Numerical Weather Prediction in New Zealand

Kevin E. Trenberth and Alex. A. Neale

New Zealand Meteorological Service, Wellington, New Zealand

(Manuscript received 19 July 1976, in final form 18 March 1977)

ABSTRACT

The main problem in weather forecasting over New Zealand and the Southern Oceans is the lack of sufficient data for good analyses, especially at upper levels. Numerical weather prediction also suffers from this problem, but it can to some degree be alleviated by producing several prognoses from reasonable alternative analyses to alert the forecaster to the sensitivity of the situation to data-blank areas. This procedure allows forecasters to assess the degree of confidence that can be placed in a forecast since unresolvable problems in the initial analyses cause uncertainty in predicting the exact timing and areas that will be affected by short-wave disturbances. It also gives them greater flexibility when later information becomes available and clearly invalidates one of the forecasts.

The performance of a five-layer quasi-geostrophic model developed for this purpose in New Zealand is described and illustrated with one case study of an unusual summer situation in the Australia–New Zealand region where a decaying tropical cyclone is absorbed into the frontal system of an extratropical cyclone undergoing explosive cyclogenesis.

1. Introduction

The New Zealand Meteorological Service has had an active interest in numerical weather prediction (NWP) since 1961 when the first experimental runs of a one-level model were made (Williamson, 1963). Multi-layer models have since been developed (Trenberth, 1973), but the lack of an on-line computer facility has delayed the implementation of a fully operational NWP system. In the meantime, experience has been gained from a semi-operational system at a remote site, but data handling, analyses and prognoses are executed without the benefits of any quality control or a man–machine interaction. Research into NWP has continued, and it is the purpose of this paper to outline the basic approach being developed in New Zealand and illustrate model performance with a case study.

There are many sources of error in general forecasting and numerical weather prediction, but in the Southern Hemisphere the greatest source of uncertainty in forecasts is nearly always analysis errors due to an insufficient data base. This is primarily the reason why NWP in this hemisphere has not produced increases in skill comparable with those that have occurred with model development in the Northern Hemisphere. VTPR (SIRS type) data from orbiting satellites have not yet proven reliable (Bengtsson and Morel, 1974) and determination of conditions over the large oceanic regions devoid of conventional data continues to depend, to a large extent, on subjective interpretation of satellite-observed cloud patterns, both visible and infrared.

Large uncertainties arise in the analysis of the initial atmospheric state in the Southern Hemisphere. Frequently there may be more than one plausible interpretation of a particular satellite cloud picture. Also the vertical motions indicated by cloud do not uniquely determine the geopotential height field. Therefore, it seems advantageous to produce several possible sets of analyses and prognoses, guided at the analysis stage by the satellite pictures and an appreciation of the dynamic consequences implied by the analyses. By this means the sensitivity of a given situation to reasonable changes in the data base can be determined. Later information enables the best analysis-prognosis to be chosen and used to initialize the analysis-prognosis sequence 12 h later. This procedure is akin to Monte Carlo forecasting (Leith, 1974).

In these circumstances, a sophisticated NWP model with a fairly long run time may be replaced advantageously by a model of lesser sophistication that can produce, in the same time, three runs using identical conventional data, but different subjectively derived "bogus" data. Such a model and its performance are described here. Analysis techniques, especially in the use of satellite pictures and derived data, will be considered, along with the interpretation of the prognosis to produce an actual forecast. The method is illustrated by a case study.

2. The NWP model

Improvements in NWP in the Northern Hemisphere have occurred 1) through incorporating improved numerical techniques and previously excluded physical effects, and 2) through the development of multi-level and primitive equation (PE) models. As these develop-

Unauthenticated | Downloaded 10/22/21 06:21 AM UTC

ments have gone hand-in-hand there has not been a convincing demonstration that the improvements are in any way due to the inclusion of ageostrophic effects, although these clearly become important in extended integrations and perhaps where a fine mesh allows small-scale details to be resolved.

The NWP model used in this study is the five-layer, limited-area quasi-geostrophic model described by Trenberth (1973). Predictions are made for 1000, 850, 700, 500, 300 and 200 mb in p coordinates and include a one-layer moisture prediction. Smoothed orography, friction, diffusion, latent heat and some diabatic heating are included, although rainfall rates are restricted to 20 mm day^{-1} by the quasi-geostrophic approximation. The grid is 381 km at 60°S on a polar stereographic projection, shown in Fig. 1a. The lateral boundaries are in meteorologically active areas and are a source of error. Heights are held fixed at the climatologically determined inflow boundaries, but at outflow boundaries tendencies are extrapolated from the interior and applied with an "energy sponge" technique. Simple three-point finite differences are used, and cause a substantial reduction in computed phase speeds for waves <3000 km in wavelength.

The use of the above quasi-geostrophic model to produce numerical prognoses is an approximation and the user must be aware of the model's capabilities and shortcomings. It can, however, provide valuable guidance for up to 48 h, although severe limitations on accuracy are apparent by that time.

3. Analysis

The analysis of geopotential height fields by objective methods uses a modified Cressman (1959) technique and is controlled by the use of subjectively derived "bogus" or secondary data in the form of 1000, 500 and 300 mb heights. Upper level analyses are performed every 12 h, but surface data are available at hourly, 3-hourly and 6-hourly intervals and intermediate analyses are carried out manually. By making use of continuity and all observations at the surface (such as ship reports), the analysis at the surface can be determined more reliably than that at upper levels. Therefore, the latter are constructed by a "build-up" technique in which thicknesses are added to the lower level. Thicknesses from 1000–500 and 500–300 mb are specified as bogus data, while 1000–850, 850–700 and 700–500 mb thicknesses are interpolated by regression formulas from the 1000–500 mb thicknesses using climatologically determined coefficients.

It is necessary for the analyst to check that, within the limits of the fairly coarse resolution of the numerical grid, the inserted secondary data are having the desired effect on the analysis. In practice this requires quite a large number of data points in order to insert detail into the analysis.

The positive feedback system of using the prognosis as the first guess for the subsequent analysis can be beneficial in data-sparse areas when synoptic systems have evolved in and advected out of data-rich regions. However, it can be detrimental if large errors in the forecast occur in regions where there are isolated observations only, and to avoid the loss of good data rejection criteria must be made fairly liberal. The provision of secondary data in such regions where the prognosis is seriously in error can help retention of good data without having to relax the rejection criteria too much. For this reason monitoring of the analysis is essential. Experience also shows that a 24 h cycle is too long and that a 12 h sequence of analyses and prognoses is required.

The practice of inserting three sets of secondary data to obtain three different analyses and prognoses according to the different interpretation of satellite pictures is not, as yet, fully developed in terms of optimal technique. The first set usually involves relatively little secondary data, and aims to correct any large errors in the first guess fields. In order to gain a reasonable appreciation of the different sequences of events in the subsequent two sets, based on experience it seems desirable that changes in analysis should be fairly radical. This is difficult to achieve in practice since there is a tendency for analysts to develop fixed ideas on how the situation is evolving.

4. Satellite-derived secondary data

The large oceanic expanses of the Southern Hemisphere have an advantage of providing a fairly uniform lower surface with a ready source of moisture. Therefore differences in clouds seen in satellite pictures are representative of real differences in atmospheric flow patterns. A cloud can be advected and maintain its identity, but in general its presence indicates abundant moisture and upward motion. Although our interest at this stage is in broad-scale features and processes, these may be characterized by fields of smaller scale clouds, such a cellular cumulus.

The vertical resolution of clouds from satellite pictures is limited. Separation can be made into low, middle and high types. While this gives some indication of limits to vertical motions, dry air entrainment, especially at upper levels, may also limit growth.

Cloud features have been related to atmospheric flow at certain levels by Anderson *et al.* (1973). The flow may be characterized as cyclonic or anticyclonic at the surface, 500 mb or in the 1000–500 mb shear. Regions of cold and warm advection can be found; troughs, ridges and jet streams located, and baroclinic zones related to frontal cloud bands. However, while many rules can be developed, the cloud patterns are all related to one or other of the 1000 mb or surface chart, the 500 mb and the 1000–500 mb thickness chart. These frequently do not answer questions such as: At what level does the vortex in a satellite picture apply? Is it the surface, the top of the boundary layer,

Unauthenticated | Downloaded 10/22/21 06:21 AM UTC

at 500 mb or somewhere in between? There are many unanswerable questions not resolved by single satellite pictures. More information can be obtained from a sequence of pictures. For instance, a developing vortex can look similar if stationary or moving, but whereas the former has centers of cyclonic vorticity and low pressure coincident, in the latter the low-pressure center will be located poleward of the vorticity maximum.

Several methods have been developed for estimating temperature soundings or thicknesses based on cloud classification schemes (Martin, 1968; Guymer, 1969) or identification of cloud patterns (Zillman and Price, 1972; Troup and Streten, 1972; Streten and Kellas, 1973; Nagle and Hayden, 1971). Such methods, based on mean relationships, have the advantage of keeping subjectivity to a minimum, but suffer from the disadvantage of inability to deal adequately with conditions that differ significantly from the mean.

In an attempt to quantify the satellite-derived data, the vortex cloud patterns as classified and defined by Troup and Streten (1972) and Streten and Kellas (1973) were modeled numerically. Diagnostic vertical motion fields were derived and prognoses made for 36 h which failed to reproduce vertical motion patterns matching the cloud patterns and the progression of types from wave through occluding and mature stages to the decaying vortex. This probably results from 1) the nature of the statistical samples which broaden features and remove detail, and 2) a failure to recognize some different types of development, such as the "instant" occlusion (Zillman and Price, 1972). Also, patterns associated with inverted comma-shaped clouds and frontal depressions should be treated separately in their developing stage, even though there may be little difference between their structure in the mature stage (Zillman and Price, 1972).

Further experiments were performed using patterns derived from fairly typical single cases representing each stage of development of a cloud vortex. Although these were more successful, the diversity of patterns occurring in the atmosphere limits the success of this approach. It was therefore found to be necessary to specify "bogus" observations at points in order to depict the individual features of each vortex. This is done by considering the following.

1) TRACKS OF CLOUD ENTITIES

When such features are identifiable in successive orbits over the same region, both the direction and speed of movement of the entity must be capable of being reproduced by the analyses. In the area between Australia and Antarctica, from whence originate many disturbances that affect New Zealand, the analyzed wind speeds often have been insufficient to produce the observed movement of cloud features related to short waves in the flow.

2) STATE OF EVOLUTION OF CLOUD SYSTEMS

Changes in the extent and degree of organization of cloud systems reveal aspects of their vertical structure and size. The larger a system becomes, the more it develops its own circulation and is slowed by frictional effects and nonlinear interaction with the steering current so that the long waves are affected.

3) DYNAMIC CONSISTENCY

The analyses should be compatible with the known stage of development of the system. Thermal advection patterns need to be carefully controlled with this in mind. Using the diagnostic omega equation, the analyst should ensure that the thermal and vorticity advection patterns given by the analyses are dynamically consistent with the vertical motions inferred from cloud patterns. In practice this can be fairly easily achieved; however, it is more difficult to obtain reasonable agreement between the state of evolution of the system and its subsequent development as revealed by the model.

4) REASON FOR CLOUD EXISTENCE

Experience has shown that the failure to adequately account for the presence of some clouds is a frequent source of error. A sequence of cloud pictures is essential for this task [see 1) and 2) above, in particular]. Caution is necessary since some cloud can persist and advect over considerable horizontal distances after the generating mechanism has ceased to operate.

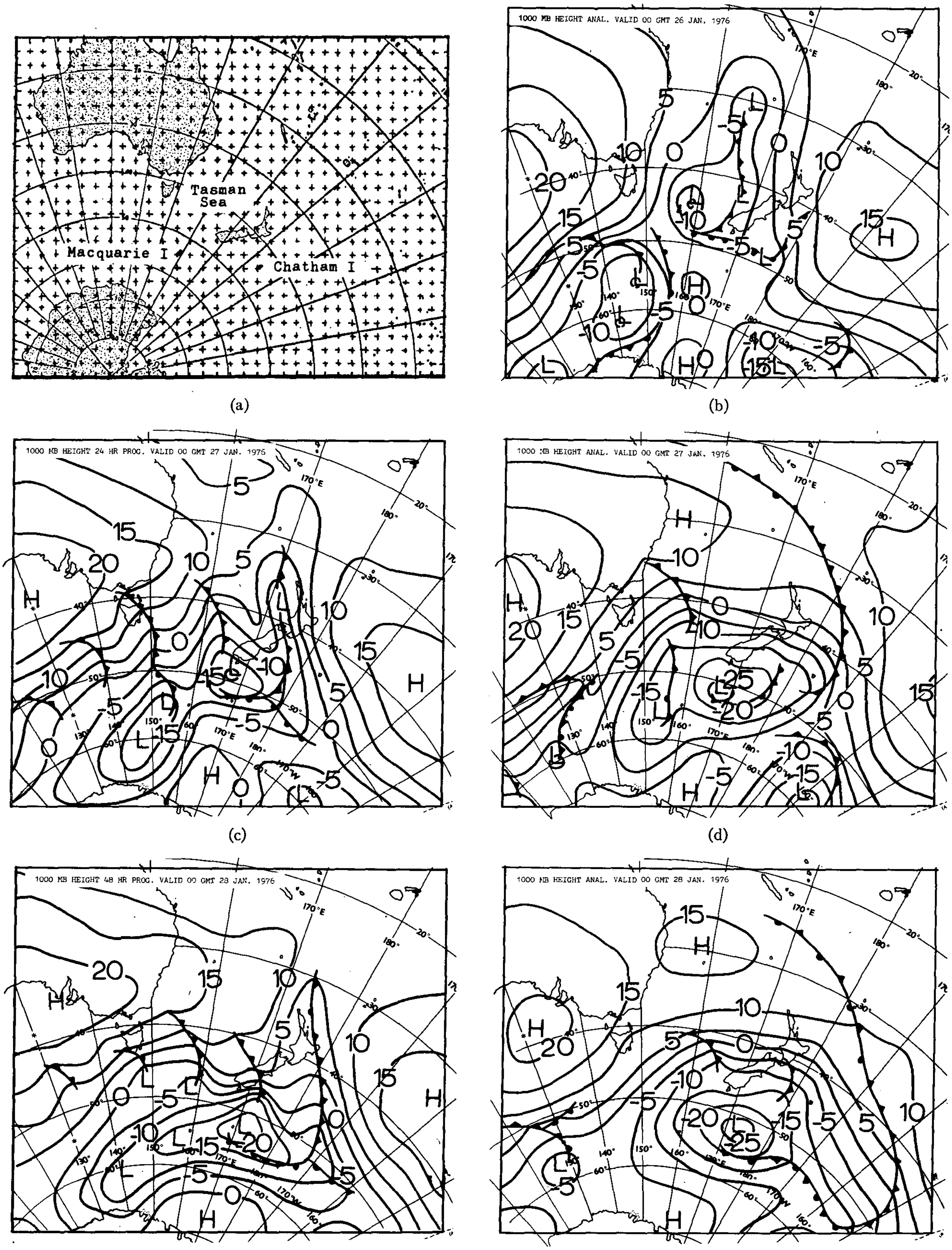
5. Case study

The performance of the NWP model and its interpretation are illustrated for an unusual situation in late January (summer) 1976 in the Australia–New Zealand region shown in Figs. 1–5.

An extratropical depression in the South Tasman Sea (place names referred to are shown in Fig. 1a) underwent explosive cyclogenesis on the 25th and 26th (Fig. 1b) and moved southeastward to lie south of New Zealand on 27 January (Figs. 1d, 1f). Meanwhile the decaying tropical cyclone Elsa, in the North Tasman Sea, moved rapidly southeastward to become absorbed into the frontal system of the depression. However, a secondary feature, developing west of the South Island (Fig. 1b), moved eastward, and in conjunction with Elsa, brought large pressure falls into the Chatham Is. area (Fig. 1d, 1f). Part of the low-pressure region west of Macquarie Is. on 26 January moved northeastward to merge into the western part of the main developing depression by the 28th (Fig. 1f). This resulted in a strong west–southwesterly air stream flowing onto New Zealand for several days.

The initially derived vertical motion field (Fig. 2a) shows good agreement with the satellite picture mosaic

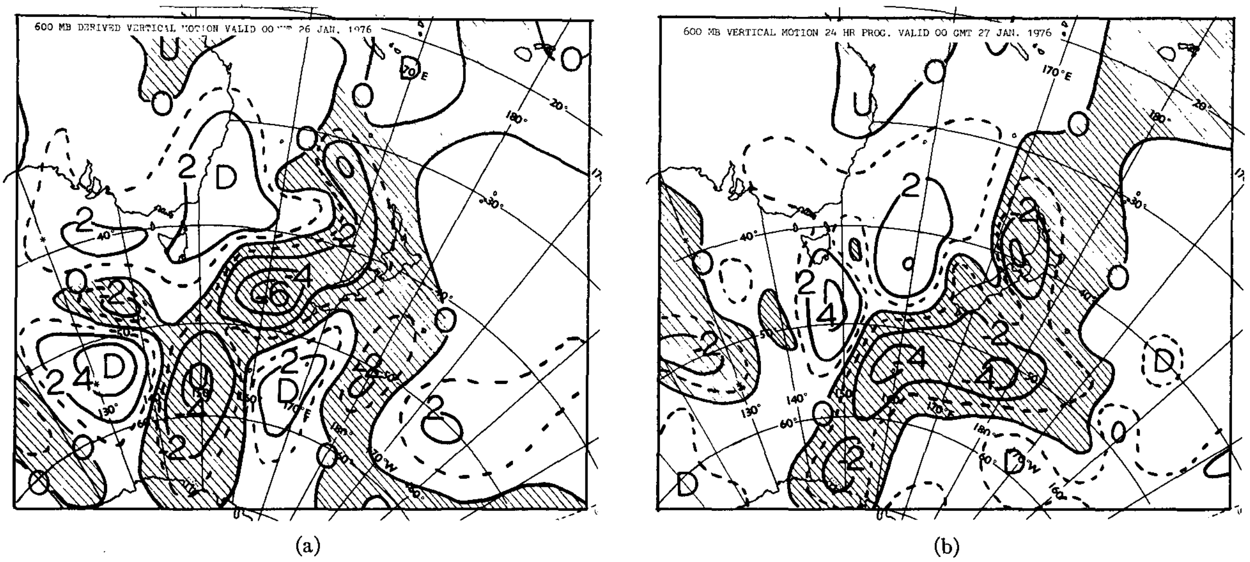
Unauthenticated | Downloaded 10/22/21 06:21 AM UTC



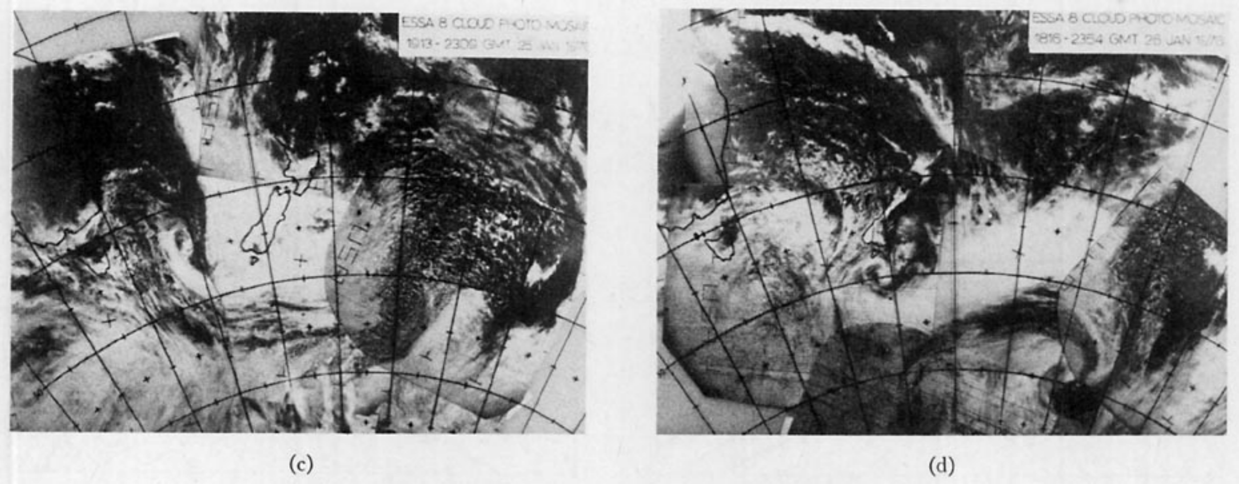
(a) (b) (c) (d) (e) (f)

FIG. 1a. NWP domain and grid points for the New Zealand model. Locations of places mentioned in the text are shown.
FIG. 1b. 1000 mb height analysis (dam) valid 0000 GMT 26 January 1976.
FIGS. 1c, 1d. 1000 mb height 24 h prognosis (c) and analysis (d) valid 0000 GMT 27 January 1976.
FIGS. 1e, 1f. 1000 mb height 48 h prognosis (e) and analysis (f) valid 0000 GMT 28 January 1976.

Unauthenticated | Downloaded 10/22/21 06:21 AM UTC



(a) (b)



(c) (d)

FIGS. 2a, 2b. Derived initial 600 mb vertical motion field valid 0000 GMT 26 January 1976 (a) and 24 h prognosis valid 0000 GMT 27 January 1976 (b).

FIGS. 2c, 2d. Satellite cloud mosaics (visible) from ESSA 8 valid about 2100 GMT 25 January 1976 (c) and 2100 GMT 26 January 1976 (d).

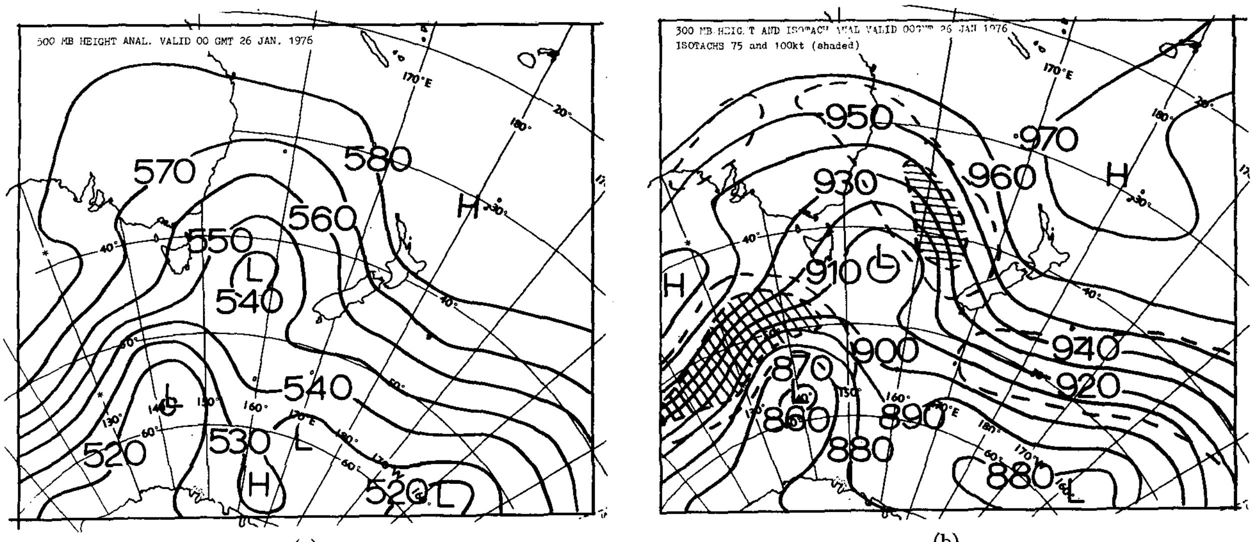
(Fig. 2c), and even represents Elsa remarkably well. Considerable uncertainty exists in the analysis south of Australia, southeast of New Zealand and in the small-scale detail in the Tasman Sea.

On the whole the prediction was quite good. The model successfully forecast the movement and deepening of the main depression and the low near Macquarie Is., but failed to reproduce the pressure falls near Chatham Is. The main error at 1000, 500 and 300 mb (Figs. 1c, 1e, 3c, 3d) was in the incorrect movement and intensification of the high to the east. The excessive buildup of pressure in this high had been a feature of model performance the previous day and was therefore not unexpected (see Brown and Fawcett, 1972). Partly as a consequence of this, the model was much too slow in the movement eastward across New Zealand of the front and heavy rain associated with Elsa, as shown by the vertical motion field (Fig. 2b) in comparison to the satellite cloud mosaic (Fig. 2d).

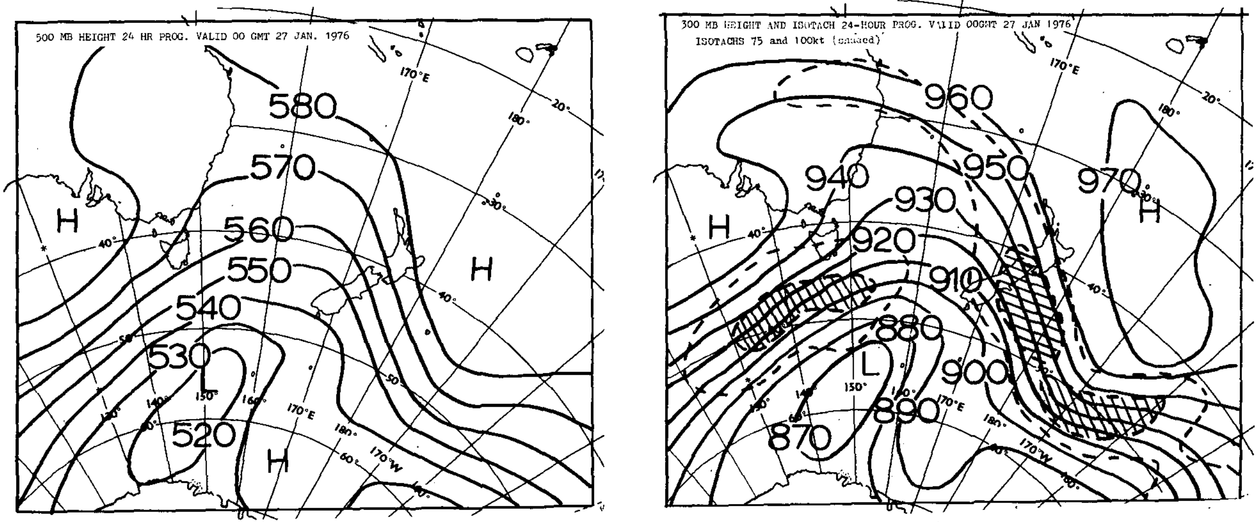
The model prediction contained many short-wave disturbances in the west-southwesterly airstream flowing from south of Australia across the Tasman Sea onto New Zealand (Figs. 1c, 1e), but was too slow in their speed of movement. Theoretically the finite-difference approximations of the model would reduce the phase speed of such short-wave features to perhaps 55% of their true value, and this too had been a feature of model performance the previous day. Other factors that need to be allowed for in the interpretation are systematic errors (Fawcett, 1969; Leary, 1971). The quasi-geostrophic approximation is responsible for some of these, such as follows:

- Highs and ridges are more intense, and lows and troughs less intense than found in practice.

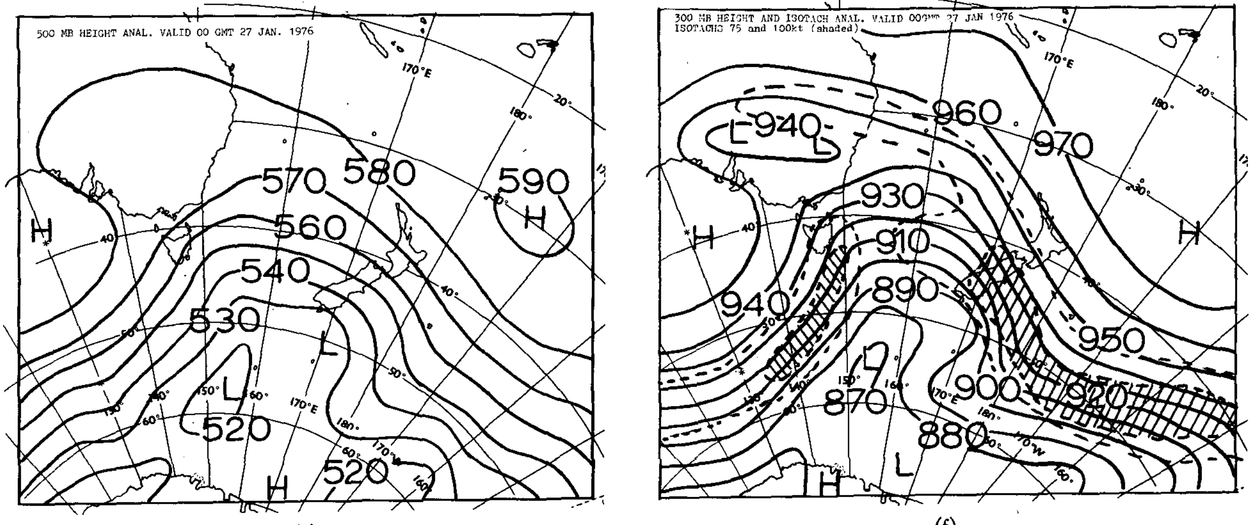
Unauthenticated | Downloaded 10/22/21 06:21 AM UTC



(a) (b)



(c) (d)



(e) (f)

FIGS. 3a, 3b. Height analysis (dam) at 500 mb (a) and height analysis (dam) and isotachs for 75 and 100 kt (shaded) at 300 mb (b), both valid 0000 GMT 26 January 1976.

FIGS. 3c, 3d. Twenty-four hour height prognosis at 500 mb (c) and height prognosis (dam) and isotachs for 75 and 100 kt (shaded) at 300 mb (d), both valid 0000 GMT 27 January 1976.

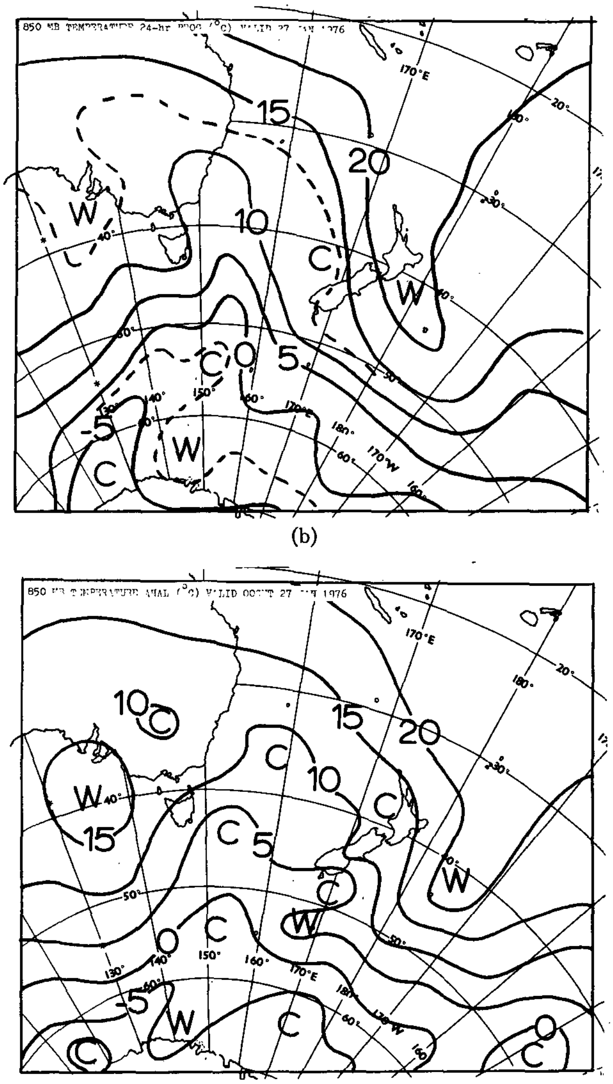
FIGS. 3e, 3f. Height analysis (dam) at 500 mb (e) and height analysis (dam) and isotachs for 75 and 100 kt (shaded) at 300 mb (f), both valid 0000 GMT 27 January 1976.

Unauthenticated | Downloaded 10/22/21 06:21 AM UTC

- The occlusion process is poorly handled which causes errors in the shape and amplitude of the warm tongue ahead of the main frontal system (Fig. 4).
- Systems are poorly handled in the tropics which, combined with the model's inability to satisfactorily resolve Elsa, probably caused difficulties in predicting developments in the eastern Tasman Sea in spite of the apparent ability of the model to reproduce the vertical motion field over Elsa.
- Planetary-scale waves are poorly handled (Kasahara, 1976). This is also caused by the limited domain. They are controlled by a large Helmholtz-term (Trenberth, 1973; Cressman, 1958) which also has the effect of reducing other wave speeds and deepening rates.
- The dynamic effect of smoothed orography is included in the model, but is inadequate in coping with the large height and narrow width of the mountain chain in the South Island of New Zealand.
- The restriction on the rainfall rate.

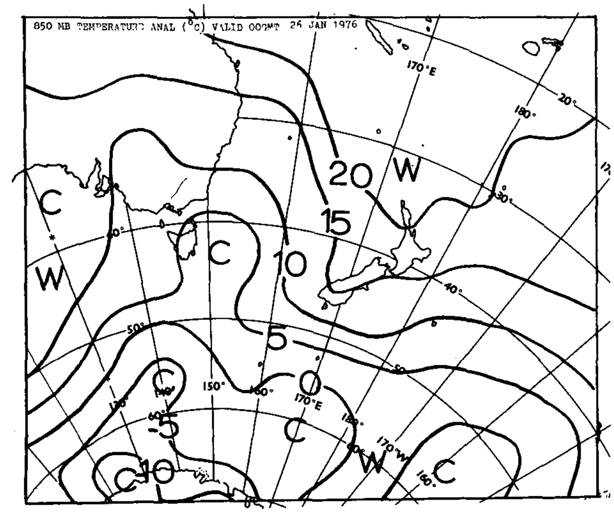
Consideration of the points listed above should have given reasonably good subjective height forecasts. However, it was not possible to anticipate that the remnants of tropical storm Elsa would move southeast at 48 kt from 0000 GMT 26 January to 0000 GMT 27 January compared to a speed of less than 20 kt in the previous 24 h. Therefore the forecasts would be too slow in moving Elsa and in developing the strong westerly across the North Island of New Zealand associated with the ridging along 30°S behind Elsa. In spite of these errors, changes in the jet stream at 300 mb were forecast rather well.

The rugged topography that exists in New Zealand produces large contrasts in weather across the mountains, and subjective manual modification of rainfall and other weather parameters is essential for local regions although the model does predict some orographic effects. In practice the rainfall prediction (Fig. 5a) should provide excellent guidance for anticipating the actual rainfall (Fig. 5b) although the timing may have been in error.



(b)

(c)



(a)

FIG. 4. 850 mb temperature analysis (°C) (based on 850–700 mb thickness) valid 0000 GMT 26 January 1976 (a), 850 mb 24 h temperature prognosis valid 0000 GMT 27 January 1976 (b), and 850 mb temperature analysis valid 0000 GMT 27 January 1976 (c).

Several other analysis-prognosis cycles were run for this case and the results for one of these are shown in Fig. 6. The height gradient and structure of the disturbances south of Australia and in the Tasman Sea were altered (Fig. 6a). These changes produced differences in the 24 h prognoses in the Tasman Sea and east of New Zealand (Fig. 6b), and fairly large differences were evident in the New Zealand region by the 48 h prognoses. The first prediction is superior to that in Fig. 6. Better forecasts were made of the movement

Unauthenticated | Downloaded 10/22/21 06:21 AM UTC

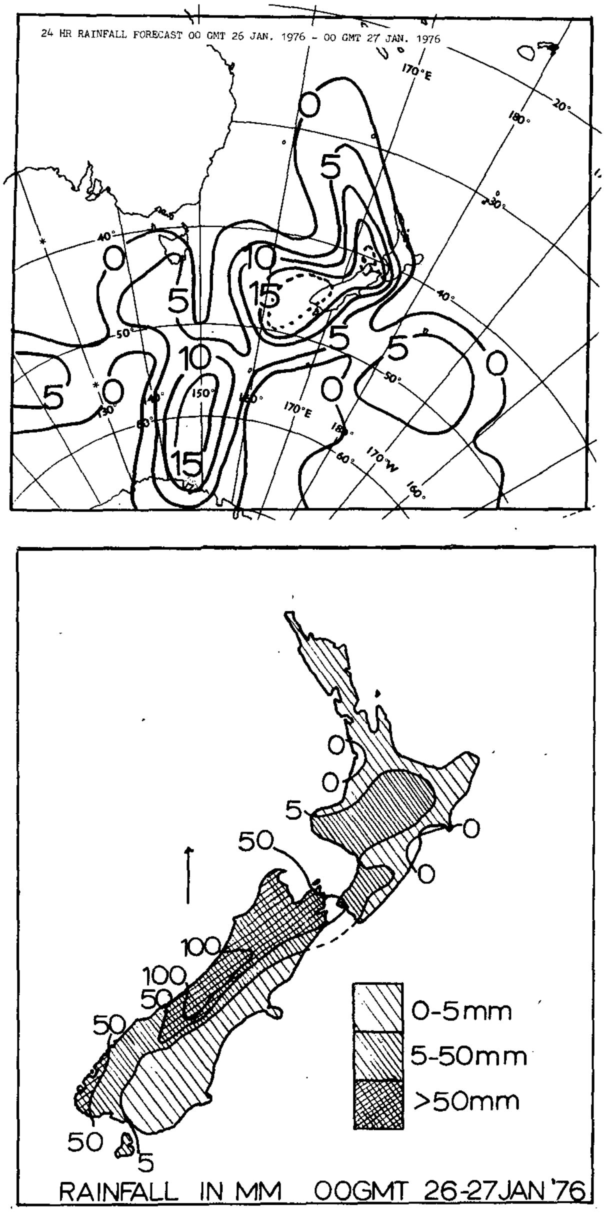
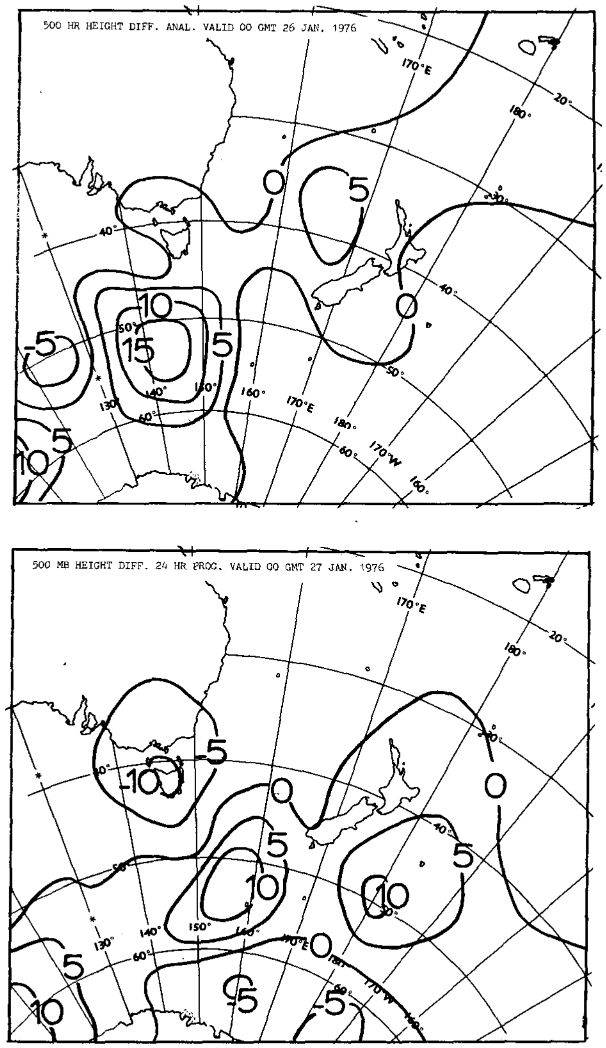


FIG. 5. 24 h forecast (a) and observed (b) rainfall (mm) for 0000 GMT 26–27 January 1976.

of the main front and the short waves, and in the amplitude and shape of the 500 mb trough in the Chatham Is. area (cf. Figs. 1e and 6c with Fig. 1f). The sharp trough approaching Tasmania in Fig. 6c could not be identified as one of the further cyclogenetic disturbances originating from south of Australia that moved rapidly northeastward (at ~30 kt) into the south Tasman Sea. Also, the ridging near Tasmania (Fig. 1f) subsequently extended northeastward into the north Tasman Sea and was forecast more accurately in Fig. 1e. It was not possible to determine which was the better forecast until 24 h later, by which time there were definite indications that the broad belt of westerlies south of Australia were as strong as depicted in



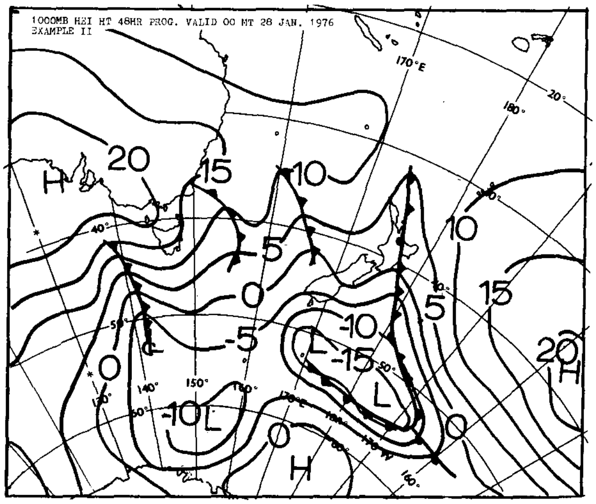


FIG. 6a, 6b. Height differences in 500 mb analysis (dam) from Fig. 3a (a) and in 500 mb 24 h prognosis (dam) from Fig. 3c (b), both for the second analysis-prognosis cycle.

FIG. 6c. 100 mb height 48 h prognosis (dam) for the second forecast, valid 0000 GMT 28 January 1976.

Unauthenticated | Downloaded 10/22/21 06:21 AM UTC

Fig. 3. What the comparison shows for this case is that the region extending from the Tasman Sea across New Zealand to the Chatham Is. is an area sensitive to unresolvable problems in the analysis. Consequently difficulties must be expected in predicting the timing and areas to be affected by short-wave disturbances.

6. Conclusion

The quasi-geostrophic NWP model used in New Zealand has shown encouraging results. In the case study presented here, several features are forecast quite well. It is certainly capable of predicting cyclogenesis. However, compared to PE models, a number of further assumptions are included within the model formulation and care is necessary in interpreting the results. Corrections should be made to the height forecasts based on known limitations inherent in the model as well as on any bias revealed by the manner in which the model has handled the situation in the recent past.

In the Southern Hemisphere, owing to uncertainty in analyses resulting from the absence of good data coverage, a model of lesser sophistication can be used to advantage and produce, say, three analysis-prognosis cycles to test the sensitivity of the prognoses to reasonable alternate analyses based on satellite data in what are otherwise data blank regions. This provides added flexibility to the forecaster when later information becomes available, and gives an indication of the degree of confidence that can be attributed to the forecast. On many occasions, uncertainties in the analyses may not be as great or are more remote, so that they do not affect the main area of interest, which is the New Zealand mainland and immediately surrounding waters, and forecasts can be made with greater confidence.

REFERENCES

Anderson, R. K., J. P. Ashman, G. R. Farr, E. W. Ferguson, G. N. Isayeva, V. J. Oliver, F. C. Parmenter, T. P. Popover, R. W. Skidmore, A. M. Smith and N. F. Veltishchev, 1973: The use of satellite pictures in weather analysis and forecasting. WMO Tech. Note. 124, WMO No. 333.

Bengtsson, L., and P. Morel, 1974: The performance of space observing systems for the first GARP Global Experiment. GARP Working Group on Numerical Experimentation, Rep. No. 6.

Brown, H. E., and E. B. Fawcett, 1972: Use of numerical guidance at the National Weather Service's National Meteorological Center. *J. Appl. Meteor.*, **11**, 1175–1182.

Cressman, G. P., 1958: Barotropic divergence and very long atmospheric waves. *Mon. Wea. Rev.*, **86**, 293–297.

——, 1959: An operational objective analysis system. *Mon. Wea. Rev.*, **87**, 367–374.

Fawcett, E. B., 1969: Systematic errors in operational baroclinic prognoses at the National Meteorological Center. *Mon. Wea. Rev.*, **97**, 670–682.

Guymer, L., 1969: Estimation of 1000–500 mb thickness patterns from satellite pictures of convective areas. *Proc. WMO Interregional Seminar Interpretation of Meteorological Satellite data*, Melbourne, Bureau of Meteorology, 51–55.

Kasahara, A., 1976: Normal modes of ultra-long waves in the atmosphere. *Mon. Wea. Rev.*, **104**, 669–690.

Leary, C., 1971: Systematic errors in operational National Meteorological Center primitive equation surface prognoses. *Mon. Wea. Rev.*, **99**, 409–413.

Leith, C. E., 1974: Theoretical skill of Monte Carlo forecasts. *Mon. Wea. Rev.*, **102**, 409–418.

Martin, D. W., 1968: Satellite studies of cyclone developments over the southern ocean. Internal Antarctic Meteor. Res. Centre, Tech. Rep. No. 9, Bureau of Meteorology, Melbourne.

Nagle, R. E., and C. M. Hayden, 1971: The use of satellite-observed cloud patterns in Northern Hemisphere 500 mb numerical analysis. NOAA Tech. Rep. NESS 55.

Streten, N. A., and W. R. Kellas, 1973: Aspects of cloud pattern signatures of depressions in maturity and decay. *J. Appl. Meteor.*, **12**, 23–27.

Trenberth, K. E., 1973: A five-layer numerical weather prediction model. New Zealand Meteor. Serv. Tech. Note No. 222.

Troup, A. J., and N. A. Streten, 1972: Satellite-observed Southern Hemisphere cloud vortices in relation to conventional observations. *J. Appl. Meteor.*, **11**, 909–917.

Williamson, E. A., 1963: Initial report on numerical weather prediction in the New Zealand Meteorological Service. New Zealand Meteor. Serv. Tech. Note No. 150.

Zillman, J. W., and P. G. Price, 1972: On the thermal structure of mature southern ocean cyclones. *Aust. Meteor. Mag.*, **20**, 34–48.

Unauthenticated | Downloaded 10/22/21 06:21 AM UTC