Can we predict the weather?

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The title of this paper poses a challenging question. Is it referring to tomorrow's weather, weather over the next few days, a month ahead? Rather than answer the question directly I propose to explain the scientific practice that underpins the weather forecast and indicate its application to the forecasting of winds and ocean waves, a component theme of this workshop.

People through the ages have monitored the weather in the hope of gaining an understanding of how today's and yesterday's weather might foreshadow that of tomorrow, next week, next season and longer. The knowledge that past generations gleaned about the weather and its likely behaviour from observation was often summarised in proverbs. For instance, "red sky at night, sailor's delight; red sky in morning, sailors take warning" is code for a weather forecast. We know today that this English sailing proverb has a sound scientific basis explained by the differential scattering by air molecules of the colours that make up white light. But its use in centuries past was not based in an understanding of atmospheric physics, just its observed utility as an indicator of weather to come.

Modern meteorology might be said to have had its beginnings with the invention of the thermometer by Galileo Galilei in 1607 and Evangelista Torricelli's invention of the barometer in 1643. The ability to measure and assign numbers to two important attributes of the atmosphere was a necessary requirement for rigorously defining and comparing weather both spatially and temporally. However it would be another two centuries before Samuel Morse's invention of the telegraph enabled a synopsis of reported weather over large areas to be composited in real time. This synopsis, now popularly described as the weather map, is referred to by meteorologists as the mean sea level (msl) synoptic chart.

The analysis of weather data is the first step in the forecast process. It is done both manually by the meteorologist as well as by the computer.

The data needed by the meteorologist and the computer includes surface and upper air measurement of pressure, temperature, moisture and wind. The surface measurements are taken by people on land and at sea as well as by automatic weather stations. The upper air observations are taken by remote sensors attached to balloons and also deduced from measurements taken from satellites, both geostationary (36 000 km above the equator) and polar orbiting (900 km altitude) satellites.

The computer analysis presents the data in a regular grid array (Figure 1) on numerous levels from the surface to the stratosphere. Computers require the data

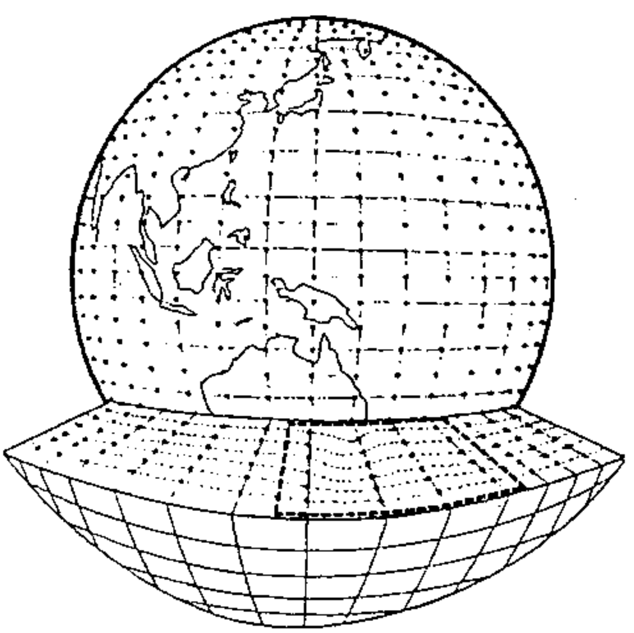

Figure 1 A schematic view of a course global grid structure for computer modeling

this way as input to the prediction models.

The manual analysis depicts the areas of high and low pressure, the fronts that separate warmer and colder air masses, and by implication, the winds. By studying a sequence of analyses, indications of a strengthening or weakening of features, as well as their direction and speed of movement, is evident. And, in some situations, a good first guess at the weather forecast for a few hours ahead, and sometimes longer, can be deduced by simple extrapolation of features.

Although there is a perception amongst some that a weather forecast can be inferred from the msl chart alone, this is not so. The atmosphere is three dimensional and many clues to its future state are hidden in the skies above. Patterns at the surface can be drastically changed in as little as 6-12 hours by complex interactions high in the atmosphere. The developments that brought storm force winds to waters in and east of Bass Strait on Sunday 27 December 1999 dramatically illustrate how rapidly weather patterns can change. Figure 2 shows the genesis of a low at 3 am Sunday 27 December just north of Tasmania's Northwest coast. Figure 3 shows the low fully developed east of Bass Strait just 12 hours later. Figure 4 is the satellite picture about that time.

Atmospheric prediction requires not only a depiction of weather patterns at the surface, but additionally, the fullest possible depiction of the distribution of winds, temperature and moisture through the total depth of that part of the atmosphere in which precipitation and clouds are confined. This part of the atmosphere is called the troposphere and extends to about 16 km at the equator and 9 km or so at the poles.

The area over which the analysis is performed depends on how far ahead we wish to predict. A prediction for 24-48 hours ahead would start with a full description of the atmosphere at the surface and through the troposphere over Australia and surrounding oceans; but for four or more days ahead, the analysis needs to be global.

Once the analysis is completed, the next step is to formulate future states of the atmosphere 24 hours to several days ahead. For much of this century this was done solely by a qualitative approach using conceptual models based in the laws of physics. However, over the past three or so decades, a quantitative approach, facilitated by supercomputers and global communication, has been gradually changing the way weather predictions are done. Computer models are now to the fore as the principal influence behind the forecast. The meteorologist's knowledge and experience are still important as a reality check on the models, and the model output still needs to be fine tuned for local effects and smaller scale influences; but increasingly, computer predictions have become the cornerstone of modern day weather prediction.

The Bureau runs a global prediction model twice daily. Additionally, meteorologists in the Bureau routinely refer to model predictions for the Australian region from the UK Meteorological Office, the USA National Weather Service, and the European Centre for Medium Range Weather Forecasting (ECMWF). These global predictions are valid out to seven days. A sequence of four charts for the Australian region from the Bureau's global prediction is published daily in most metropolitan newspapers across the country. These predictions, although broadscale, are usually a reasonably good indication of

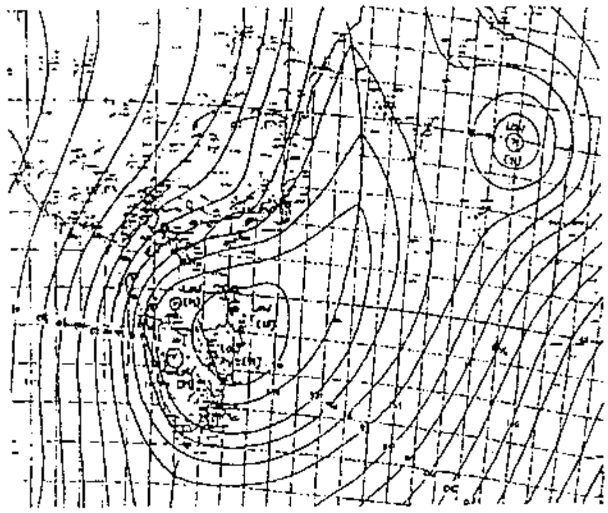

Figure 2 MSL Analysis 3 am 27-12-1998

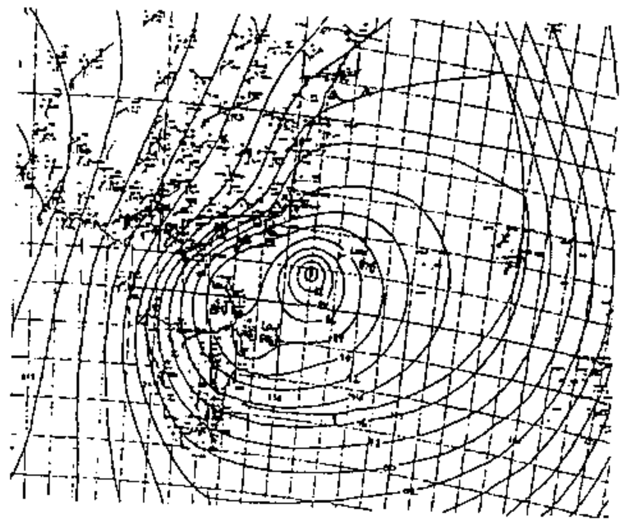

Figure 3 MSL Analysis 3 pm 27-12- 1998

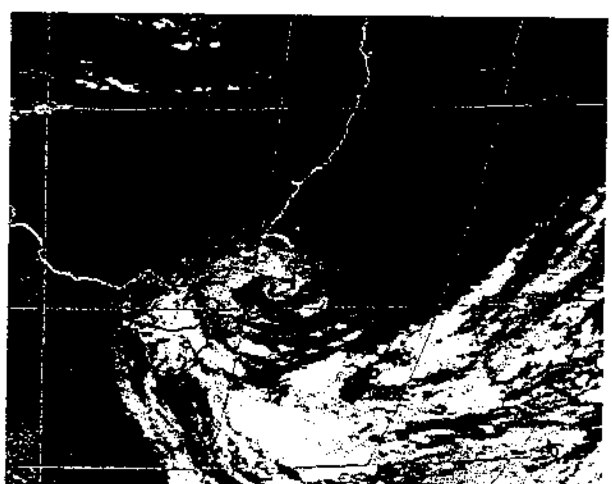

Figure 4 Satellite photo 3 pm 27-12-1998

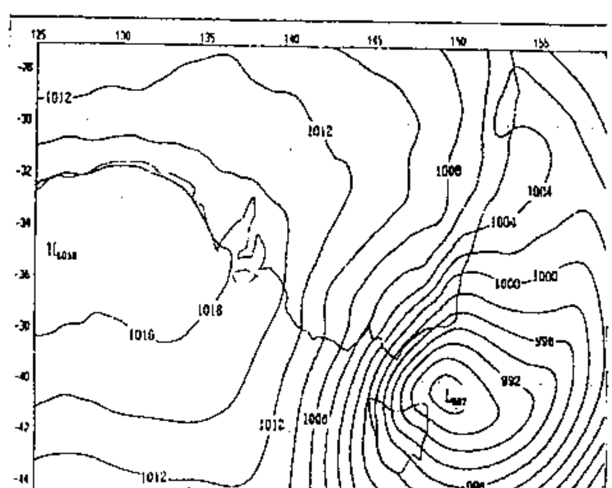

Figure 5 MSL Prediction 3pm 27-12-98

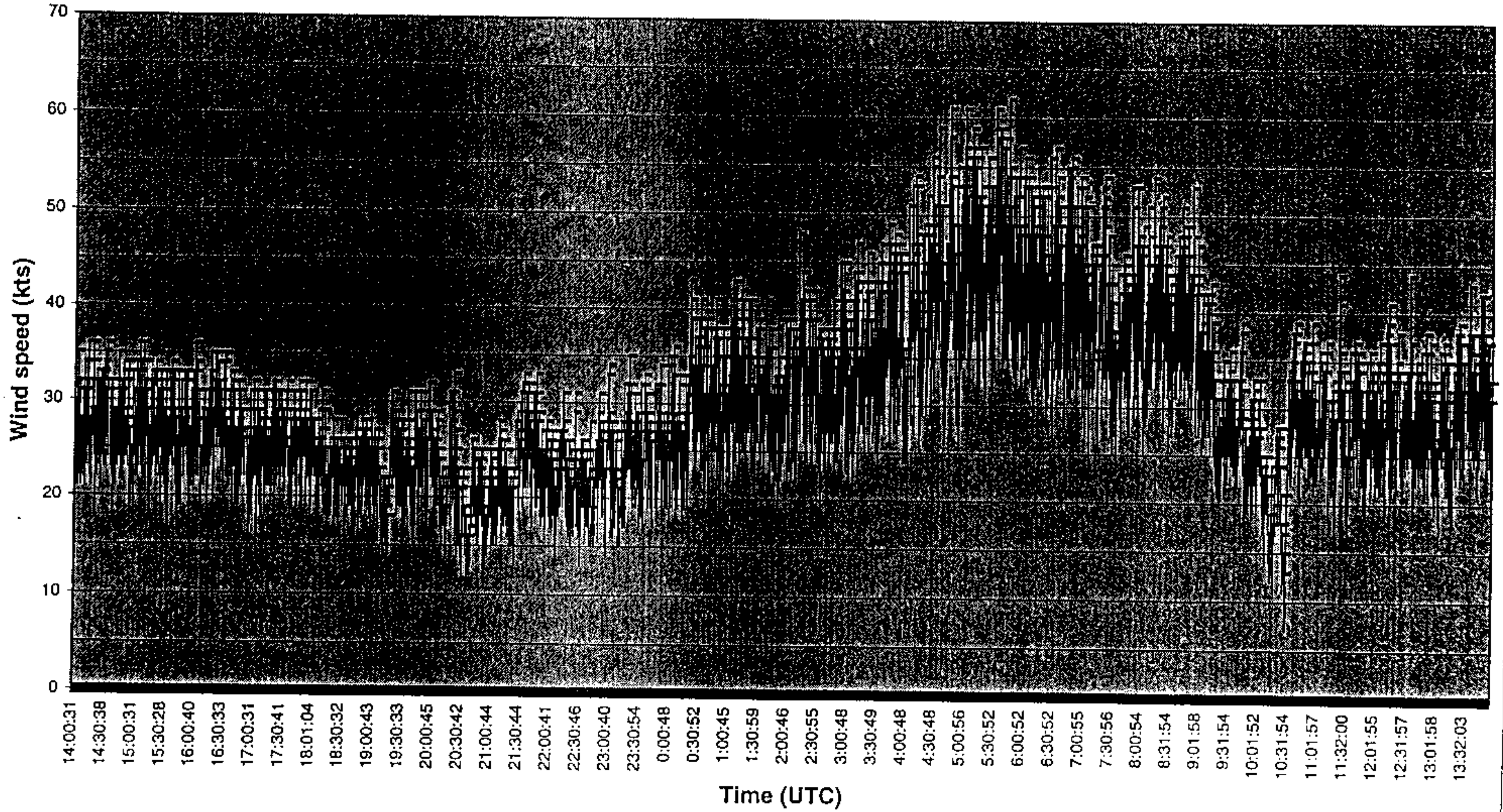

Figure 6 Wind speed recording at Mascot Airport 7 August 1998

the larger weather pattern, at least out to four or so days.

In addition to the global model, the Bureau models the atmosphere on a regional scale covering Australia, and on a much finer scale over southeast and southwest Australia. Finer scale models portray detail not presented by the global models. However the time frame of their prediction is limited. Currently the finest scale model run operationally by the Bureau is a 25 km resolution model. This provides a limited area prediction out to 36 hours. Models with resolution down to 5 km are being run in research mode.

A 30 hour prediction over southeast Australia by the 25 km resolution model, available early Saturday afternoon, 26 December 1998, and valid for Sunday afternoon, is at Figure 5. The computer model run of which this prediction is part was the principal influence in the decision to issue a Storm Warning soon after 2 pm Saturday, for the following afternoon, in coastal waters south of Merimbula and east of Wilsons Promontory.

Now let us return to the title of this paper: Can we predict the weather? As indicated in the opening paragraph, the Bureau's capability in this respect would take as an example the prediction of winds and ocean waves.

When a meteorologist refers to wind, the reference is to a mean wind at 10 metres above the surface, averaged over 10 minutes. This is the wind that is forecast. Being an average, it excludes the short duration gusts and the lulls that are part of the real wind. These need to be accounted for by the user noting that they can vary the wind by up to 40% from its mean value. An example of a 24 hour wind speed recording is at Figure 6. This is the wind speed recording for Sydney Airport for 7 August 1998, a day of exceptionally strong winds (and heavy rain) in Sydney. Figure 6 illustrates the great variability in wind speed from moment to moment, and the impossibility of succinctly describing its every detail other than in digital or graphical form. The international convention is to refer to the average wind over a ten minute period. Gusts are implied.

Wind forecasts derived from computer predictions are found to be a good estimate of actual winds provided the computer predictions themselves are an accurate representation of the weather patterns that occur. Clearly any large inaccuracies in the prediction of the weather pattern will incur similar inaccuracies in the wind forecast. And that statement invites the question, how good are the model predictions? This is best answered in terms of performance trends.

The trend in models' performance can be assessed in qualitative terms based on the day to day guidance they provide meteorologists forecasting the weather. Against this benchmark of performance, meteorologists would say that the models' performance is good and improving.

A quantitative measure of the trend is also available and is presented in Figure 7. The skill score used is one in which low values indicate higher accuracy. Skill score graphs are included for the Bureau's global model (GASP) as well as the global models of the United Kingdom Meteorological Office, the USA National Weather Service and the European Centre for Medium Range Weather Forecasting.

From the downward slope of the skill score graphs for each of the models, it is clear that the overall trend is one of improvement and, over the past decade or so, improvement in skill is 25% or more for a 24 hour prediction. As the model predictions have a significant influence on wind forecasts, it is a reasonable conclusion that the meteorologists' ability to forecast the wind has shown a commensurate improvement.

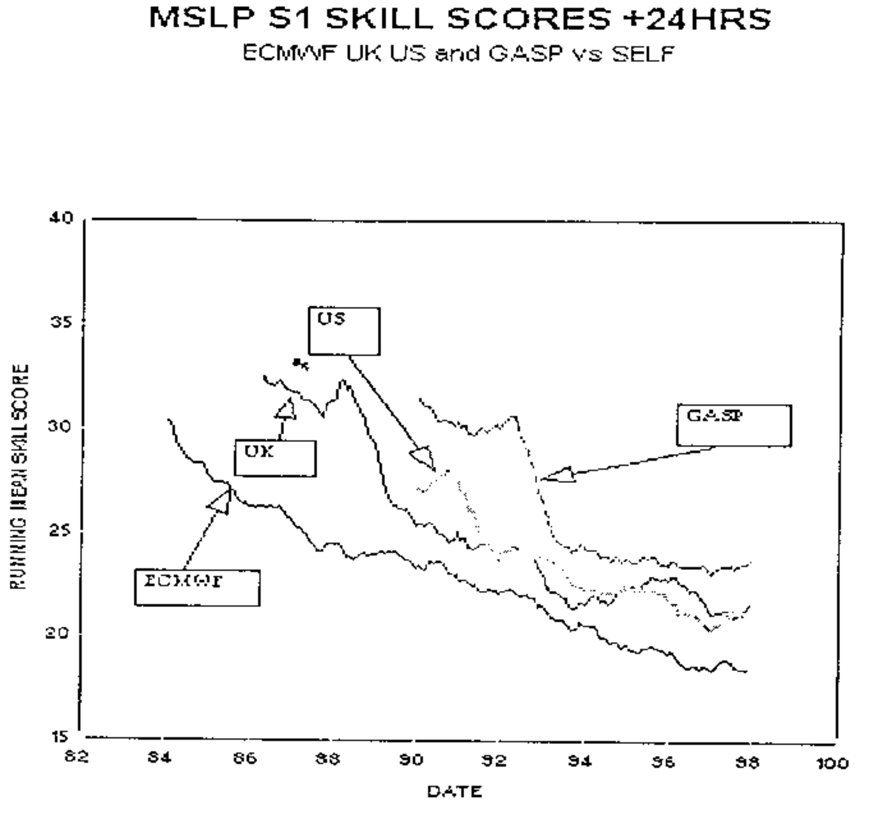

Figure 7 Model Performance 1984-1998

Wave height forecasts for both sea waves (waves generated in situ by the wind) and swell waves (waves generated distant from the locality of interest) is the significant wave height. This is the average height of the highest one-third of the waves. It has been found to approximate the average height of the waves as estimated by an experienced observer. The sea wavés and swell waves interact in a complex way to produce a combined significant wave height. Because the significant wave height is an average height, waves both higher and lower than the significant wave height occur. It is estimated that in every 1000 waves, a wave up to1.86 times the significant wave height will be experienced. Thus for a significant wave height of 7 metres with a period of 7.2 seconds, a wave of 13 metres can be expected every two hours or so. Figure 8 is an example of wave rider buoy data recorded off the west coast of Tasmania. It shows the relationship between significant wave height and maximum wave height, the latter at times being virtually double the former.

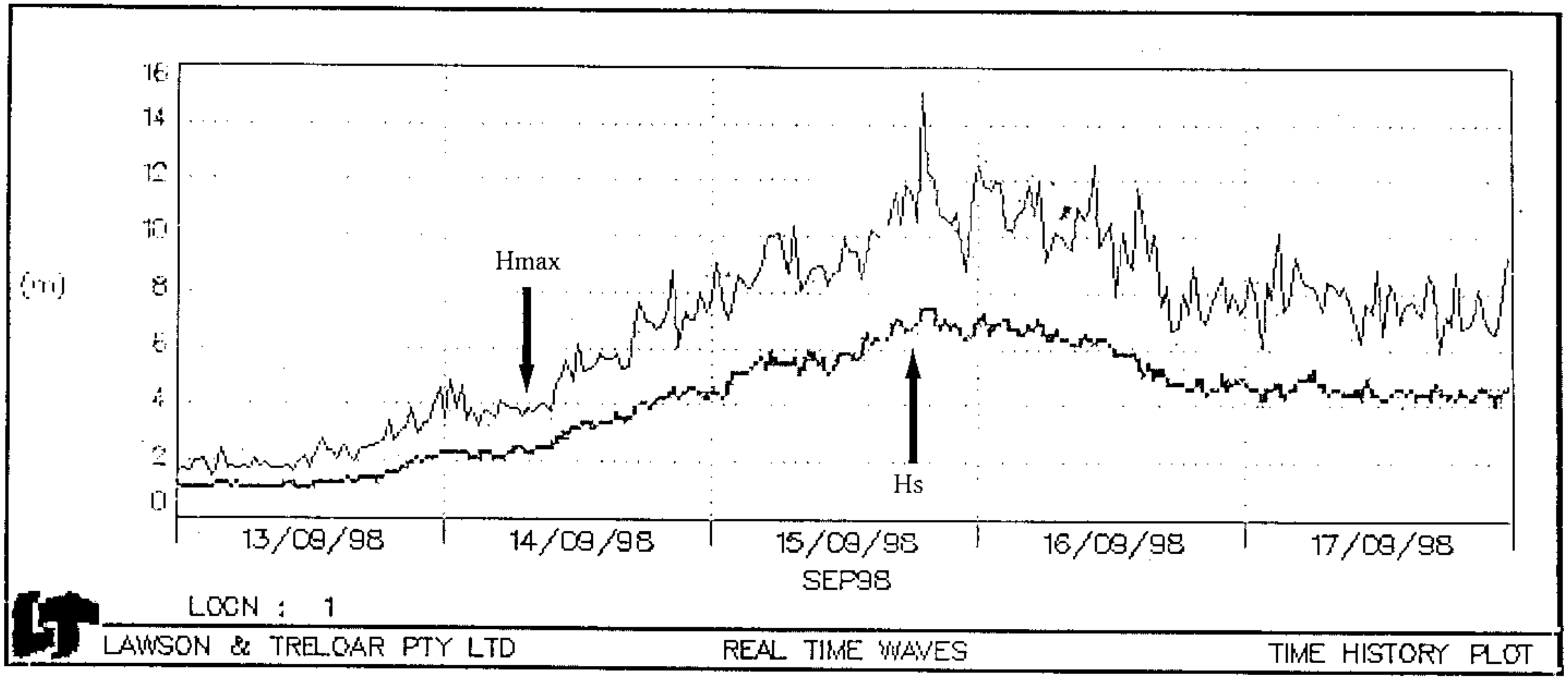

Figure 8 Wave rider buoy data (Tasmanian west coast) 13 - 17 September 1998

The computation of expected deep water wave height depends on three considerations - the wind speed, the duration of the wind and the wind fetch. Understanding how wave heights depend on these three parameters enables significant wave heights to be calculated either by use of computing algorithms utilising the wind fields output by the models, or by reference to nomograms which combine the three effects. Users must then be cognisant that wave heights will vary significantly about this value due to a complex interaction between different wave trains, both sea and swell, and the surface ocean current.

The accuracy of the wave height forecast is very much dependent on the accuracy of the wind forecast and an understanding of the way in which winds, waves and currents interact. It seems reasonable to assume that higher accuracy with respect to wind forecasts must inevitably be improving our ability to more accurately forecast significant wave height.

It can fairly be said that with respect to winds and ocean waves in particular, and the weather generally, the steady increase in the accuracy of computer model predictions of the atmosphere, on scales ranging from global to local, inevitably feeds into the forecast process in such a way that forecasts of winds and waves, and weather, are also achieving higher standards of accuracy.

In conclusion, it must be said that the question which is the title of this paper has not been answered explicitly. Yes, we can predict the weather but the claim cannot be made without qualification. There will always be a requirement for information on future states of the weather just beyond whatever our capability is at any particular time. If we predict the weather accurately to four days, then people ask what about the fifth, sixth, seventh day? Next week? Next month? And so on. The challenge of forecasting the weather is unending.