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The sensitivity of a numerical prognosis to moisture detail in the initial state

G. A. Mills, Australian Numerical Meteorology Research Centre, Melbourne

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The sensitivity of the ARPE model prognosis to changes in the initial specification of moisture distribution is demonstrated for a heavy rainfall situation over southwestern Western Australia. It is shown that by manually modifying the objective moisture analyses, using both surface data and satellite imagery, improvements in both mean sea level pressure and precipitation forecasts are achieved.

It is shown that the improvement in the precipitation forecast over southwest Western Australia was due to the changed distribution of moisture associated with a middle-level cloud layer, while the improvement in the forecast movement of a low pressure system was caused by the interaction of the model's cumulus parameterisation scheme with the changed moisture distribution of a deep cloud mass associated with the low.

Introduction

Moisture fields in the troposphere are frequently characterised by zones of strong horizontal gradients which can be seen in satellite imagery as abrupt transitions from areas of one cloud type to another. The radiosonde network in Australia is such that many of these moisture features will not be resolved by the existing observations, and thus not appear in objective analyses used to initialise numerical weather prediction models. It has been demonstrated by, for example, Smagorinsky et al. (1970) that even though initial moisture fields may be inadequately specified, numerical prognosis models develop moisture structure consistent with their broadscale convergence/divergence patterns in a time-scale which is generally sufficiently short to produce reasonable rainfall totals after 24 hours. However, initial rainfall rates are artificially low as the model takes time to 'spin up', particularly if the model is initialised with non-divergent wind fields. Several authors (e.g. Perkey 1976; Lejenäs 1979; Wolcott and Warner 1981) have demonstrated that enhancement of detail in the humidity fields used to initialise a numerical prognosis leads to an improvement in the accuracy of the forecast rainfall rates during the early stages of these prognoses. While these studies have not demonstrated any strong positive impact on forecasts of fields such as mean sea level pressure (MSLP) it has been argued by, for example, Kreitzberg (1976) that because of the interrelationships between latent heat release and flow pattern changes, improved forecasts of moist processes should have positive impact on the accuracy of a forecast.

The operational limited area prognosis model used by the National Meteorological Analysis Centre (NMAC) of the Bureau of Meteorology is the Australian Region Primitive Equation (ARPE) model, which has been shown to be capable of providing useful 24-hour precipitation forecasts by Mc Gregor et al. (1978) and Leslie et al. (1981). It is the purpose of this paper to demonstrate, by means of a case study, the sensitivity of the forecasts from this model of both pressure and rainfall to changes in the initial moisture distribution. The case chosen was a flood rain situation in southwestern Western Australia and was investigated as part of a broader study into the phenomena of tropical cyclone/mid-latitude interactions in that area.

The following sections briefly describe the operational objective moisture analysis scheme and the methods used to modify these analyses. The sensitivity of the ARPE model 24-hour forecast of MSLP and precipitation to the changed analysis is described in some detail, and some attempt is made to identify the factors causing this sensitivity.

Moisture analysis

Operational System

Initial fields for the NMAC operational limited area (Australian Region) numerical prognoses are prepared using the objective analysis scheme described by Seaman et al. (1977). The actual moisture variable analysed is dew-point, using a successive correction method (Cressman 1959) analysis of radiosonde observations. The background field for this analysis is provided by the dew-point depression field predicted by the SLYH precipitable water forecast model (see Younkin et al. 1965), which is driven by an earlier run of the ARPE model. No analysis is made of dew-points at levels higher than 500 mb.

Modification Methods

The dew-point analyses were modified in the following way. First, the infrared geostationary satellite imagery for the analysis time was carefully examined, and a manual nephanalysis was prepared, in which regions of relatively contiguous cloud types were delineated, and where possible approximate levels of the cloud tops were assigned. Then, using all available surface observations to provide information on cloud-base height, and any radiosonde observations which may be present, a vertical dew-point depression profile was assigned to each distinct cloud area. Naturally this process requires some subjectivity where surface and/or radiosonde data are not present, and in areas of, say, scattered cumulus, where an 'average' dew-point depression for the whole area must be assigned. Further, if the observed cloud-base lies mid-way between analysis levels, it is necessary to decide what dew-point depressions to assign to the lower level.

As there are no independent data available with which to verify the modifications made to the analyses, the worth of the changes will be judged by the effects which they have on a numerical prognosis. The prognosis model used was the ARPE model which was described by Mc Gregor et al. (1978). In the form used in this study, it was operated with a horizontal grid spacing of 250 km and with 6 levels in the vertical, as is used for operational purposes by the NMAC.

The precipitation scheme used in the ARPE model consists of two parts. The first is a large-scale condensation check. If any model level exceeds a threshold relative humidity, excess moisture is removed as precipitation, and the level temperature is increased to conserve moist static energy. The second part is an Arakawa-Schubert type convective parameterisation scheme. In this stage the column of air above each grid-point is treated in isolation from the other grid-points and its thermodynamic properties are adjusted to be compatible with the cumulus activity expected from this column of air.

The operational version of the model used updated boundary conditions, rather than the fixed boundary conditions used for simplicity in this study, and did not use the model's internal moist processes to predict rainfall, but rather used the output of the ARPE model to drive a separate precipitation forecast model (the SLYH model). Accordingly, rather than use the operational prognosis as a control against which to compare the forecast based on the modified analyses, a control forecast was prepared using the same model parameters as were used in the tests, but with the analysis archived by the NMAC as initial conditions.

The 20 January 1982 situation

The MSLP analyses for 0000 GMT 20 and 21 January 1982 are shown in Figs 1 and 2. During this time a low pressure centre moved slowly south-southwestwards from near Exmouth Gulf while a ridge of high pressure remained relatively stationary near latitude 38°S. Infrared satellite imagery corresponding to Figs 1 and 2 are shown in Figs 3 and 4. A notable feature of these pictures is the

Fig. 1 MSLP analysis 0000 GMT 20 January 1982.

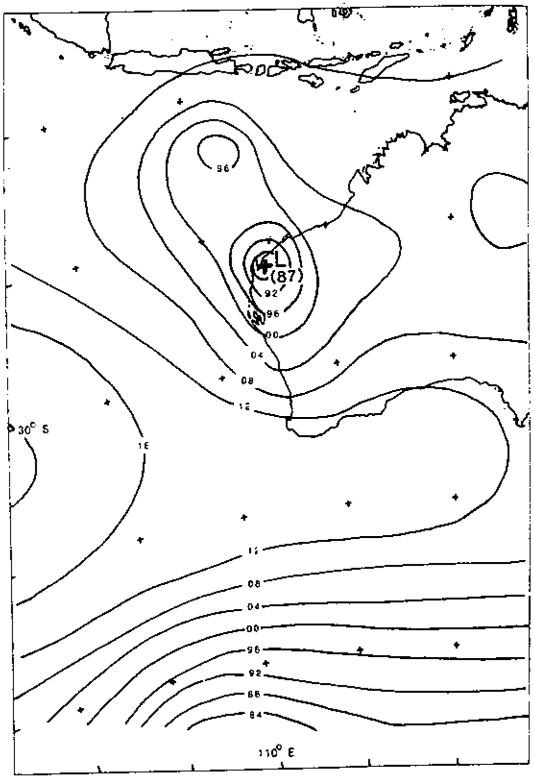


Fig. 2 MSLP analysis 0000 GMT 21 January 1982.

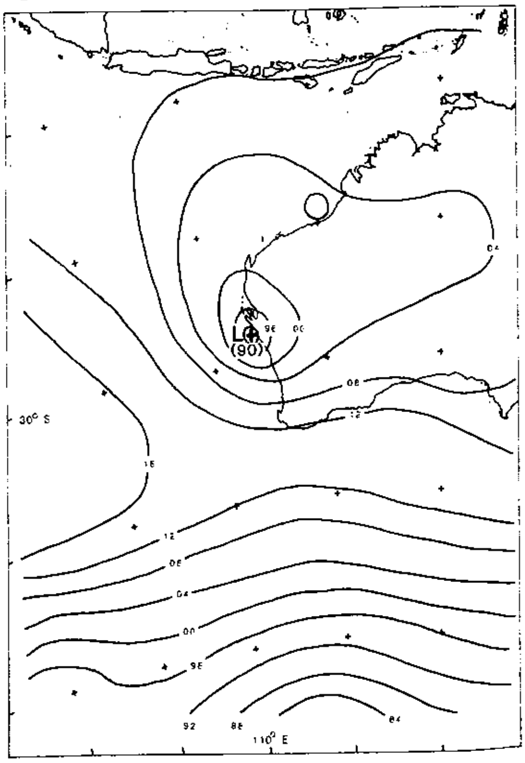


Fig. 3 GMS infrared satellite imagery 0000 GMT 20 January 1982.

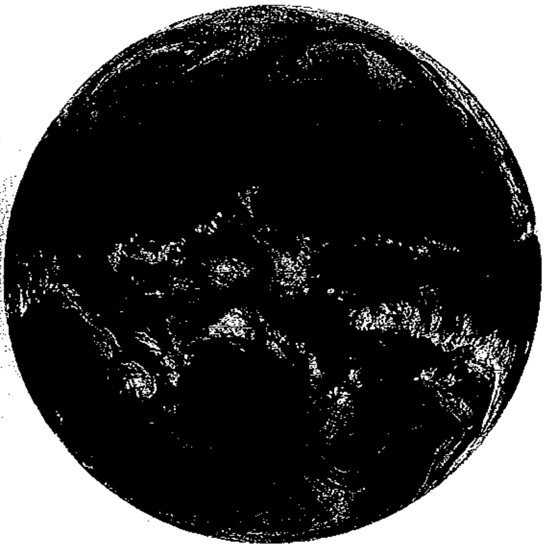


Fig. 4 GMS infrared satellite imagery 0000 GMT 21 January 1982.

Fig. 5 Average observed precipitation (mm) over 250 km grid squares for the 24-hour period to 0900 WST 21 January 1982.

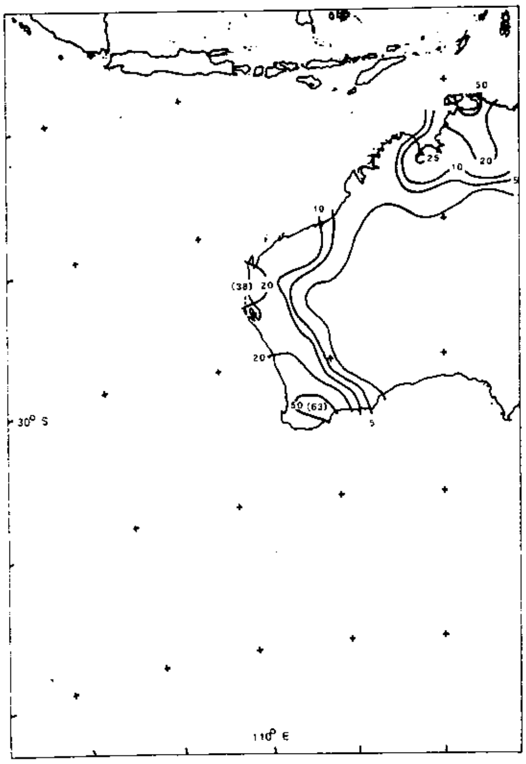


Table 1. Dew-point depressions °C assigned to each analysis level for each cloud area. The cloud area numbers refer to those shown in the nephanalysis of Fig. 7.
(* indicates no change made to analysis)

	Level				Comments
Area	1000	850	700	500	
1	2	2	2	2	Deep convective clouds — tropical cyclone
2	4	4	4	4	Scattered deep convective clouds
3	5	7	7	12	Scattered stratocumulus
4	*	5	5	*	Scattered stratocumulus
5	*	5	5	5	Scattered stratocumulus and altocumulus
6	*	8	3	3	Altostratus — small convective elements
7	3	3	3	3	Scattered deep convective clouds
8	4	4	4	4	Scattered deep convective clouds

marked extension of the cloudband south of the Australian continent during this 24-hour period. Around 0300 GMT, rain commenced falling over southwestern Western Australia and continued through and beyond this period, with rainfall totals greater than 150 mm being reported in some areas in the 24-hour period to 0900 WST (Western Standard Time = GMT + 8 hours) 21 January. Figure 5 shows an isohyet map of observed rainfall on the 250 km resolution analysis grid. This was prepared by taking each rainfall observation (including zero rainfall) from the rainfall observation network to the nearest grid-point on the analysis grid and averaging all observations at that grid-point. This procedure can lead to some anomalies due to the variable density of the observation network, the coarse grid, and the natural spatial variability of rainfall, but does show the distribution of rainfall on that day. Figure 6 shows a more detailed manual isohyet analysis over southwestern Western Australia for the same period, and the narrow band of heavy rainfall can be seen.

The manually prepared nephanalysis based on the

Fig. 6 Manual isohyet analysis (mm) over southwestern Western Australia for the 24-hour rainfall observations to 0900 WST 21 January 1982.

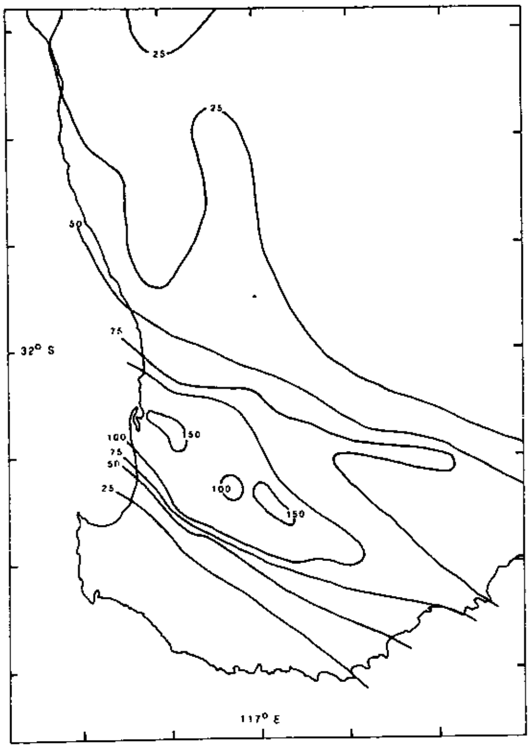


Fig. 7 Manual nephanalysis zones from the satellite imagery of Fig. 3.

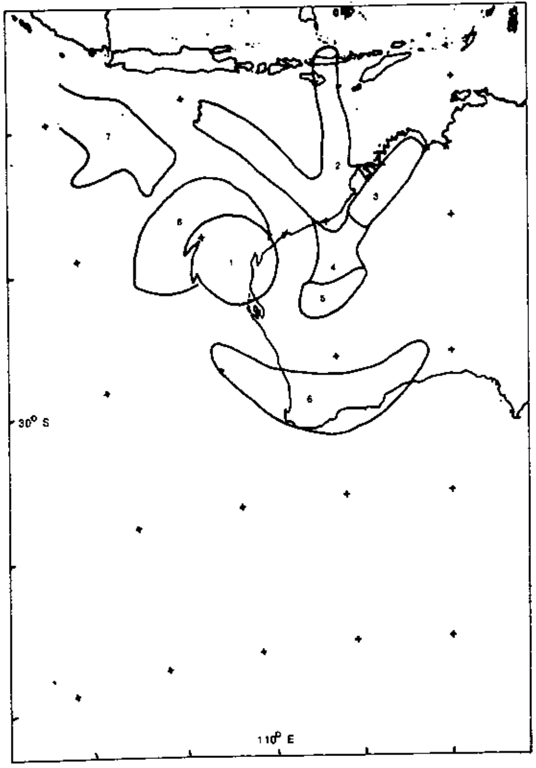


Fig. 8 700 mb mixing ratio (gm/Kgm) computed from the archived analysis for 0000 GMT 20 January 1982.

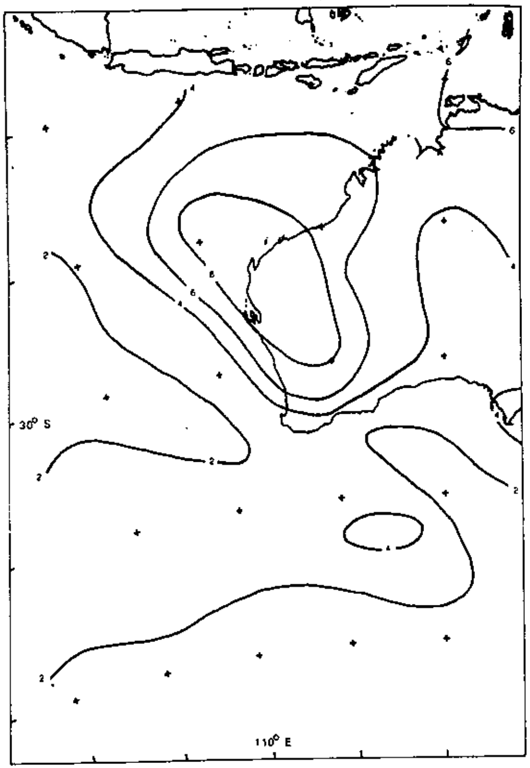
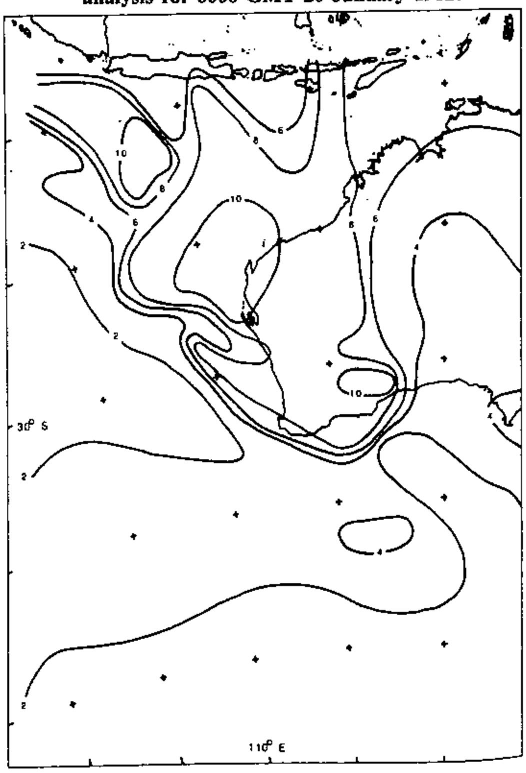


Fig. 9 700 mb mixing ratio (gm/Kgm) from the modified analysis for 0000 GMT 20 January 1982.



satellite imagery of Fig. 3 is shown in Fig. 7 where the numbers refer to the different areas which were assessed to have relatively homogeneous distribution of cloud type, at least on the 250 km square scale of the analysis grid. Table 1 shows the dew-point depressions which were assigned to each numbered area in Fig. 7 at each analysis level, together with comments on the cloud type in the area, and Figs 8 and 9 show the mixing ratio patterns computed from the archived and the adjusted 700 mb analyses.

The degree of subjectivity necessary in assigning these dew-point depression profiles varied from area to area, depending on the location of radiosonde ascents relative to the cloud areas, and on the amount and reliability of surface observations of cloud type and amount. Area 1 was readily identifiable as a tropical cyclone and would be expected to be extremely moist through a considerable depth of the troposphere. This was confirmed by the radiosonde ascent at Carnarvon (24° 53′S, 113° 39′E), and a dew-point depression of 2° was assigned to all levels in this area. Area 8 was interpreted as part of the spiral banding associated with this cyclone, and a lesser degree of saturation was assigned to this area to make some subjective allowance for the cloud-free parts of this area.

The cloud band in area 6 appeared to be relatively continuous middle-level cloud, although some small convective elements could be discerned. Two radiosonde ascents penetrated this layer. The first, from Perth (approximately 32°S, 116°E) was well within the cloud area, and indicated a layer with dew-point depression of 2° from 700 mb to 350 mb. Albany (approximately 35°S, 118°E), on the edge of the cloud area, showed a layer from 700 mb to 600 mb with a dew-point depression of about 7°. As Albany was on the edge of the cloud area, greater weight was given to the Perth sounding, and dew-point depressions of 3° were assigned to the 700 and 500 mb levels of the analysis to represent that cloud area.

Areas 3 and 4 were assessed from cloud photos to be predominantly scattered stratocumulus, with either this or middle-level cloud being reported by surface observations, and so dew-points were enhanced slightly at the 850 and 700 mb levels. In area 5 the cloud tops were higher than those in areas 3 and 4, and so the moisture was increased at the 500 mb level as well. Areas 2 and 7 were interpreted as deep, but not well organised, tropical convection, and so deep, moist profiles were assigned to these areas. The greater proportion of clear air in area 2 led to a slightly drier profile being assigned than that of area 7.

These assignments carry a considerable degree of subjectivity, and more will be said later about the possible consequences of errors due to this subjectivity.

The adjusted analysis (Fig. 9) shows much more detail in the moisture field than was present in the

Fig. 10 **24-hour MSLP prognosis, valid 0000 GMT 21 January 1982, based on archived analysis.**

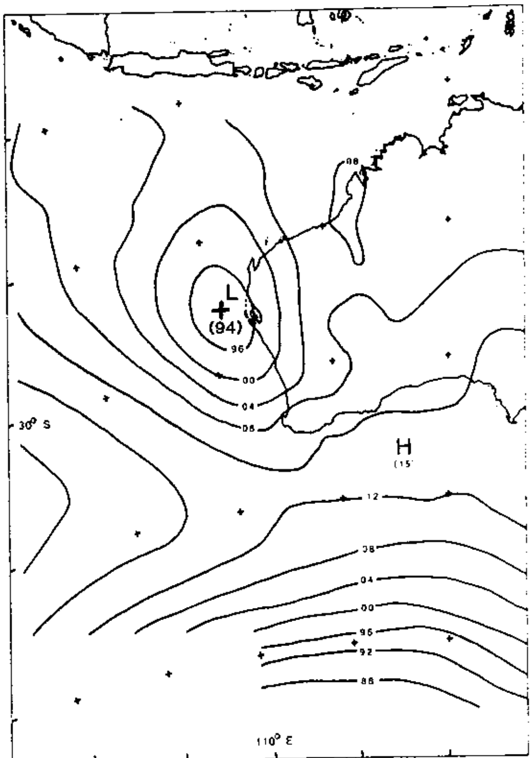


Fig. 11 **24-hour MSLP prognosis, valid 0000 GMT 21 January 1982, based on modified analysis.**

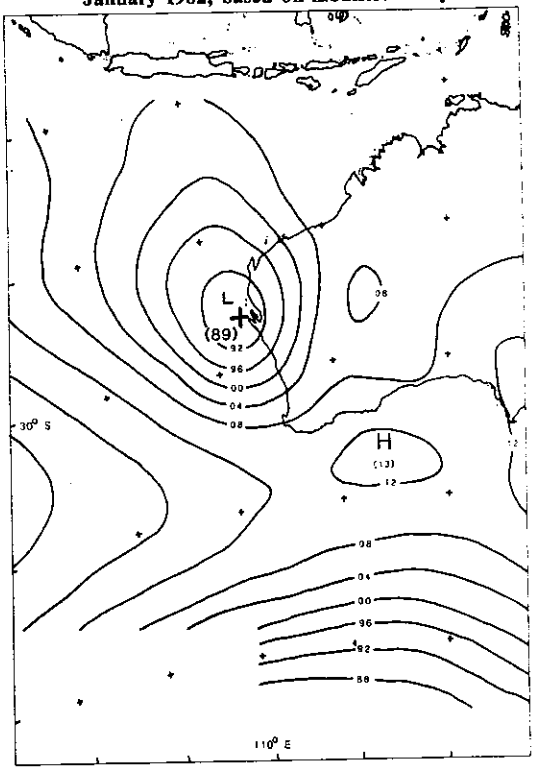


Fig. 12 24-hour precipitation forecast (mm) corresponding to Fig. 10.

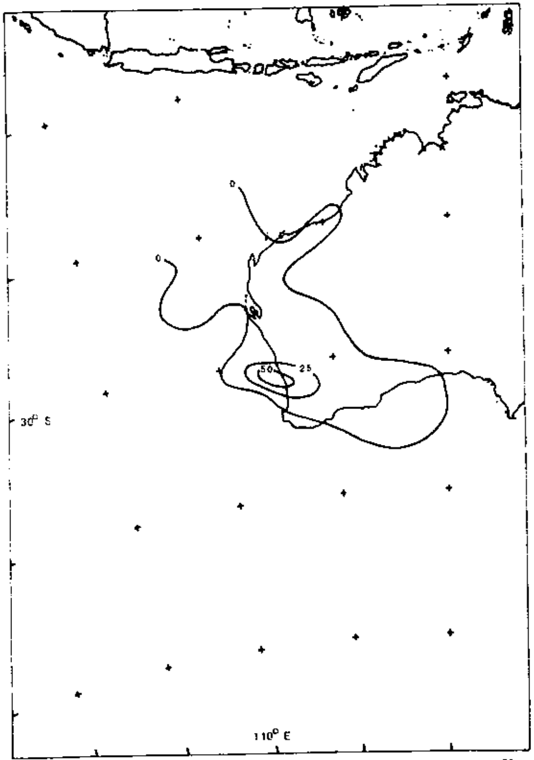
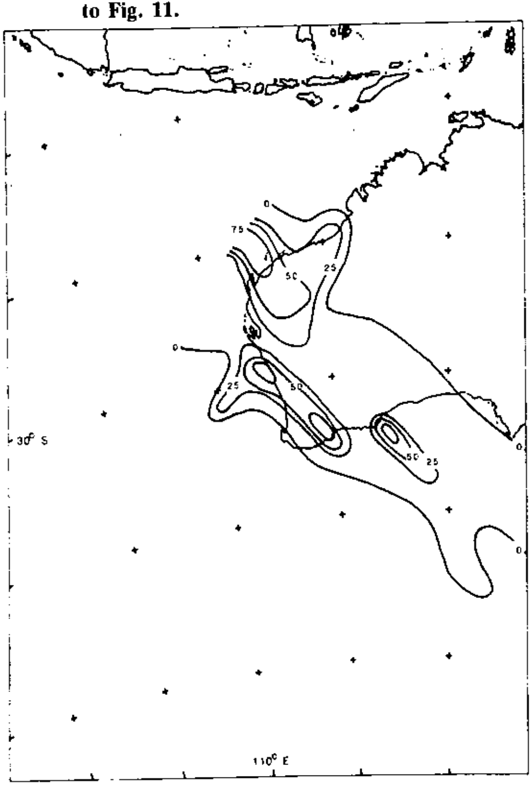


Fig. 13 24-hour precipitation forecast (mm) corresponding to Fig. 11.



initial analysis, (Fig. 8) and of course shows a strong correspondence to the assumed cloud distribution. As no smoothing was done after the dew-point fields were adjusted, strong gradients of mixing ratio are observed along the boundaries of the modified areas.

Figures 10 and 11 show the 24-hour MSLP prognoses based on the archived and the modified analyses respectively. The changes made to the moisture fields of the analysis have resulted in a considerable improvement in the predicted direction of movement and intensity of the low pressure system. The 24-hour precipitation forcasts from the two prognoses are shown in Figs. 12 and 13. The modified analysis has resulted in a much stronger band of rainfall through the southwest of Western Australia, and which agrees quite well with observations (Figs 5 and 6). The orientation of the band of heaviest rainfall is farther north than observed at its northwestern end, but given the 250 km resolution of the prognosis model, this error is not great. (It should be remembered that there is a 3-hour time difference between the valid time of the forecast, 0000 GMT, and the time of the rainfall observations, 0900 WST.)

Other areas of rain are also considerably enhanced in the forecast based on the modified analysis. The area around Exmouth shows more rainfall than was observed, however 38 mm was reported on average over a 250 km square, and individual totals in the area exceeded 65 mm.

The other area where a significant change was made to the forecast rainfall was near 35°S, 125°E where an area of heavy rainfall was forecast, with a considerable extension southeastwards of this rainfall area. As most of this heavy rainfall area lies over the ocean it is difficult to verify the forecast rainfall amounts. The location, though, is not unreasonable given the large cloud band through this area at 0000 GMT 21 January (Fig. 4) and given ship observations of rainfall near 37°S, 125°E at 1200, 1800 and 2400 GMT on 20 January.

It is of course, possible, to 'tune' the rainfall produced by the model by simply changing the degree of saturation specified in the various cloud areas, and some sensitivity tests were carried out. For example, the dew-point depressions at all levels in area 1 were changed from 2° to 4° in one test, and the 700 and 500 mb dew-point depressions in area 6 were changed from 3° to 5° in a second test. The essential change was in the *amount* of rainfall produced, as would be expected, however, the distribution of rainfall was essentially unchanged. Further, the changes in total rainfall did not appear to be unduly sensitive to the small changes in dew-point depressions made in these tests.

Apart from these sensitivity studies, no attempt was made to tune the results using hindsight, although the amount of rainfall near Exmouth and that near 35°S, 125°E could have been varied by

Fig. 14 24-hour MSLP prognosis, valid 0000 GMT 21 January 1982, based on modified analysis with no changes from archives in area 1.

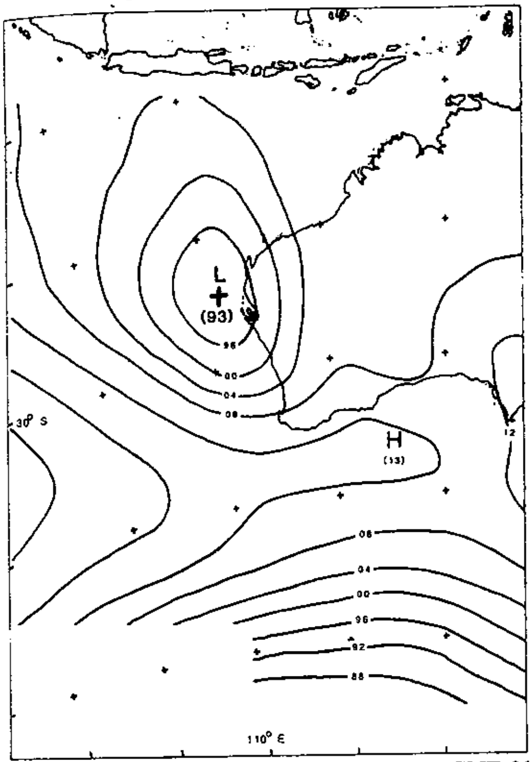


Fig. 15 24-hour MSLP prognosis, valid 0000 GMT 21 January 1982, based on modified analysis with no changes from archives in area 6.

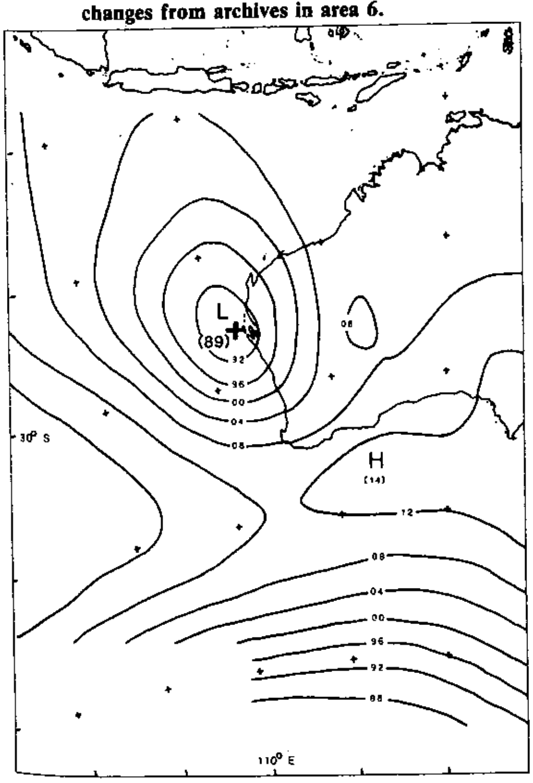


Fig. 16 24-hour precipitation forecast (mm) corresponding to Fig. 14.

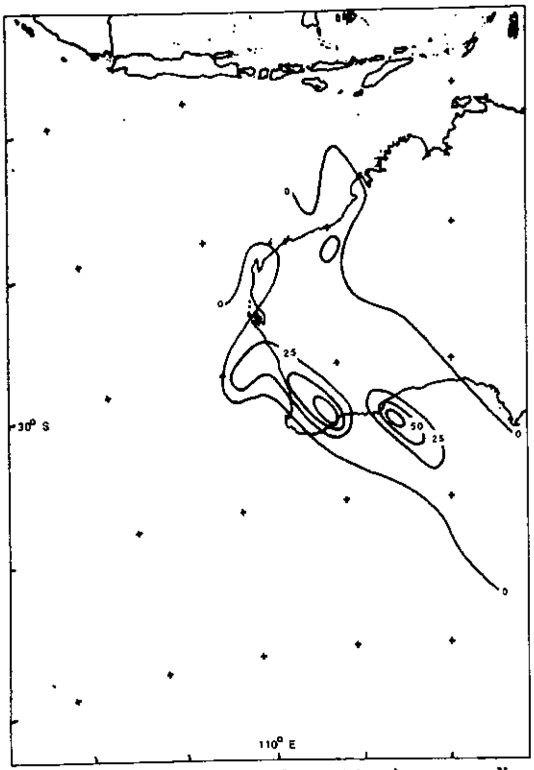


Fig. 17 24-hour precipitation forecast (mm) corresponding to Fig. 15.

changing the dew-point depressions in Table 1 or by subtly varying the nephanalysis.

Factors influencing prognosis impact

There appear to be two significant improvements made to the forecast by the changes to the moisture analysis i.e. the improved position and central pressure of the low pressure system, and the improved position and greater amount of the precipitation area over southwestern Western Australia.

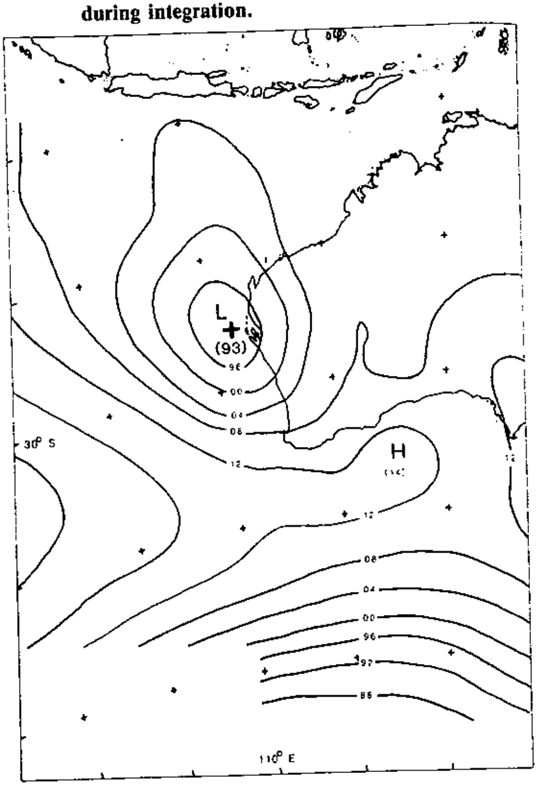
Effects of cloud areas

In order to gain greater insight into the effects of the changes in the different areas of the moisture analysis, two additional 24-hour prognoses were made. In the first, no changes were made to the moisture analysis in area 1 of the nephanalysis (see Fig. 7) and in the second no changes were made in area 6, but, changes were made in all other areas in each case. The MSLP forecasts are shown in Figs 14 and 15 respectively, with the corresponding rainfall forecasts in Figs 16 and 17. The improved forecast position and intensity of the low pressure system appear to have been produced by the changes in moisture distribution in area 1, with the changes made in area 6 making very little difference to the MSLP forecast. However, comparison of Figs 13, 16 and 17 shows that the changes in area 6 contribute most of the rainfall in the southern part of the rain-band, and that the changes in area 1 contribute significantly to the rainfall in the northern part of the band. Timing of rainfall at the two ends of the rain-band also differs, with that near 34°S having virtually ceased by the end of the 24-hour prognosis period, while that near 30°S was slower to start, but was still active at the end of the integration.

Effect of model convective parameterisation

It was noted during these tests that most of the rainfall associated with the area 6 changes was falling as broadscale precipitation, while that associated with the area 1 changes was partitioned between the broadscale and the convective parameterisation schemes. As changes in divergence patterns brought about by latent heat release are the cause of the changes in the forecast movement and intensity of pressure systems, a final forecast was made in which the modified analysis was used to initialise the prognosis model, but the model was integrated with the convective parameterisation scheme turned off: i.e. only broadscale rain processes were allowed. The 24-hour MSLP forecast is shown in Fig. 18, and it is seen that much of the difference in the forecast positions and most of the change in the central pressure of the low pressure system in the control and the modified forecasts (Figs 10 and 11) was produced by the interaction of the convective parameterisation scheme with the changed moisture distribution in that area.

Fig. 18 24-hour MSLP forecast, valid 0000 GMT 21 January 1982, based on modified analysis. Convective parameterisation scheme turned off during integration.



Discussion

It has been shown that, in this case, changes made to the moisture field in the initial analysis made significant positive impact on the forecast of both rainfall and of low pressure centre movement and intensity. It was further shown that the interaction between the cumulus parameterisation scheme and the changed moisture analysis contributed significantly to the improved forecast of low pressure system movement.

Given that there has been strong positive impact in this case, using a manually intensive and subjective method of analysis modification, two questions immediately need to be asked. These are (1) how often will this sort of impact be experienced and (2) could a technique be devised which would allow moisture fields to be modified in an operational context? Such a technique should, of course, be as objective as is possible.

It is not difficult to design an operational practice which could be used to routinely check, and enhance where necessary, the operational objective moisture analyses. A major source of data which has not been mentioned in this paper is that which can be derived from satellite sounding data, and Hayden et al. (1981) have described techniques by which quite accurate moisture data in cloud-free areas may be obtained from satellite-sensed radiances. These data would, of course, be suitable for use in the objective analysis scheme. In addition, satellite infrared imagery can provide cloud-top temperatures and percentage cloudiness. An experienced analyst could then, using an interactive graphics terminal, overlay the objective moisture analysis and the satellite imagery, and modify the moisture analysis in the cloudy areas as desired.

The remaining question to be answered is the frequency with which such techniques would make significant positive impact on a prognosis. Naturally impact can only be demonstrated when a significant rainfall event occurs, or is forecast to occur. In a country such as Australia such events do not occur much of the time and at other times are accurately forecast. One may therefore expect that significant positive impact would not be found on most occasions. However, because of this lack of frequent rainfall events over much of Australia, an event, when it occurs, is highly significant, and any technique which may enhance the accuracy of forecasts in such situations is worthy of consideration.

The situation of 20 January 1982 was, at the least, unusual. Rainfall amounts of the magnitude observed, while not unknown in southwest Western Australia, are rare, and it may thus be argued that the situation was one in which it was 'easy' to show impact. The fact remains, though, that the operational analysis system did not have available to it sufficient data to adequately define the moisture fields over Western Australia and that, had these fields been better represented, improved guidance would have been provided to the forecasters in the Western Australian Regional Forecast Centre.

Acknowledgments

This study was prompted by the interest developed in the case by Dr L. Leslie following a visit to the Western Australian Regional Forecast Centre. His interest and comments are gratefully acknowledged.

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