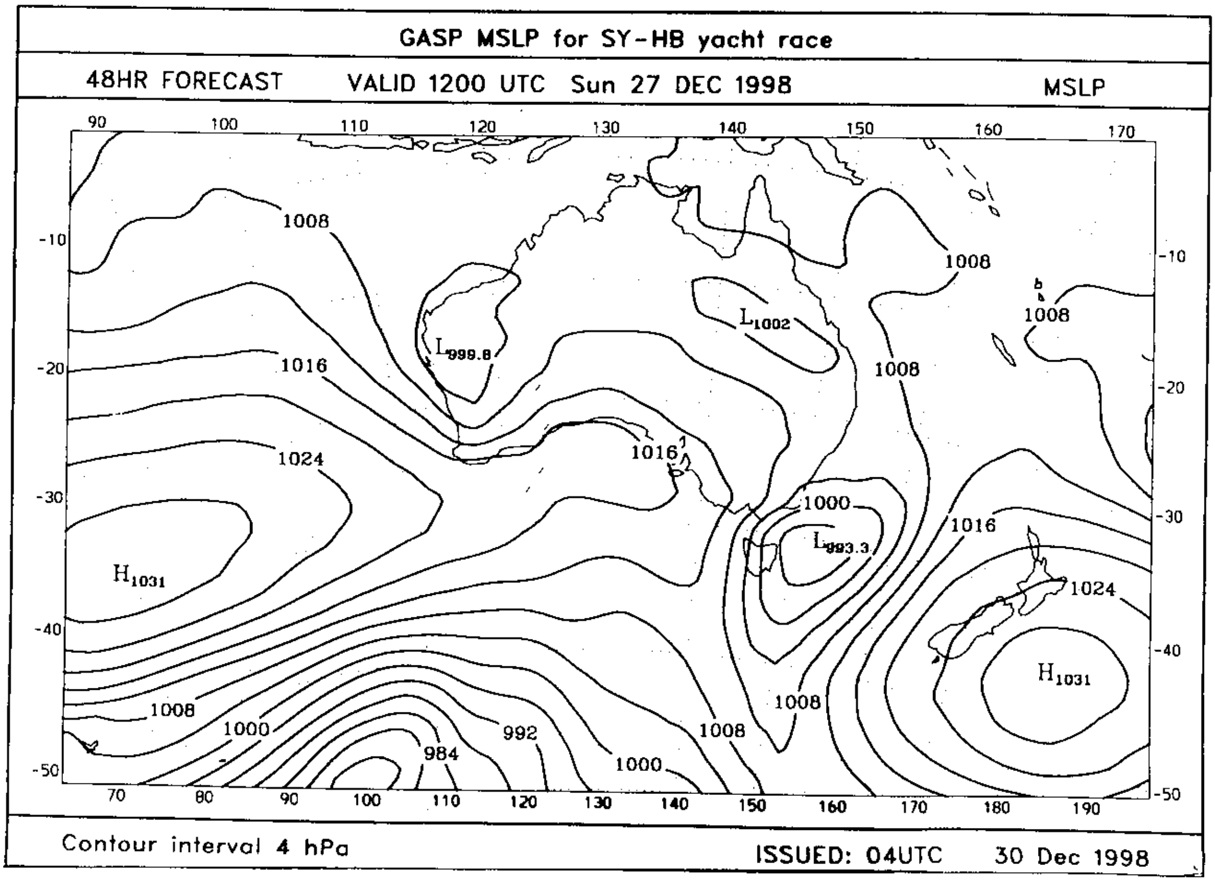

Figure 4(c): **2 Day (48 hour) prognosis from the GASP model, valid 11 pm EDST (12 UTC), Sunday 27 December. Available at around 6am EDST on 26 December.**

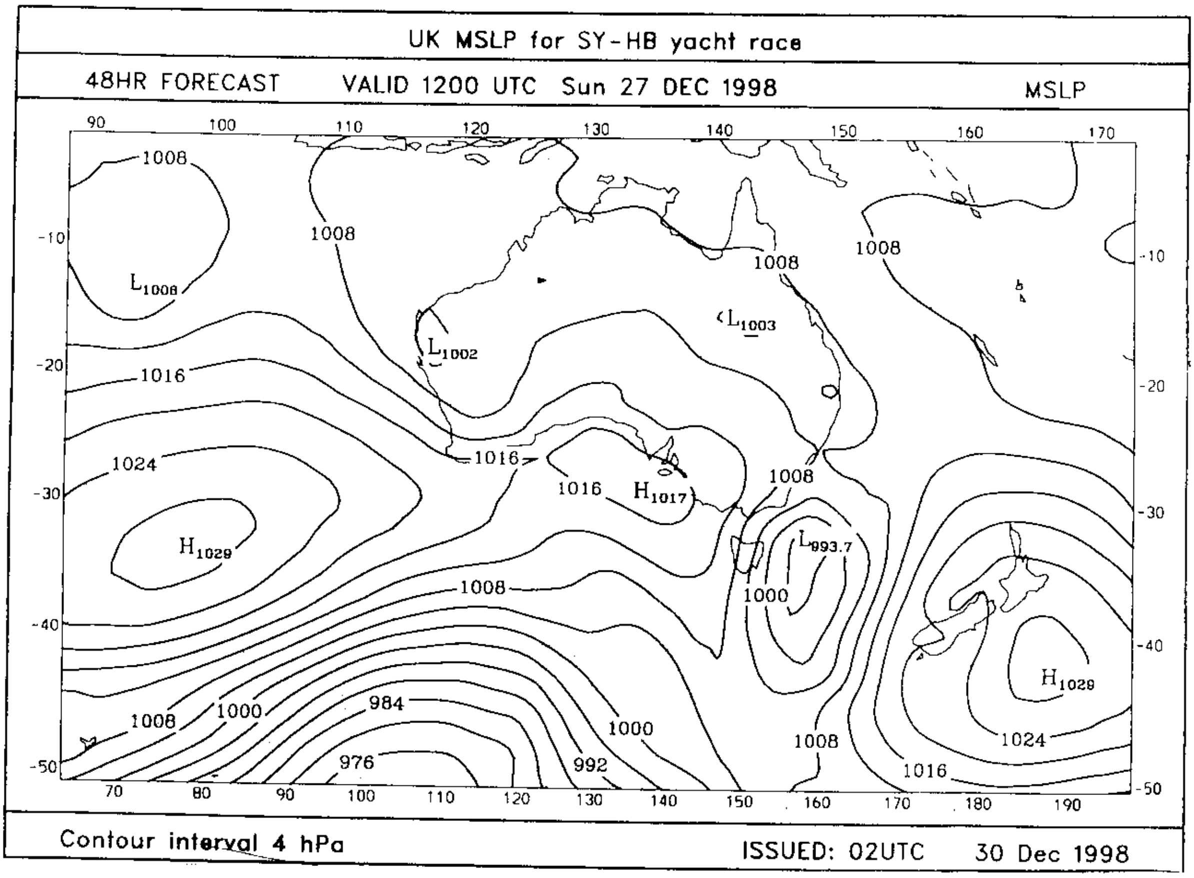

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Figure 4(b): 2 Day (48 hour) prognosis from the UK model, valid 11 pm EDST (12 UTC), Sunday 27 December 1998. Available at around 8 am EDST on 26 December.

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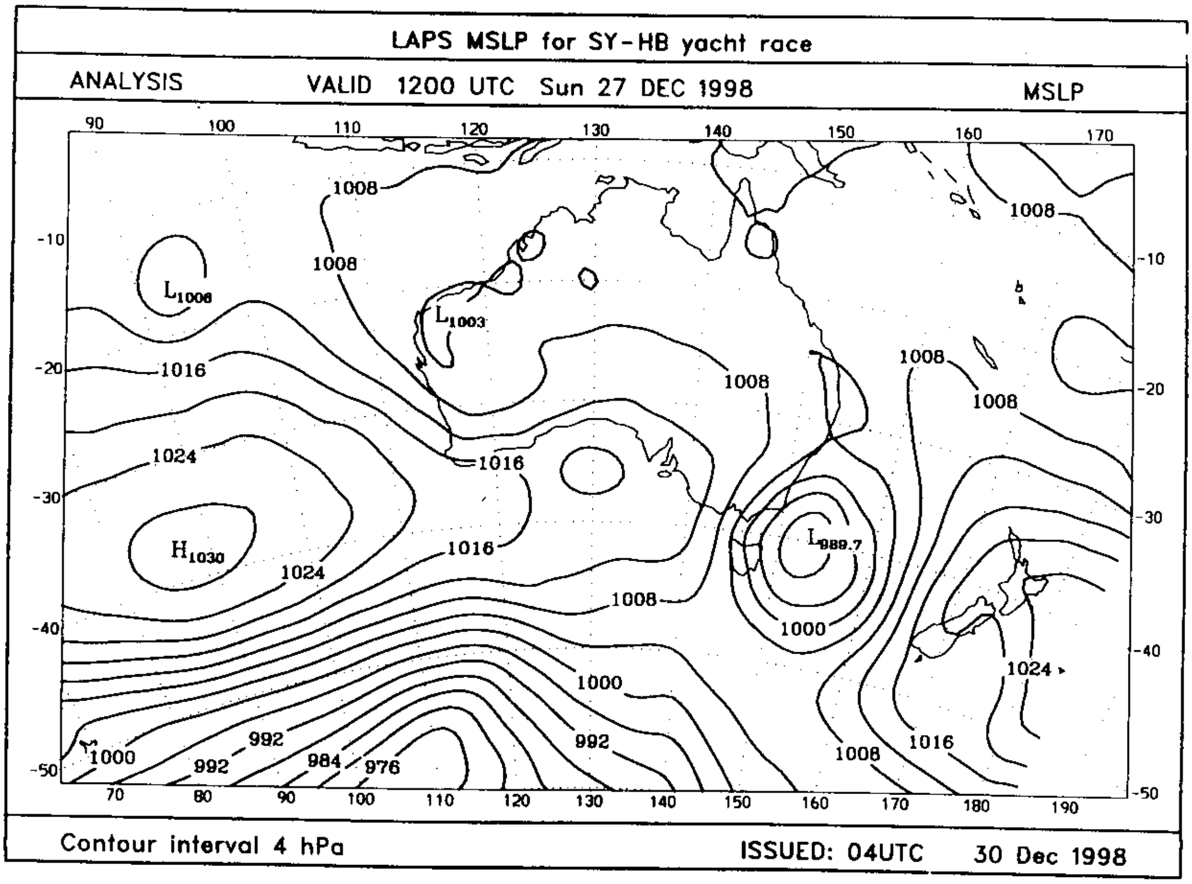

Figure 4(d): Verifying analysis from LAPS, valid 11 pm EDST (12 UTC), Sunday 27 December 1998.

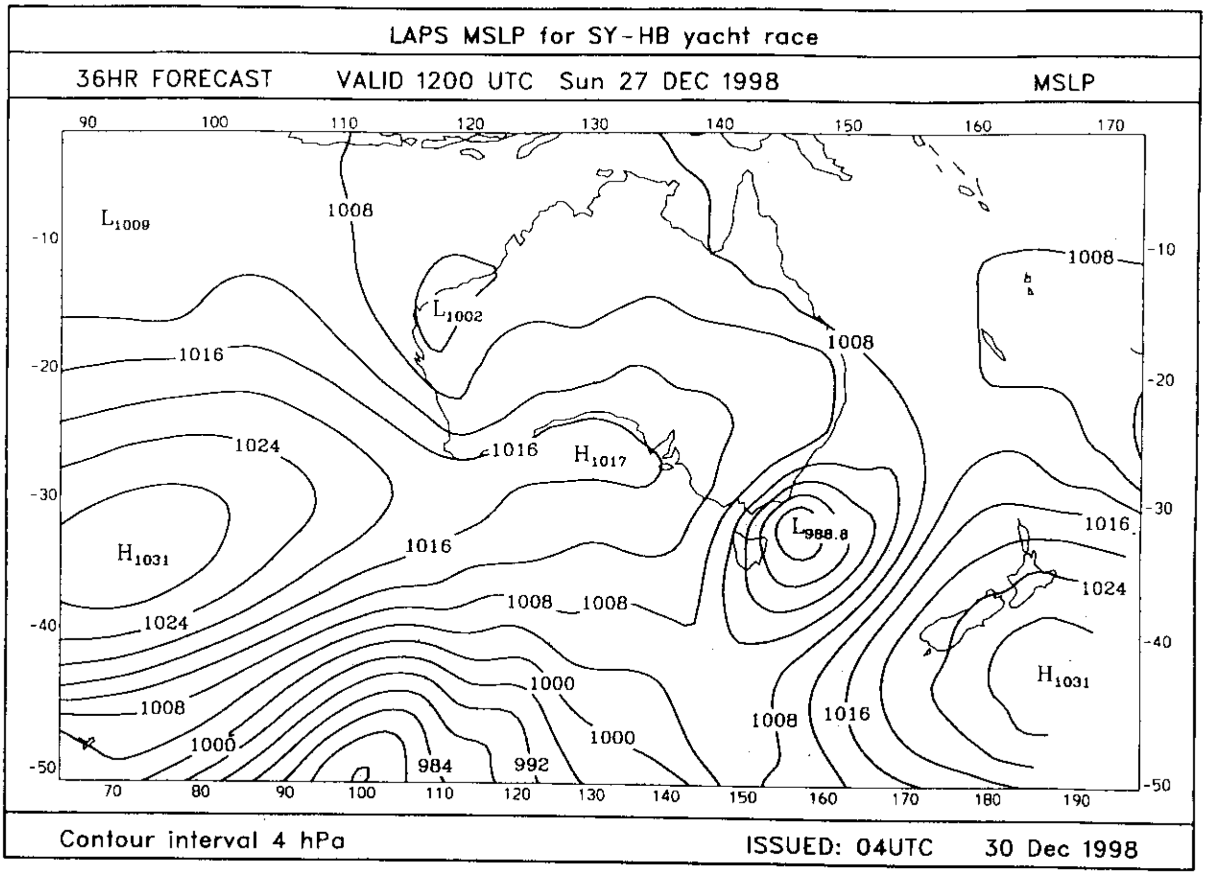

Figure 5(a): 36 hour prognosis from LAPS, valid 11 pm EDST (12 UTC), Sunday 27 December 1998. Available at around 12 pm (noon) EDST on 26 December.

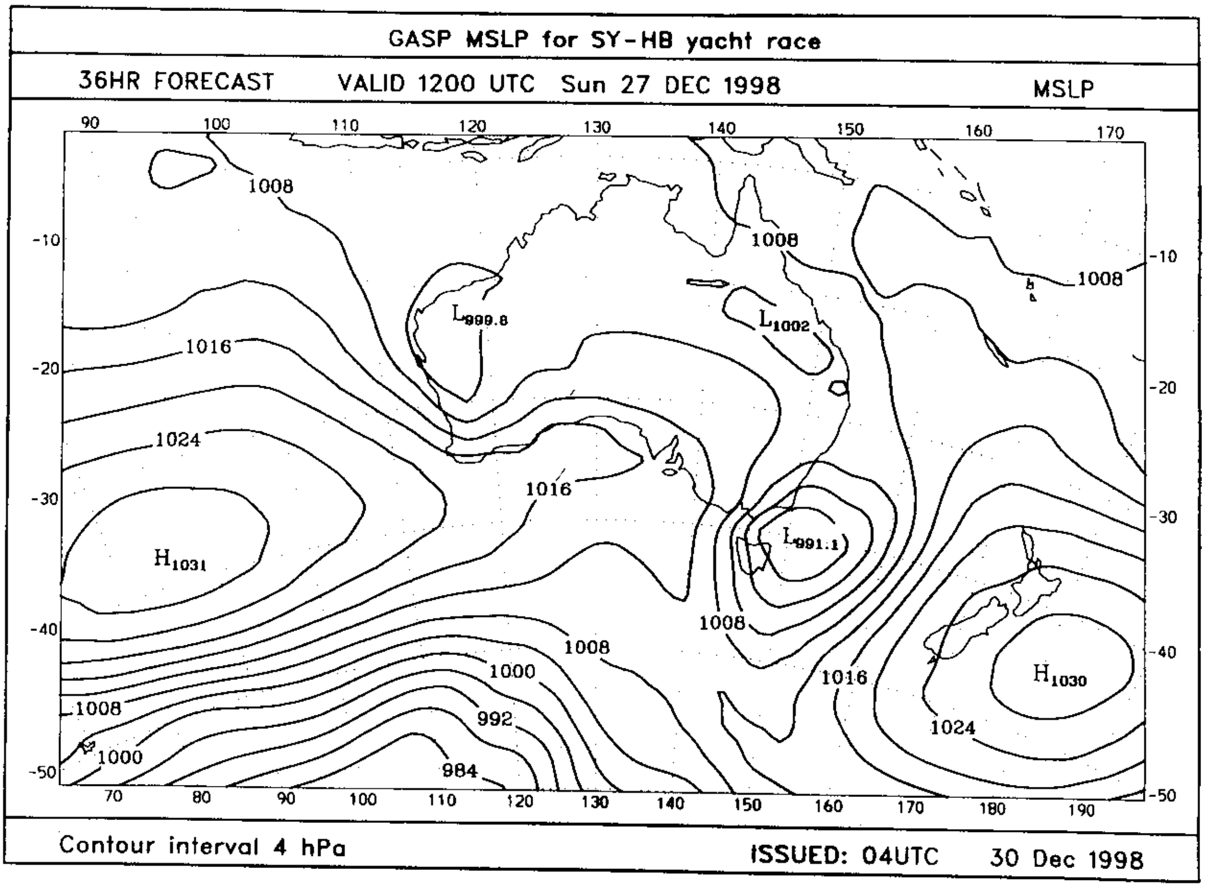

Figure 5(c): 36 hour prognosis from the GASP model, valid 11 pm EDST (12 UTC), Sunday 27 December 1998. Available at around 6 pm EDST on 26 December.

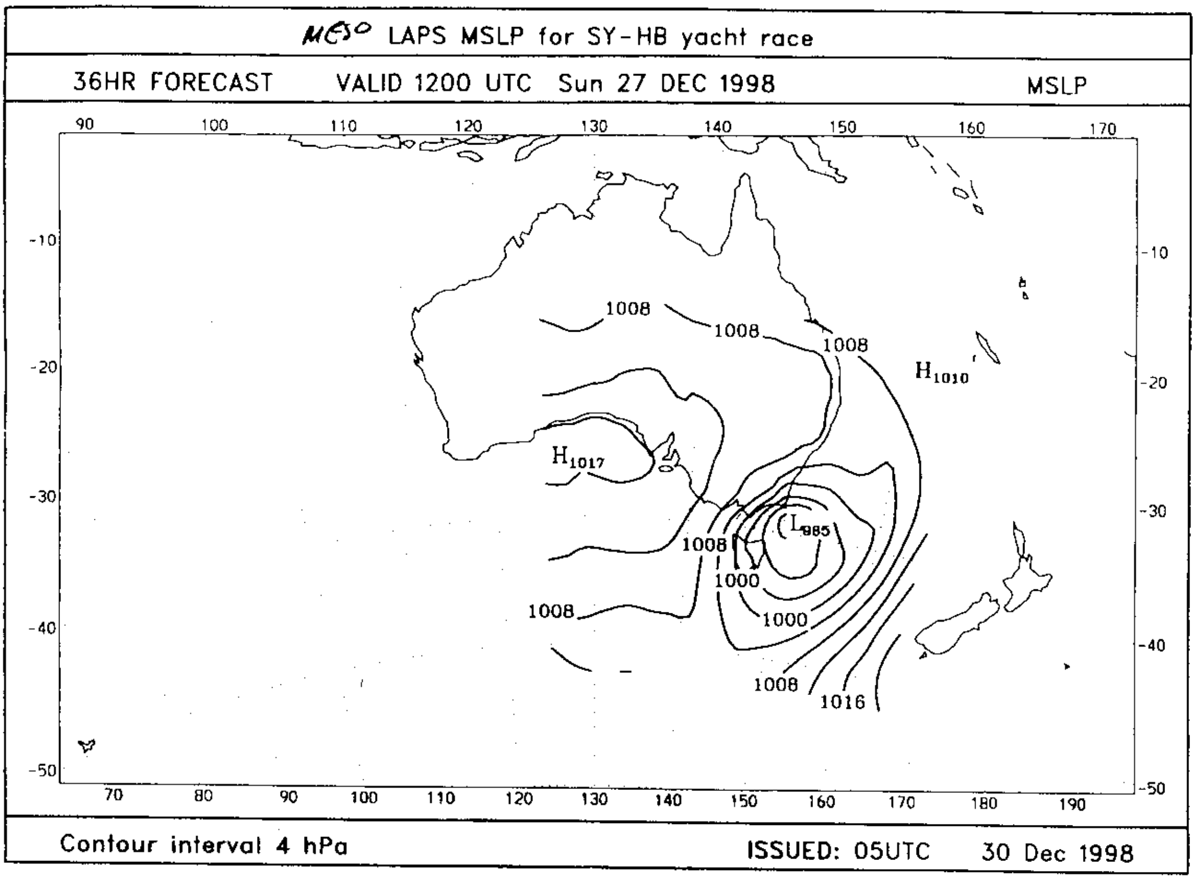

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Figure 5(b): 36 hour prognosis from meso-LAPS, valid 11 pm EDST (12 UTC), Sunday 27 December 1998. Available at around 1 pm EDST on 26 December.

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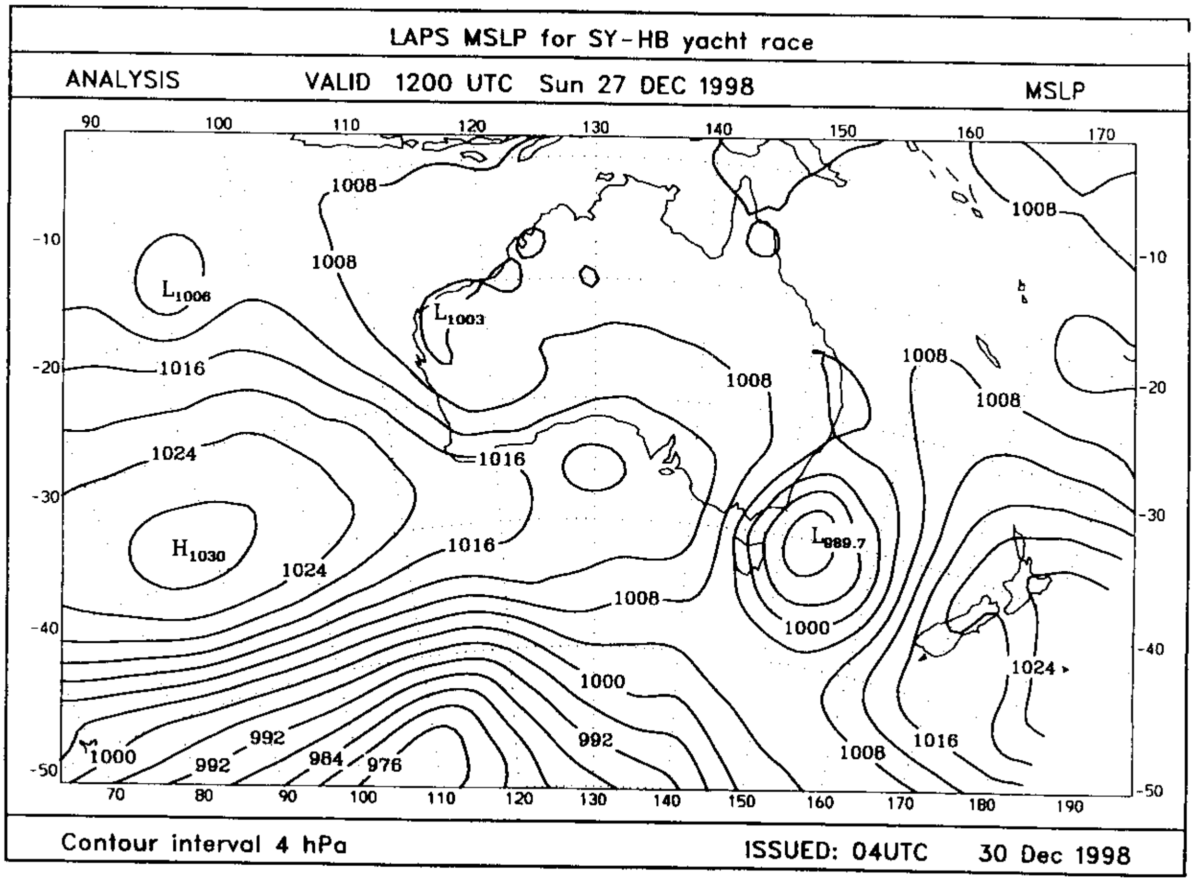


Figure 5(d): Verifying analysis from LAPS, valid 11 pm EDST (12 UTC), Sunday 27 December 1998.

A PRELIMINARY STUDY INTO THE DEVELOPMENT OF A MESOSCALE CYCLONE ON 26/27 ECEMBER 1998

By Dr Graham Mills and Diana Greenslade
Bureau of Meteorology Research Centre

Method

The broad-scale synoptic environment in which the mesoscale cyclone formed, and its structure and evolution of the cyclone have been studied in detail using numerical weather prediction models used for operations and for research by the Bureau of Meteorology. The broad-scale evolution is described using the regional-scale assimilated analyses generated each 6-hours, using well-established techniques for diagnosis of the key 4-dimensional processes acting to create the environment in which the low developed. The advantage of using these objective assimilated analyses. First, all available observations are used in the assimilation analyses is that all observations are used in the assimilation stage. The use of a sophisticated primitive equations numerical weather prediction (NWP) model to link the analyses provides dynamically balanced 3-dimensional gridded values of temperature, wind, and humidity. This dynamic balance allows diagnosis of the forcing of pressure change which cannot be achieved using observations alone.

2. The development of the low and associated strong wind band is studied using a very high resolution NWP model being developed in the Bureau. This model has a grid spacing of approximately 12.5 km, and 29 vertical levels. Comparison of model forecasts at intervals as close as 1 hour with observations, satellite imagery, and the subjective re-analyses of surface pressure show a very accurate simulation of the storm was achieved. Having established that the forecast was very realistic in simulating those aspects of the storm and its environment that we can verify it can be assumed that the structure of the simulated atmosphere is well represented. Then these high-resolution model fields can be used to diagnose both the intricate processes operating to initiate the low, and also describe aspects of its structure. Of particular interest will be the structure and intensity of the band of storm-force winds that affected the yacht fleet.

Broad-scale Description and Diagnosis

3. The broad-scale diagnosis shows that in the two days prior to 9pm EDST 26 December a southern ocean trough amplified from far south of the Bight to form a deep upper-level cut-off low over Bass Strait. A particular feature of this amplification is the movement of a southerly jet stream from the western side of the trough to be located at the apex of the trough by 9pm 26 December. As this upper low amplified and approached western Victoria, pressures fell in that region, a surface low developed over southern Victoria, and this then moved eastward through Bass Strait.

4. As the surface low developed, its low-level circulation brought warm, moist air from the eastern flank of another large low pressure system that was well to the northeast, in the Tasman Sea. This warm, moist air was brought to the southwest, and then caught in the

circulation of the developing low just east of Bass Strait, and brought around its southern side, and then northwards over Tasmania to Bass Strait. At the same time cold, dry southern air was being brought northeastwards over Victoria. The confluence of these two different-density airstreams reinforced and strengthened the pressure gradient which already lay through Bass Strait as a result of the upper low over Tasmania. This confluence has three results that are critical in the discussion of the meso-scale development and structure of the secondary low-pressure system that is to follow:

- First, the strong pressure gradient produced a band of very strong winds from west of Tasmania through to eastern Bass Strait that persisted for some 24 hours;
- Second, the rotation of the flow generated a temperature gradient that was in the opposite direction to the low-level wind flow. This is known as a "reversed shear" situation, and has the result that the strongest winds are in the lowest levels of the atmosphere, just above the levels affected by the friction of the surface; and
- Third, the deep, warm, moist air moving northwards over Bass Strait decreased the static stability of the atmosphere there (that is, the atmosphere's resistance to upward vertical motion associated with cloud and storm formation was reduced) in this area.

Detailed Diagnosis of the Secondary Cyclogenesis

5. The high-resolution modelling studies show the secondary low forming over northeastern Tasmania in the early-morning hours of 27 December. The low moved in a curving arc north and then east through Bass Strait as it intensified through the middle of the 27th and into the evening. The strongest winds are shown to be a perturbation on the already 30-35 knot background current, and the highest speeds increase as the low, and the area of highest winds, moves eastwards. The strongest winds cross near Kingfish B in the late morning of 27th, and move eastwards and continue to strengthen as they pass 150°E. The strongest winds at 10m in this model forecast are around 60 knots, and occur in a very narrow band near 38°S south and east of Gabo Island from mid afternoon to the evening of 27 December.

6. Contemporary theories relate surface cyclogenesis to the advection of upper tropospheric air with large values of cyclonic Isentropic Potential Vorticity (IPV) over favourable low-level environments. Low-level warm anomalies, particularly those with low-level static stability are particularly favoured. This usually occurs on the eastern side of upper tropospheric troughs or lows.

7. In this case the secondary cyclone formed on the *western* side of the upper level low. Detailed examination of the upper level IPV forecasts show a streamer of high IPV air being "wrapped around" the upper low, starting on the western side, but being brought right around the eastern, southern, and finally western side of the upper-level low. This is indirectly confirmed by the water-vapour channel satellite imagery from the GMS-5 satellite. The dark zones in the imagery correspond to these "streamers" of high IPV air in the upper troposphere. This streamer of high IPV air was moving northwestwards over Bass Strait at around 6am 27 December, and provides the forcing for the secondary cyclone. At the same time, the static stability of the lower half of the troposphere over Bass Strait was reducing as the warm, moist air from the Tasman Sea was brought over this region. With a reduced static stability, any response to a forcing of low-level pressure falls is likely to be rapid, and have a small radius.

8. The movement of this filament of high IPV air and the low-level cyclogenesis are very closely associated, and it is proposed that this was the development mechanism for this secondary low. The pressure falls induced by the upper-level IPV advection increased the pressure gradient, and thus the winds, over a relatively small part of the pre-existing strong wind band through Bass Strait. It was this enhanced wind maximum which passed near Kingfish B during the middle of the day on 27 December, and which met the yacht fleet later that day.

Structure of the Secondary Cyclone, and Other Studies

9. The low was "warm-cored", in that it formed in the warm air advected to the western side of the occluding low. This warm air had originated far to the northeast, in the Tasman Sea. Such "pockets" of warm air near the centre of mature cyclones have been referred to as "warm seclusions" in recent literature, because the warm air becomes almost entirely surrounded by colder air late in the cyclone's life cycle – the "occluding" phase, when the low-pressure system becomes vertical. A few studies have shown that rapid cyclogenesis can occur in this warm seclusion. Norwegian meteorologists from the Bergen school in the 1930s knew of the existence of "hurricane-like" storms that sometimes formed in what they termed "the non-frontal trough". This non-frontal trough was an area of warmer air to the west of the main cyclone centre, and which developed late in the low's life cycle. Whether the "non-frontal trough" and the "warm seclusion" are distinctly different entities perhaps need to be examined.

10. Some similarities have can also be seen to the "reversed shear" polar lows, and also to the rare but intense "Type 3" east-coast lows which affect the east coast of Australia. All these systems occur in the warm air to the west of a maturing deep-tropospheric low, and so the Sydney-Hobart secondary low may well fit into this broad class, and we could coin the term "western flank storm" to alert the public to such rare events. (It might be noted that the Norwegian meterological service uses the expression "the poisonous sting in the tail of the occlusion" due to the very strong winds experienced on the Norwegian coast with these storms). Very few of these studies though have addressed the issue of the upper forcing of this cyclogenesis, and so this study does add to our understanding of such systems, and also points to the need for further study of similar systems.

11. The effect of the reversed thermal shear is seen in the structure of the low-level jet. The 12.5 km resolution forecast model predicts wind speeds at 10 m above the surface of up to 60 knots at the peak of the storm. The unfolding development over the period 26-27 December 1998 is shown in Figs. 1-7. Friction at the surface was reducing the speed from that which the pressure gradient could support, and so wind increased very rapidly with height until the effects of the reserved thermal gradient began to reduce the wind speeds. The net effect was an intense low-level jet on the northern flank of the secondary low, with simulated wind speeds of more than 90 knots between 500 and 600 m above the surface just south of Gabo Island in the late afternoon and evening of 27 December.

Study of the Wave Field Generated by the Storm

12. The 10 m winds calculated by a higher resolution version of the numerical weather prediction model have been used to drive a high resolution limited area version of the Bureau's numerical wave prediction model (the WAM model). This model is capable of

responding to the immediate changes in the wind regime resulting from the rapid development and intensification of both cyclone centres and the extraordinary low level jet which affected the area to the east of Bass Strait during the second half of 27 December. It also is responsive to ambient wave conditions outside its immediate domain, with swell energy effectively propagated through the boundary by forcing from the larger scale operational regional WAM model which has a resolution of approximately 100 km.

13. The results of this study show that the ocean surface waves responded strongly to the onset and rapid development of the low-level jet. Waves with significant wave height between 7 m and 8 m were depicted off Gabo I. during the second half of 27 December. The band of large waves, oriented in a south-west to north-east direction, gradually moved eastwards and began to dissipate early on the 28 December. This development is shown in Figs. 8-13.

Resolution of Models Needed to Forecast Such a Storm

14. While the precursor synoptic-scale forcing of a mesoscale system can be accurately resolved in a numerical analysis, the subsequent forecast may not resolve the atmospheric response to that forcing if the model does not have a sufficiently high resolution. It was described earlier that the operational meso-LAPS model (25 km grid, 19 levels) produced a very useful forecast for the forecasters, but that the regional scale LAPS forecast (75 km grid, 29 levels) produced a much less useful forecast. The 12.5 km model run used in the diagnoses above was far superior to the operational 25 km model, but used a revised analysis, and also had 29 vertical levels.

15. To demonstrate the sensitivity of the simulation to the model's grid resolution, four forecasts with different horizontal resolution have been produced. These have 75 km, 37.5 km, 25 km and 12.5 km grids. All have 29 levels, the same package of physical parameterisation, and all are initialised with the same analysis field. This analysis field was generated using all available data, some of which was not available to the operational model run, and used the latest version of the analysis scheme developed in the BMRC. Some hint of the low's structure is seen at 37.5 km, but the definition of the pressure field increases rapidly with increasing resolution, particularly between 75 km and 25 km. In particular, the definition of the pressure fall centre was very broad until the resolution of the models reached 12.5 km. Similarly, the maximum wind speeds, at 10m, forecast at 4pm 27 December near Gabo Island increase in the order 42, 51, 58, 60 knots as we increase the resolution from 75 km to 12.5 km.

16. Figs. 14-17 show the increasing capability of the models to capture the development of the storm, as resolution is increased from 75 km to 12.5 km.

17. Fig. 18 shows the mid-tropospheric situation (at around a height of 7.5 km) precursing the development of the storm, on the morning of 27 December 1998, with the associated water vapour distribution. The significant features to note in this diagram are:

- the clearly defined cyclonic circulation over eastern Bass Strait as depicted by the wind arrows;
- the IPV maximum shown in blue and located concentrically with the circulation of the low; and

- the associated curving band of relatively stronger westerly winds passing over eastern Victoria which wraps around the circulation to form a narrow "jet" of 50-60 knot easterly winds at around 40°S.

18. Such a configuration is consistent with the rapid spin-up and intensification of the low pressure system at the surface during 27 December.

19. It should also be mentioned that as the grid resolution of the model is increased, increased detail is also seen in the structure of the upper-level IPV structure.

Summary

20. The following main points result from the post-event diagnostic study:

- The broad synoptic environment prior to the development of the mesoscale cyclone could be well-explained by classic mid-latitude amplifying trough concepts;
- The secondary cyclogenesis was extremely unusual, but could be explained using diagnostic techniques applied to very high resolution numerical forecast fields. The exact forcing mechanism for such cyclogenesis has not been previously described for Australian storms before;
- The pre-existing low in the Tasman Sea provided a source of warm, moist air which preconditioned the atmosphere over Bass Strait to small scale, rapid cyclogenesis;
- The high winds experienced were generated as a result of a narrow (approximately 50 km wide) low level jet, with wind speeds up to 60 knots, which was oriented east-west across Bass Strait and to the east of longitude 148°E. This band of winds developed during the early hours of 27 December, strengthened and progressed rapidly eastwards to impact directly on the main body of the fleet as it tracked into waters south of latitude 37°S during the day;
- In response to the intense, short-lived low level jet, waves of 5 m to 6 m significant wave height had developed off Gabo I. during the early afternoon of 27 December. During the afternoon and evening of 27 December, waves of between 7 m and 8 m significant wave height were generated in a band running north-east from about 100km east of Gabo I. This band persisted into the morning of 28 December, as it moved eastwards into the Tasman Sea and began to dissipate; and
- Only with very high resolution numerical models could such a low be forecast.

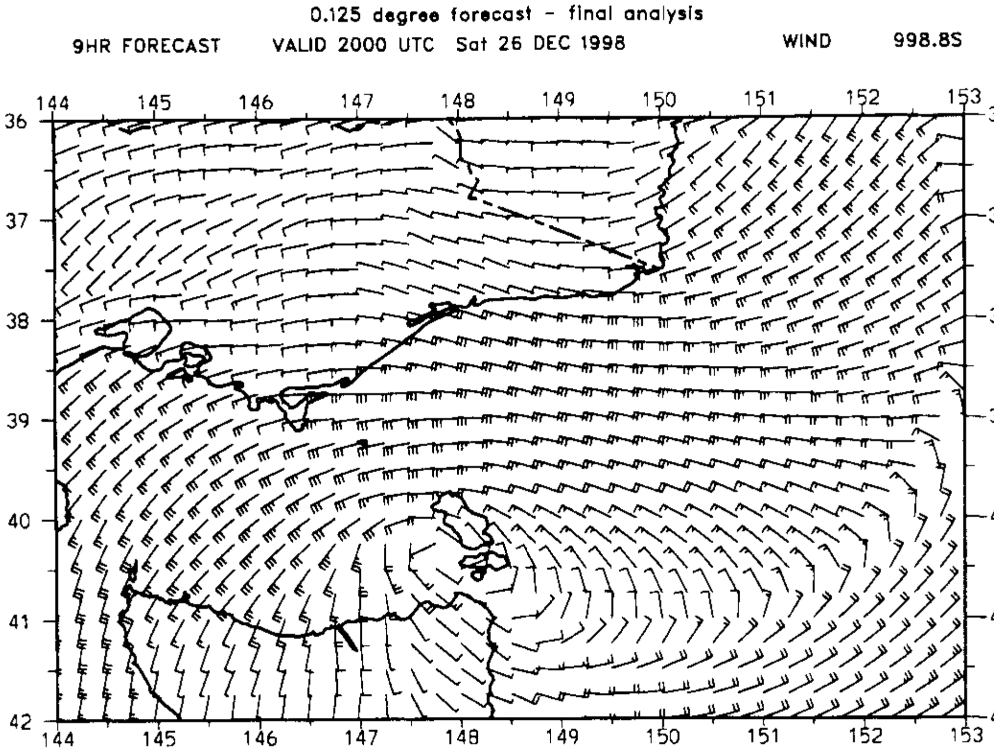
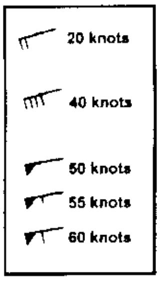


Figure 1. Modelled surface winds for 7am 27 December 1998



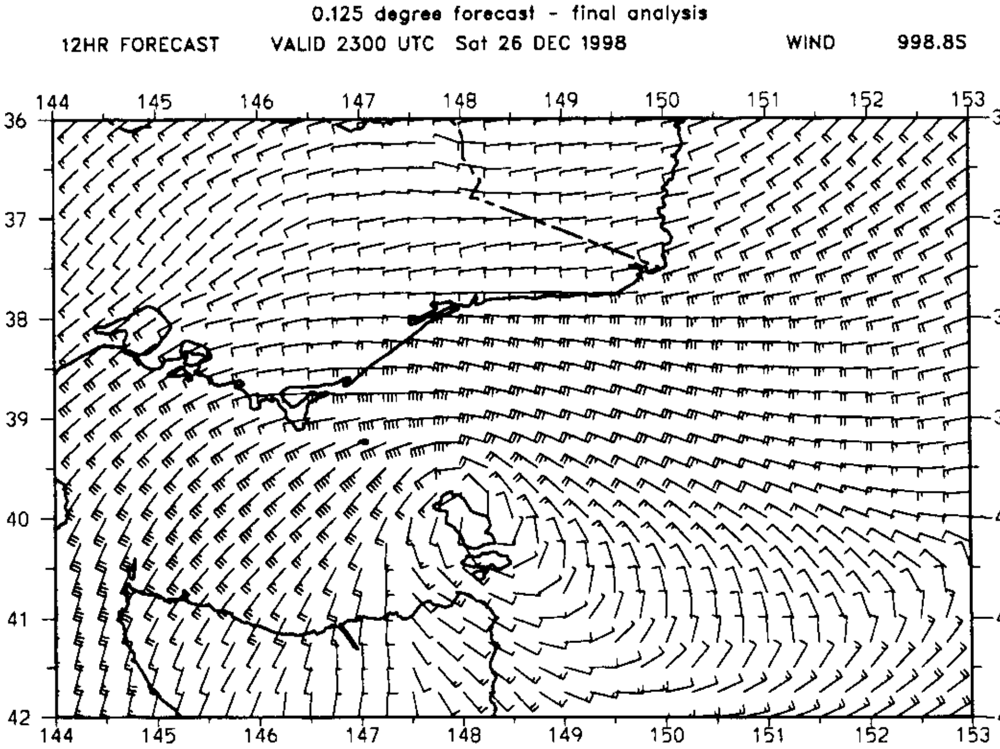


Figure 2. Modelled surface winds for 10am 27 December 1998

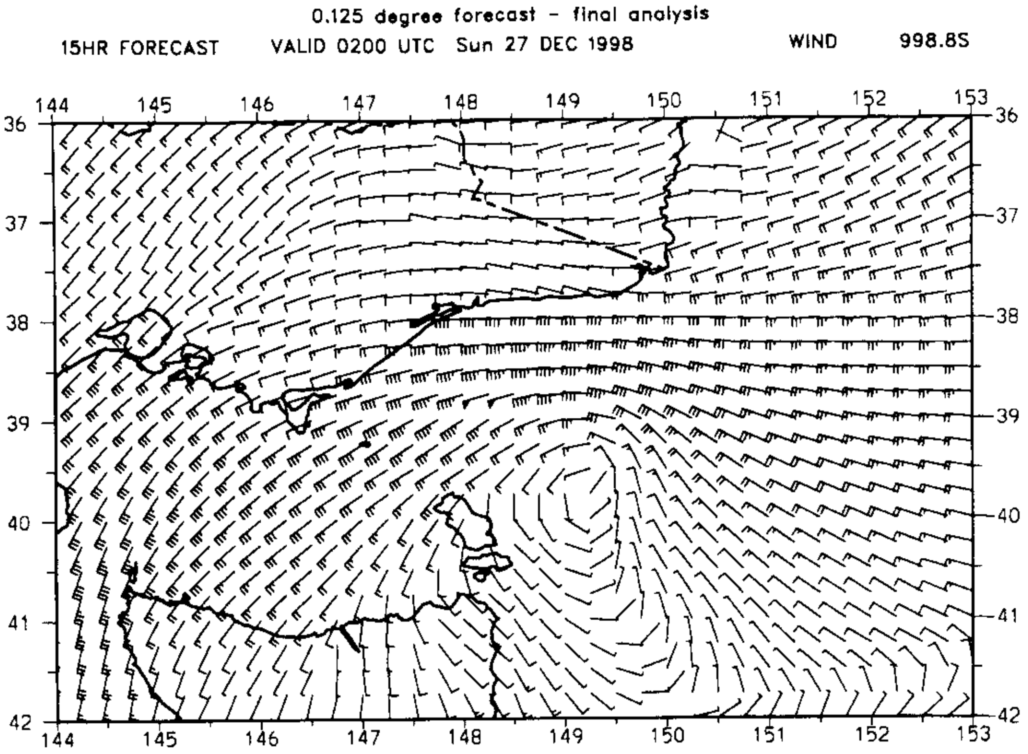
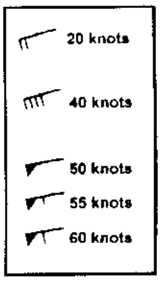


Figure 3. Modelled surface winds for 1pm 27 December 1998



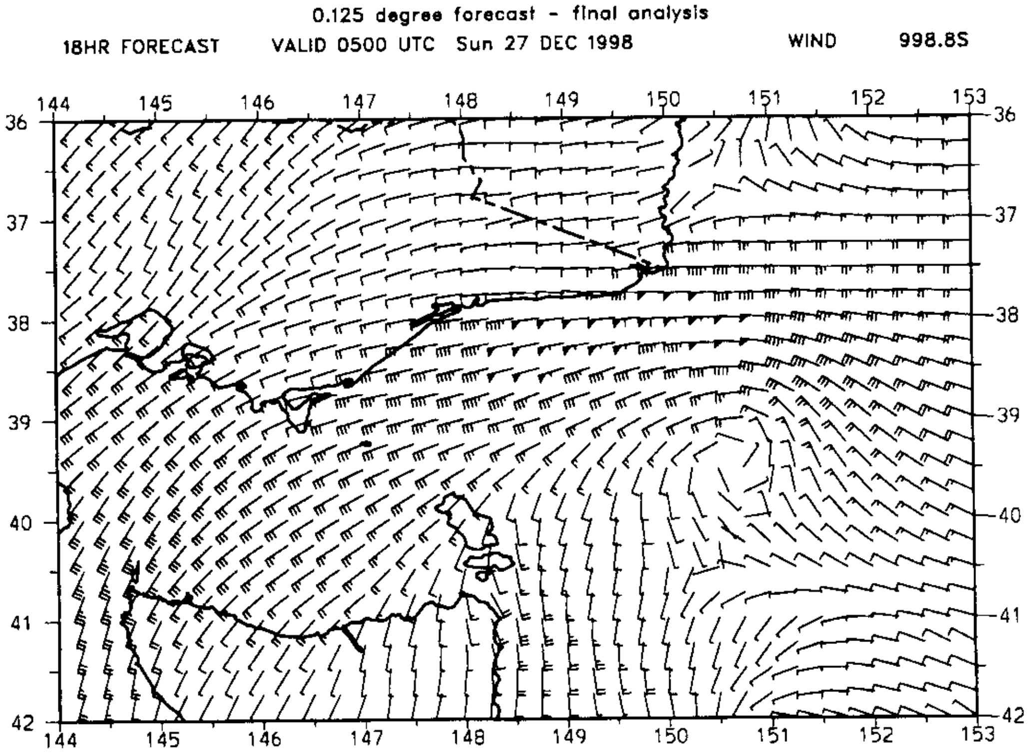


Figure 4. Modelled surface winds for 4pm 27 December 1998

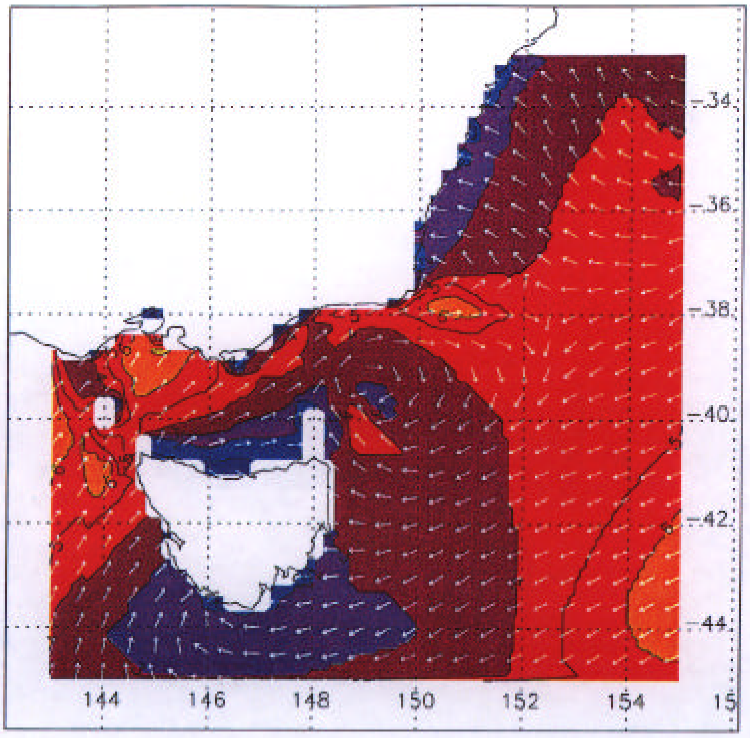


Figure 8. Modelled significant wave height (m) and direction for 2pm 27 December 1998.

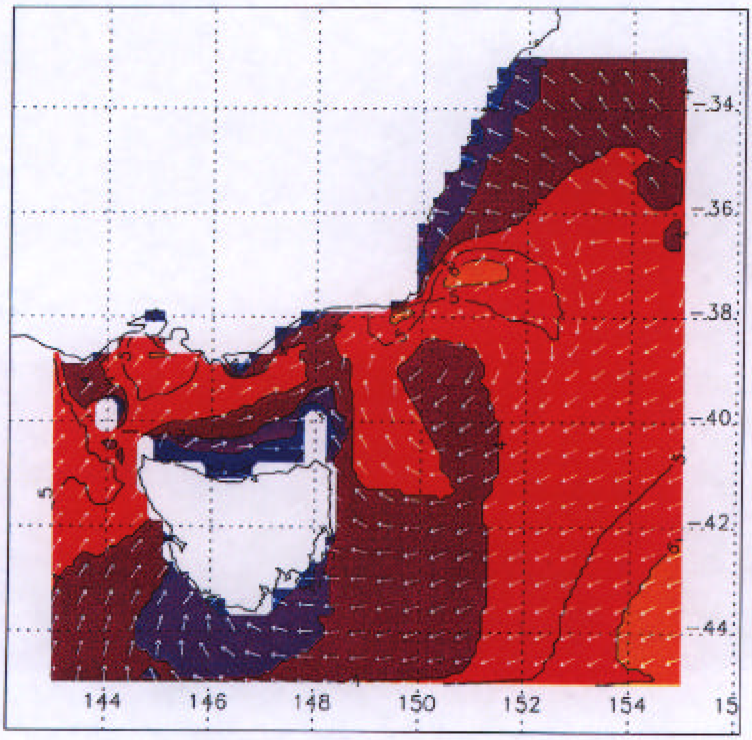


Figure 9. Modelled significant wave height (m) and direction for 5pm 27 December 1998.

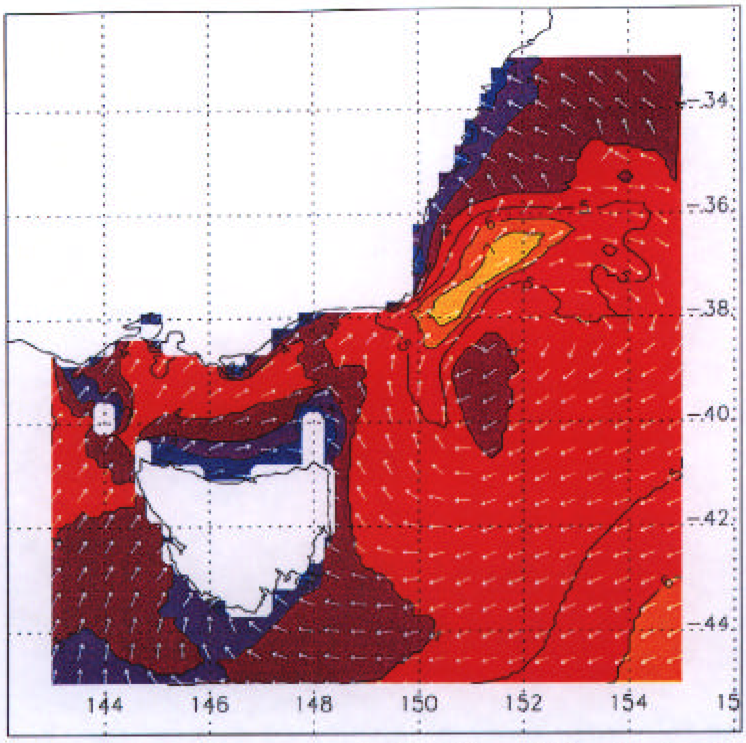


Figure 10. Modelled significant wave height (m) and direction for 8pm 27 December 1998.

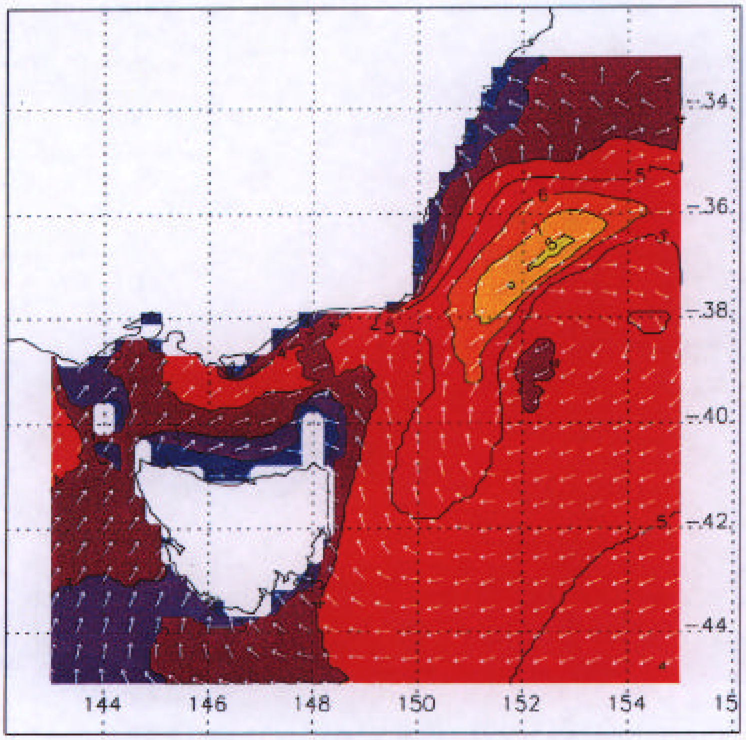


Figure 11. Modelled significant wave height (m) and direction for 11pm 27 December 1998.

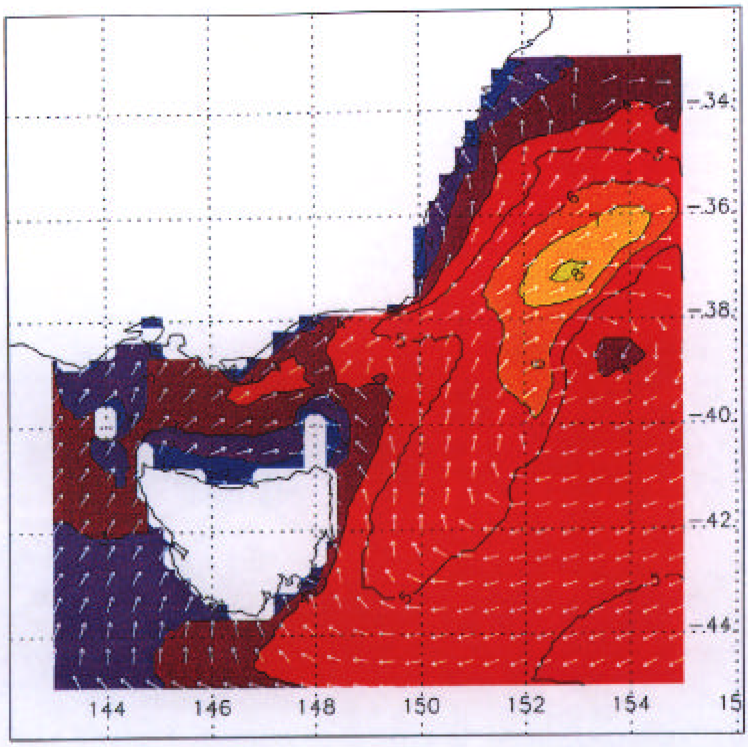


Figure 12. Modelled significant wave height (m) and direction for 2am 28 December 1998.

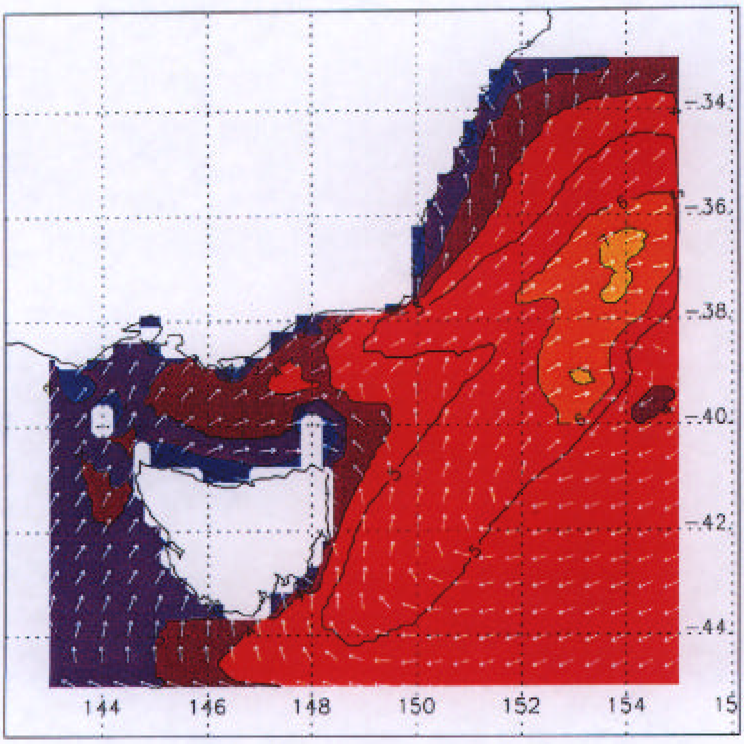


Figure 13. Modelled significant wave height (m) and direction for 5am 28 December 1998.

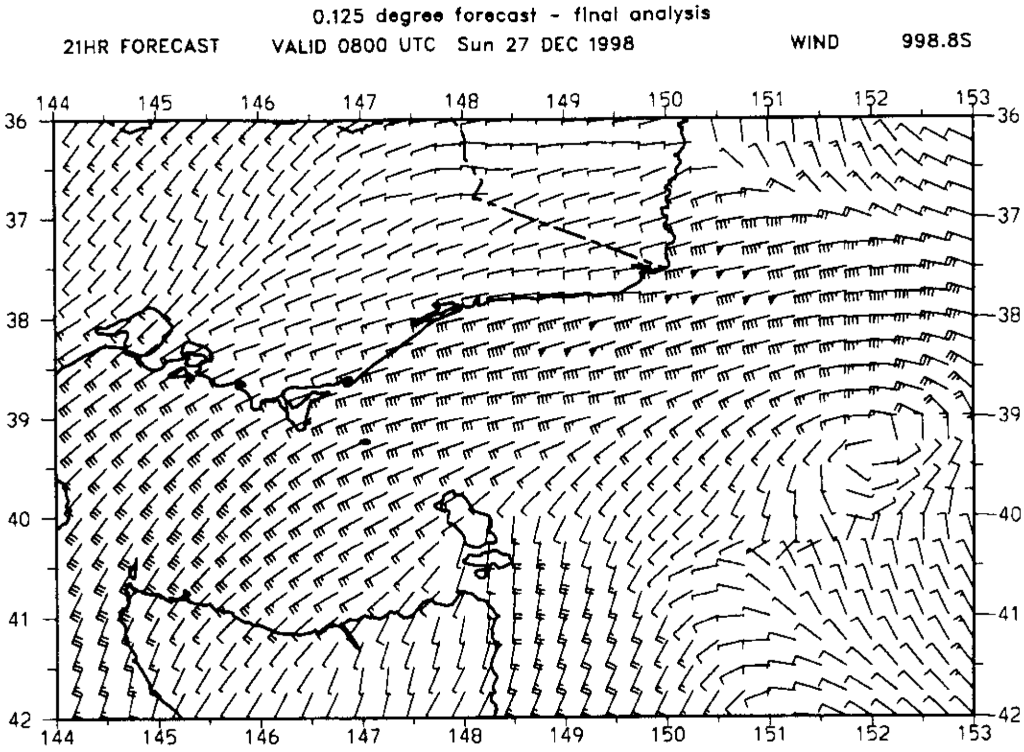
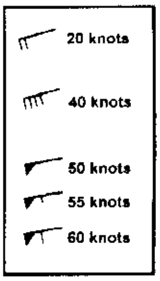


Figure 5. Modelled surface winds for 7pm 27 December 1998



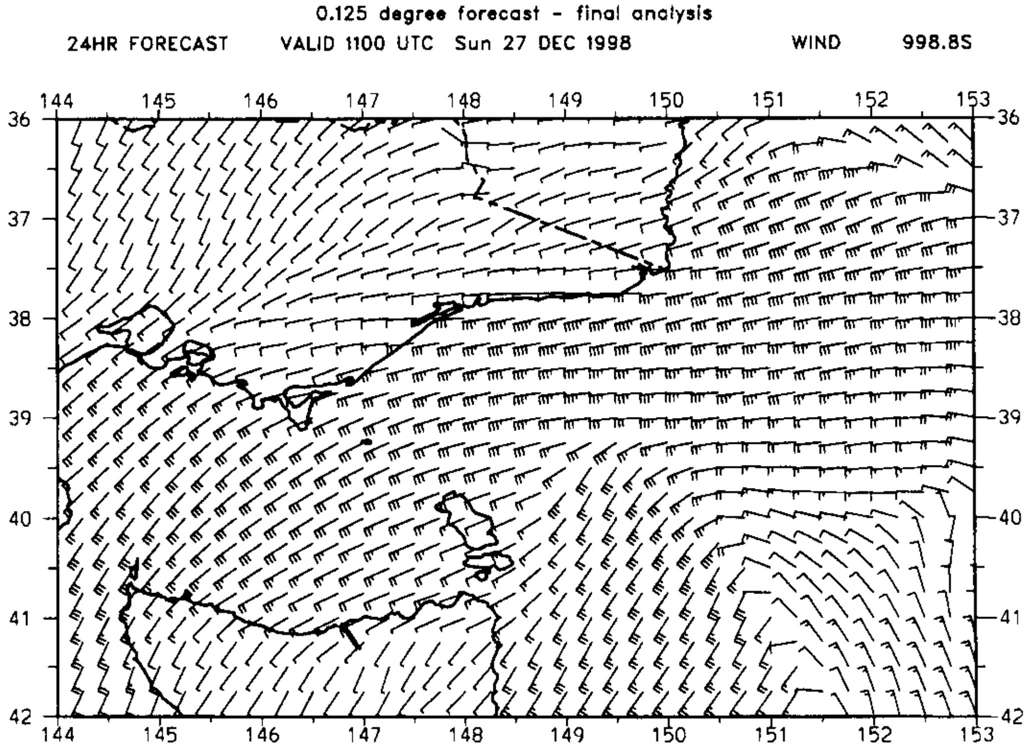
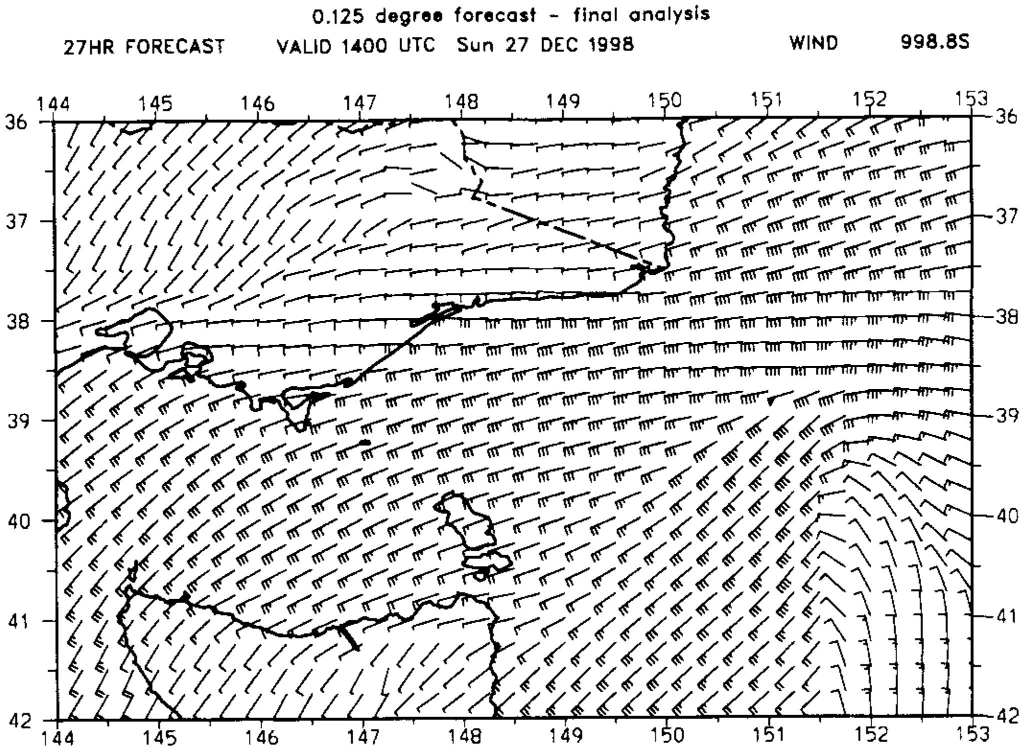


Figure 6. Modelled surface winds for 10pm 27 December 1998



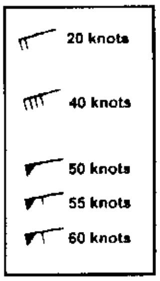


Figure 7. Modelled surface winds for 1am 28 December 1998

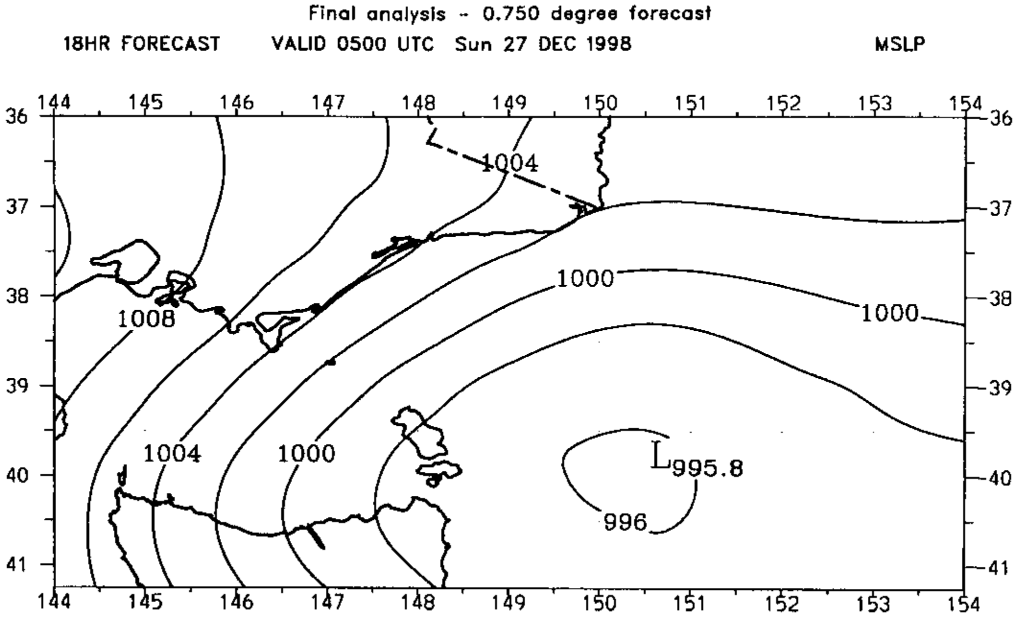


Figure 14. Analysis of Mean Sea Level Pressure (hPa) for 4pm 27 December 1998, using the meso-scale model at 0.75 degree (75km) grid resolution.

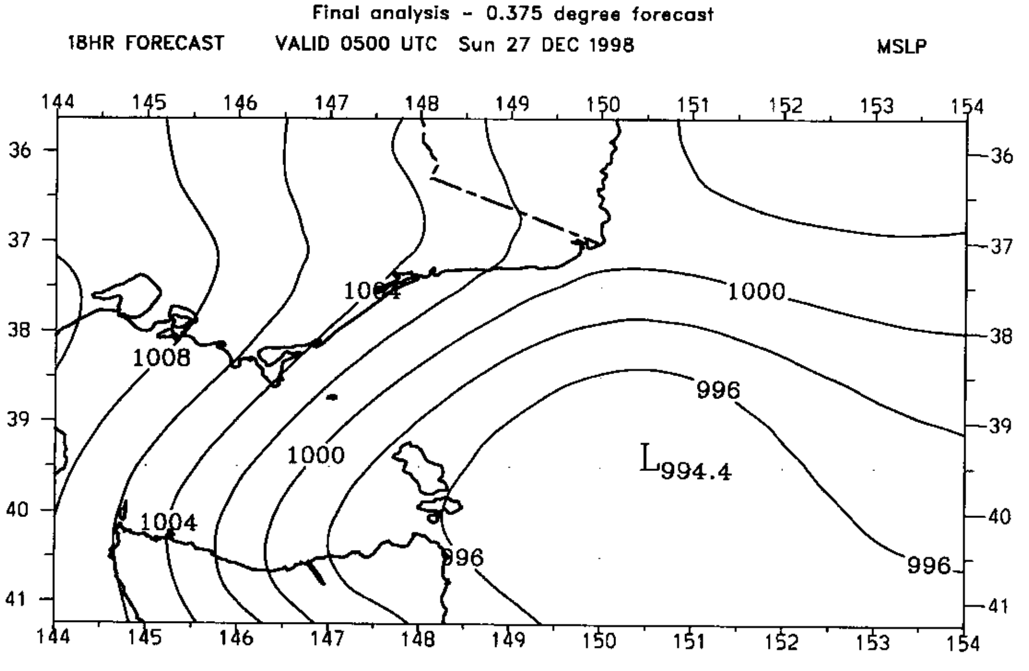


Figure 15. Analysis of Mean Sea Level Pressure (hPa) for 4pm 27 December 1998, using the meso-scale model at 0.375 degree (37.5km) grid resolution.

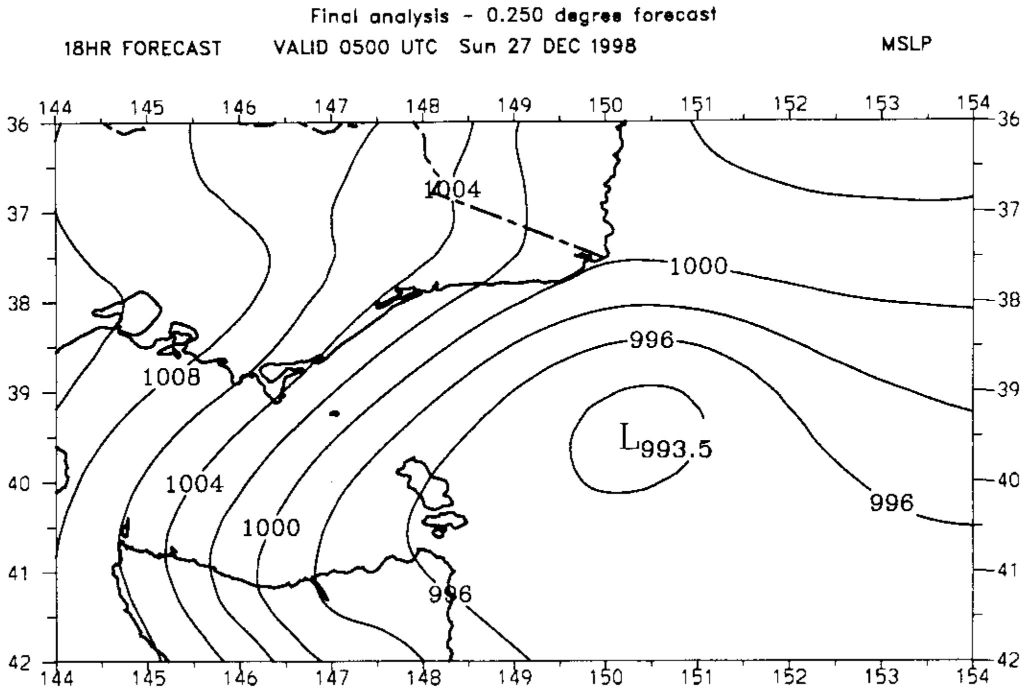


Figure 16. Analysis of Mean Sea Level Pressure (hPa) for 4pm 27 December 1998, using the meso-scale model at 0.25 degree (25km) grid resolution.

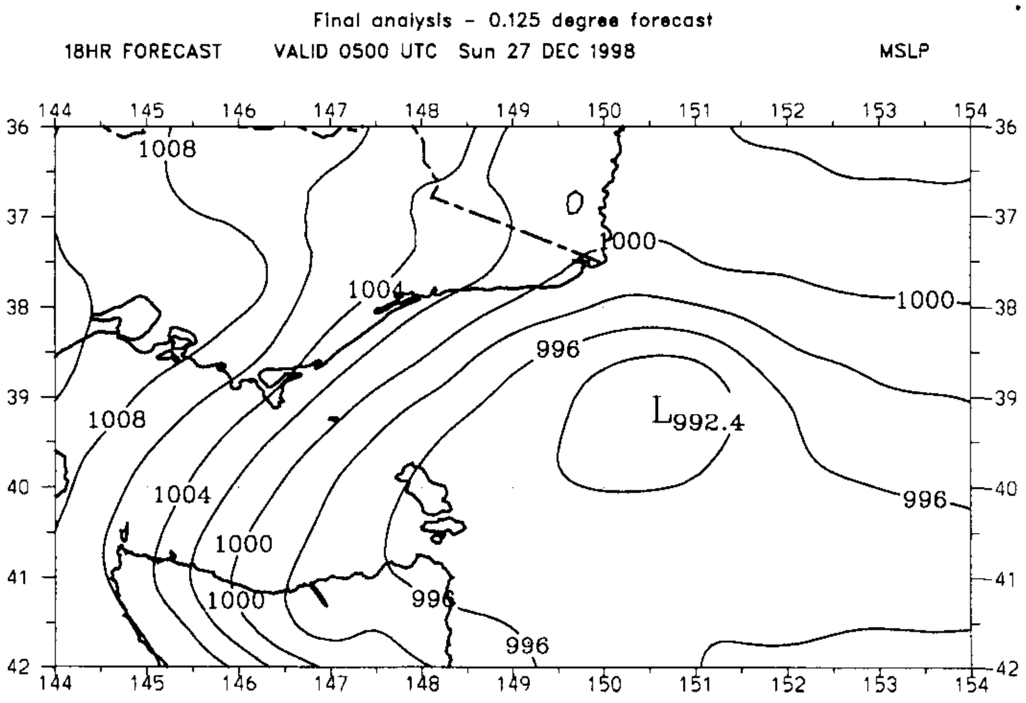


Figure 17. Analysis of Mean Sea Level Pressure (hPa) for 4pm 27 December 1998, using the meso-scale model at 0.125 degree (12.5km) grid resolution.

Attachment F

ANIMATIONS OF THE 12.5 KM RESOLUTION MODEL FORECAST OF THE CYCLONE WHICH AFFECTED THE SYDNEY-HOBART YACHT RACE ON THE 27 DECEMBER 1998

There are 3 separate animations presented on the accompanying disks, all from the 12.5 km resolution model forecast, which was based on data collected at 1100 UTC (10pm) 26 December 1998. The files are explained below.

Mean Sea Level Pressure: file *syd-hob mslp.ppt* (Powerpoint presentation on Disk 1)

2. The time interval between frames is 3 hours. The forecasts cover the 24 hour period from 10pm 26 December to 10pm 27 December 1998. This file shows the mean sea level pressure forecasts, centred over Bass Strait, with the infra-red satellite imagery overlain. Aspects of this animation to note are:

- The low moves initially southwestwards towards northeastern Tasmania, but then curves towards the north and then east as it intensifies;
- Another low develops to the northeast of Bass Strait and by late in the period is moving westwards towards Tasmania, south of the low in eastern Bass Strait;
- The cloud vortex (spiral) is seen to be east of the secondary low. The clouds in the centre of this spiral have tops near 7-8 km above the surface.

Surface winds: file *syd-hob winds.ppt* (Powerpoint presentation on Disk 2)

3. The time interval between frames is 3 hours. The forecasts cover the 24 hour period from 10pm 26 December to 10pm 27 December 1998. This loop shows the evolution of the near-surface wind field. Only every fourth wind vector is shown for clarity. Areas of stronger winds, mean over 40 knots, have been highlighted using different colors. Red wind arrows indicate mean winds between 40 and 45 knots, purple indicates winds 45 to 50 knots and light blue 50 to 55 knots. Aspects of these animations to note are:

- The winds strengthen to 30-40 knots through Bass Strait by 6 hours into the forecast;
- During the early morning and through to the mid-afternoon of 27 December winds strengthen to 50-60 knots on the northwest flank of the developing low;
- The low centres developing and evolving east and southeast of Bass Strait can be seen in the cyclonic circulations in these areas late in the forecast period.

Wave heights: file *syd-hob waves.gif* (animated gif file on Disk 1)

4. This loop shows hourly images of wave heights generated by the model and as shown in Attachment E. Arrows indicate the direction of the swell. Features to note are:

- The swell direction was predominantly from the east in the early part of the sequence;
- As the westerly winds strengthen during Sunday, an area of waves from the west develops and moves through Bass Strait to east of Gabo Island; and

- Wave heights reach their peak of 7 to 9 metres, east of Gabo Island, around 11pm on Sunday 27 December 1998.