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ON THE THERMAL STRUCTURE OF MATURE SOUTHERN OCEAN CYCLONES

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ABSTRACT

A model of the thermal structure of Southern Ocean cyclones generalised from aerological soundings through characteristic vortex-associated cloud features is presented. The idealised patterns of sea-air temperature difference, mixed layer depth, tropopause pressure and thermal anomaly fields on several constant-pressure surfaces are judged to be fairly representative for the region between about 40°S and the pack-ice limits for all seasons but the magnitudes are strictly applicable only to the October-November-December period from which most of the basic data were taken.

INTRODUCTION

Despite a limited number of published case studies (*eg* Langford, 1948; Merritt, 1963; Rutherford, 1966; Martin, 1968a) and the very extensive personal knowledge of practising Southern Ocean analysts, the literature offers little to enlighten the outsider seeking information on the structure of Southern Ocean cyclones. The material available for the most part, is so strongly influenced by the classical Norwegian concept of an occluding Polar Front that it is usually difficult and sometimes impossible to distinguish, in retrospect, the data content from the framework of the model on which it is hung.

Ancillary to the development of detailed cyclone models for the southern oceans as is being undertaken for example by Troup and Streten (1972), an idealised picture is presented here of the thermal structure of the mature oceanic cyclone derived from a study of conventional temperature soundings through various characteristic vortex-associated cloud features *without reference* to such long-controversial concepts as the frontal occlusion. The data base for the model derives largely from an unpublished study by the authors undertaken as an analysis aid for the November 1969 GARP Basic Data Set Experiment (Thompson, 1971; Phillpot *et al*, 1971).

INFERENCE OF VERTICAL TEMPERATURE PROFILES FROM CLOUD PATTERNS

Martin (1968a, b) showed that certain features of the vertical structure of the atmosphere over the ocean can be inferred, with high statistical significance, directly from the satellite-viewed cloud patterns. He employed an elaborate classification scheme designed to isolate and describe in geometric and textural terms each significant pattern visible in cloud photographs of the Southern Ocean. Several other schemes for classifying satellite cloud patterns have been devised (*eg* Boucher and Newcomb, 1962; Merritt, 1963; Guymer, 1969) whilst the same general approach to the quantitative interpretation of the cloud pictures has been adopted (with a less refined classification procedure) by Blackmer, Davis and Serebreny (1968).

The present authors motivated by the analysis requirements of the November 1969 GARP Basic Data Set Project, derived model vertical profiles of temperature and vector wind for each of several geometrically-defined sub-categories of the following six major cloud categories as observed by satellite:

- Vortices
- Major vortex-associated bands
- Essentially clear areas (well distant from land)
- Areas of low-level stratiform cloud
- Areas of open cellular convection
- Closed cellular areas

The investigation employed data, as available, mainly for the months October, November, December, 1966-69. Cloud patterns were identified in Automatic Picture Transmission (APT) photographs received in Melbourne, Christchurch, Papeete, Vacaos (Mauritius) and McMurdo Sound (Antarctica). Limited use was made of the daily 'ESSA Digital Product' and the Spin-scan photos from ATS 1. Concurrent tropospheric temperature and wind profiles were taken from the routine aerological soundings at several middle and high latitude island stations (strongly biassed towards Macquarie and Campbell Islands) and the USA Antarctic Research Vessel 'Eltanin'. Ship observations of sea-air temperature differences were assembled (with strong bias towards the eastern hemisphere) from a multitude of sources including the special collection for the November 1969 GARP Project.

The detailed results of the analysis will not be discussed here. Fig 1 illustrates the approach by superposing the first ten profiles assigned to each of two quite dissimilar cloud categories. The individual profiles, having been taken from stations at different latitudes between 40°S and 60°S, are homogenised by referencing to the surface *air* temperature. For each category, mean (model) profiles were derived, partly by arithmetic averaging and partly by visual sketching, subsequently a number of parameters (layer-mean lapse rates, thickness departures from a reference atmosphere, depth of the surface mixed layer, tropopause pressure and so on) were extracted for use as analysis aids along with subjective estimates of the probable spread about the means. A rather complex scheme for allowing for departures of surface pressure from 1000 mb was devised but, in application to routine analysis, proved too time-consuming to invoke quantitatively. A limited

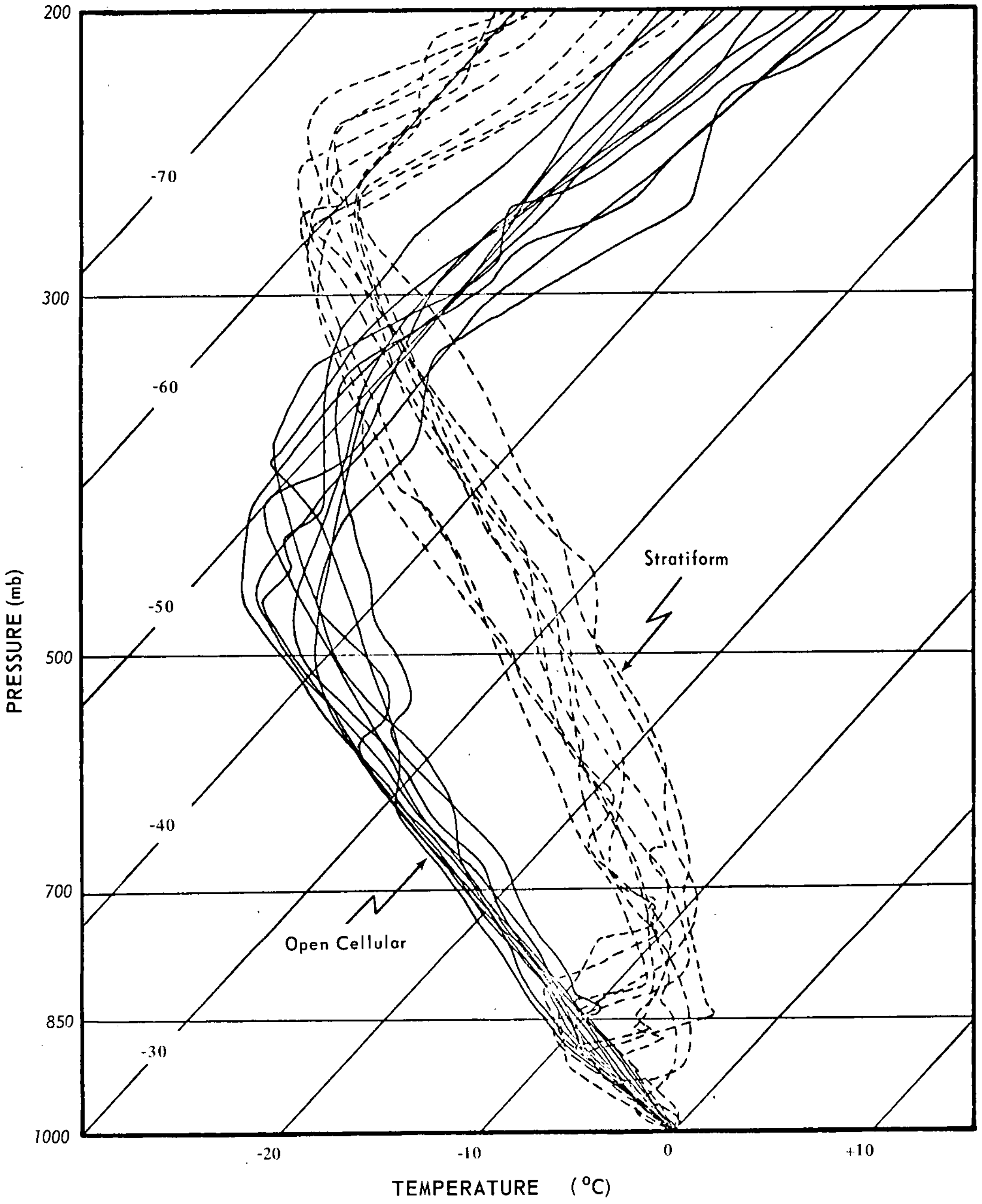

Fig 1 Ten soundings through each of two dissimilar cloud types:

(i) the forward section of a field of open cellular convection following a major vortex-associated band (solid lines)

(ii) low level stratiform cloud westward and poleward of an extensive area of cellular cloud (broken lines).

All soundings are referenced to a common surface air temperature and departures of surface pressure from 1000 millibars have been disregarded.

comparative test of these pseudo soundings and early (Nimbus III) SIRS profiles with an independent sample of radiosonde data indicated that *within well-defined cloud types* the pseudo soundings were often clearly superior and could thus serve a useful function as a supplementary analysis aid.

CLOUD CONFIGURATION FOR THE MODEL CYCLONE

At least three basic sequences of vortex development can be distinguished over the Southern Ocean. These are depicted schematically together with a possible frontal analysis using conventional symbols in Fig 2.

(i) The developing (inverted) comma formation

Within an area of cellular convection a region of enhanced vertical development, usually in the forward section (often first evident as cirrus plumes spread downstream), may assume the shape of an inverted comma before developing into a clearly formed spiral. Coincident with spiral formation the tail of the comma, initially an aggregate of cellular cloud, tends to consolidate into a well-defined band

(ii) The 'instant occlusion' sequence

Rather than form a vortex within the cellular cloud the region of enhanced convection may overtake the decelerating and sometimes decaying band of an earlier vortex to produce an 'instant occlusion' (Anderson *et al* 1969). This process appears remarkably similar to that depicted by Rossby (1959) before the advent of the satellite photograph

(iii) The 'frontal occlusion' sequence

Quite frequently new vortices develop on the band trailing northwestward from a mature or decaying vortex through a geometrical evolution which is in substantial agreement with the various stages of the classical frontal wave occlusion sequence.

Actual examples of each of the above may be found in Martin (1968a, b) and Rutherford (1969). In the final stages of all three development sequences it is possible to identify several frequently recurring cloud formations which comprise or accompany the mature vortex. Though their shape, size, orientation and degree of development of course vary from case to case the common characteristics are sufficiently pronounced to justify, as a first approximation, depiction of a single idealised or model cloud configuration for the mature cyclone (Fig 3). The important component features of this cloud distribution model are:

(a) Major band equatorward of vortex: the band consists of a solid overcast of middle and/or high level cloud at least a few degrees of latitude in width and usually oriented to the north or northwest. (In the data sample from which the mean profiles were derived two restrictions were imposed for this category: only soundings within 10 degrees of the latitude of the vortex core were included and soundings westward of any significant surface discontinuity in wind, temperature or pressure were excluded even though well within the band)

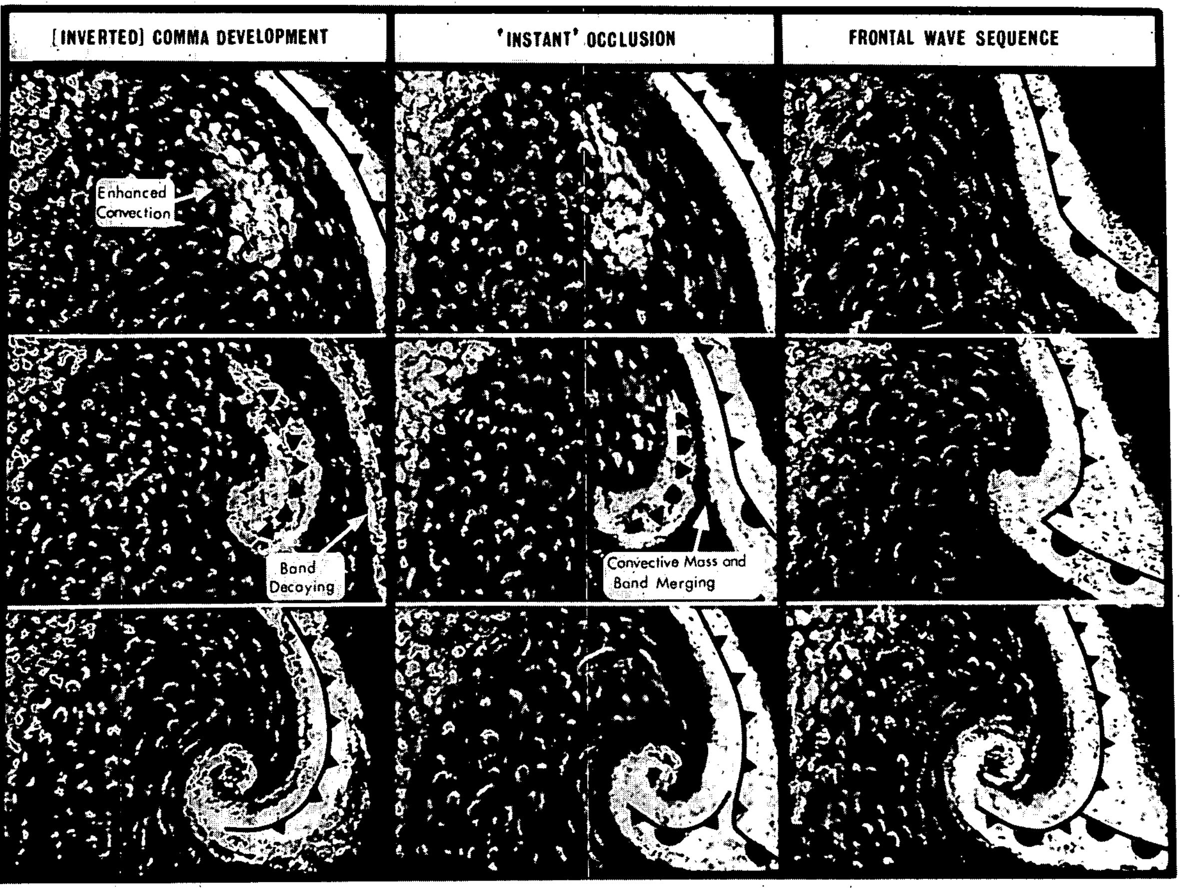

Fig 2 Schematic depiction of three basic sequences of vortex development evident in satellite photographs of the Southern Ocean. Frontal symbols indicate one scheme for representing the various evolution sequences with the equipment of conventional frontal analysis.

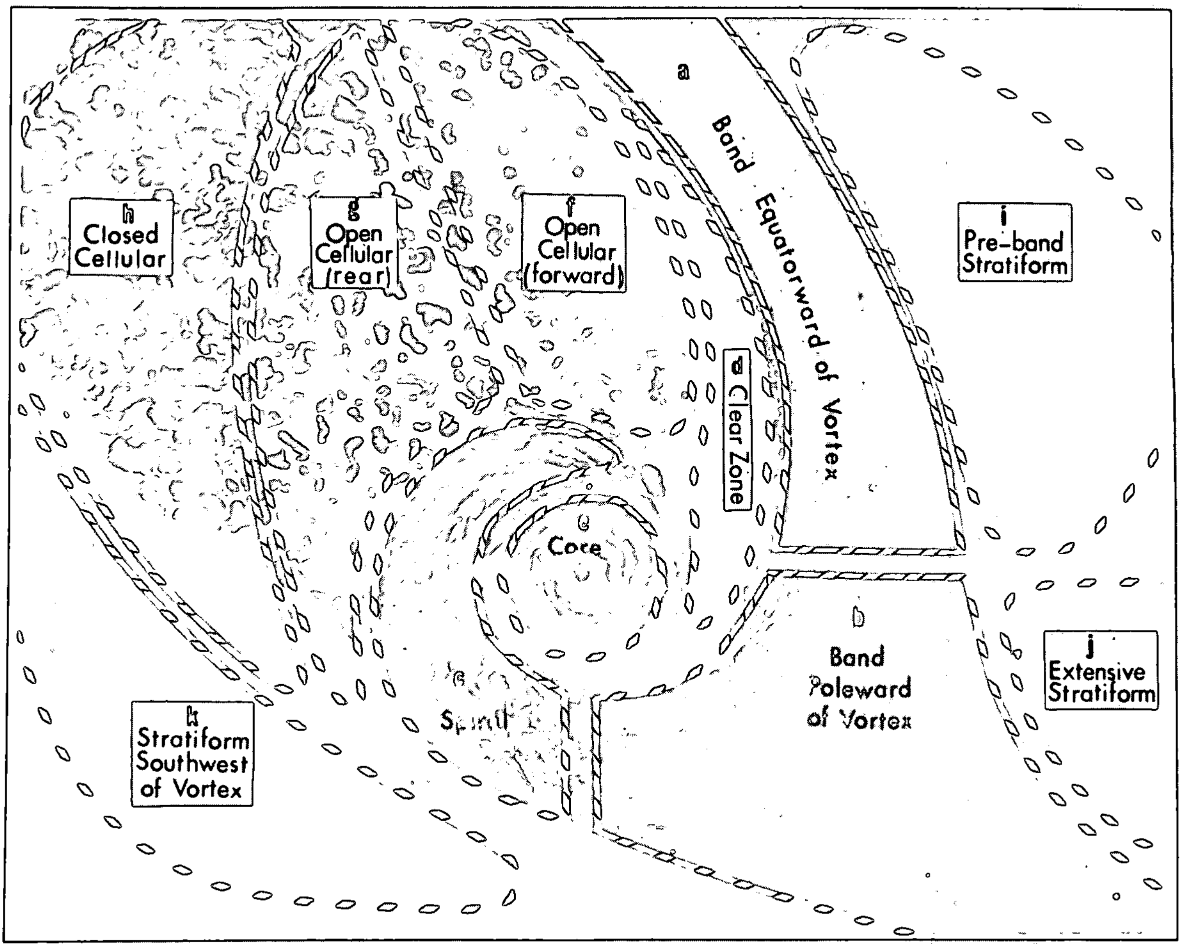

Fig 3 Schematic depiction of the distribution of cloud types as seen by satellite for the idealised mature oceanic cyclone.

(b) Major band poleward of vortex: the band may extend away to the southeast, east or northeast, but this sub-category embraces only that part of the band which lies to the south and east of the vortex core and within a radius of about 10 degrees of latitude

(c) Hook or spiral section of the band westward of the vortex core

(d) Post-band clear zone: this feature is rarely absent with a well developed cyclone

(e) Vortex core: this may consist of a tight spiral or may appear disorganised and lumpy

(f) Field of open cellular convection following a major band (forward section): it is usually within this area that the cellular cloud displays its greatest vertical development

(g) Open cellular area (rear section): vertical development tends to be less but average cloudiness greater than in the forward section of the cellular area

(h) An area of closed cellular cloud usually merging with an open cellular region to the east and stratiform cloud to the west or southwest

(i) Pre-band stratiform area: a mass of low level stratiform cloud often broken and irregular in outline lying ahead of the major band (and usually merging with it): this sub-category was restricted to stratiform cloud lying equatorward of the latitude of the vortex core

(j) Extensive stratiform area lying south and east of the vortex and frequently merging with it or with the band which trails out to the southeast

(k) Stratiform area southwest of the vortex: this may merge more or less directly with either open or closed cellular areas or the western part of the main hook or spiral; sometimes it is separated from the latter by a narrow clear area. In occurrence and both shape and structure it is the least consistent of the sub-categories considered.

Inspection of even a few months of daily satellite pictures provides convincing evidence that no two vortices are ever quite the same: it follows that no idealised cloud configuration or model structure can do justice to the individual diverse systems which are so evident in the daily infrared and video imagery of the Southern Ocean. However any attempt to diagnostically model the cloud configuration and attendant thermal structure of even the idealised cyclone is at least as valid as, and certainly of more practical value in three-dimensional analysis than, resort to the implications of some drastically over-simplified physical process such as envisaged to be operative in the formation of the classical occlusion (Bjerknes and Solberg, 1922).

THERMAL STRUCTURE OF THE MODEL CYCLONE

The model profiles derived in the pre-GARP study for each of the cloud sub-categories appearing in Fig 3 (with the exception of (c) and (d) for which no adequate data sample was available) is shown in Fig 4. By assigning to these the role of area-means for the central parts of each cloud type delineated in Fig 3 and adapting the results of the more detailed study of the spatial distribution of sea-air temperature difference in relation to cloud type, the isopleth patterns of Fig 5 have been prepared. These show, superimposed on the cloud model of Fig 3 idealised patterns of:

(a) Sea-air temperature difference $(T_s - T_a)$ in °C

(b) Sea temperature - 850 mb temperature $(T_s - T_{850})$ in °C

(c) Sea temperature - 700 mb temperature $(T_s - T_{700})$ in °C

(d) Sea temperature - 500 mb temperature $(T_s - T_{500})$ in °C

(e) Pressure at the top of the well-mixed layer in mb

(f) Tropopause pressure in mb.

It should be stressed that the isopleth patterns of Fig 5 still contain a substantial element of subjectivity. In fitting the patterns to the data we were guided in varying degree by a number of individual cross sectional studies of cyclones passing over Macquarie Island (spring 1966, 1967) and the USNS 'Eltanin' (all seasons 1968-70) as well as synoptic analyses in bordering data-dense areas. Where the patterns are judged less well defined the isopleths are shown broken. Reference to the concepts of air masses and fronts in constructing Fig 5 (and Fig 6) was avoided deliberately though the association of many of the attributes of the conventional 'front' or 'frontal zone' with the major cloud band is readily apparent. The trowel structure (Gibson 1964, Kamiko 1964) of the cloud hook or spiral is fairly well established though its origin in a classical 'occlusion' process has not been substantiated for this region or elsewhere.

Fig 5(e) indicating the top of the mixed layer warrants further comment. The isopleths indicate the approximate pressure at which a fairly abrupt decrease in lapse rate occurs above a near adiabatic layer extending to at least a few hundred metres above the sea surface. Thus defined, it extends virtually to the tropopause in the most unstable region of cumulonimbus convection (*cf* Clarke, 1969; Sheppard, 1970) even though (through latent heat release and other factors) an upward increase of potential temperature of 15°C or so occurs through the troposphere. By contrast the peripheral parts of the shaded region delineating an area with 'no mixed layer' tend to be characterised by moderate stability to 500-1000 m and there capped by a strong inversion.

A west-east cross section of temperature anomaly through the northern section of the model vortex is presented in Fig 6. For simplicity of interpretation (and consistency with Fig 5) departures of surface pressure from 1000 mb have been disregarded. The isopleths of Fig 6, like those of Fig 5, are based on the mean profiles of Fig 4, inferences on horizontal thermal gradients from the vertical shear of the geostrophic wind and detailed time-section reconstructions through a number of individual cyclones. The baroclinic character of the major cloud band and following clear zone is readily apparent as is the coldness and instability of the open cellular area; also apparent is the westward descent of the stable layer associated with the transition from open, through closed cellular, to stratiform cloud.

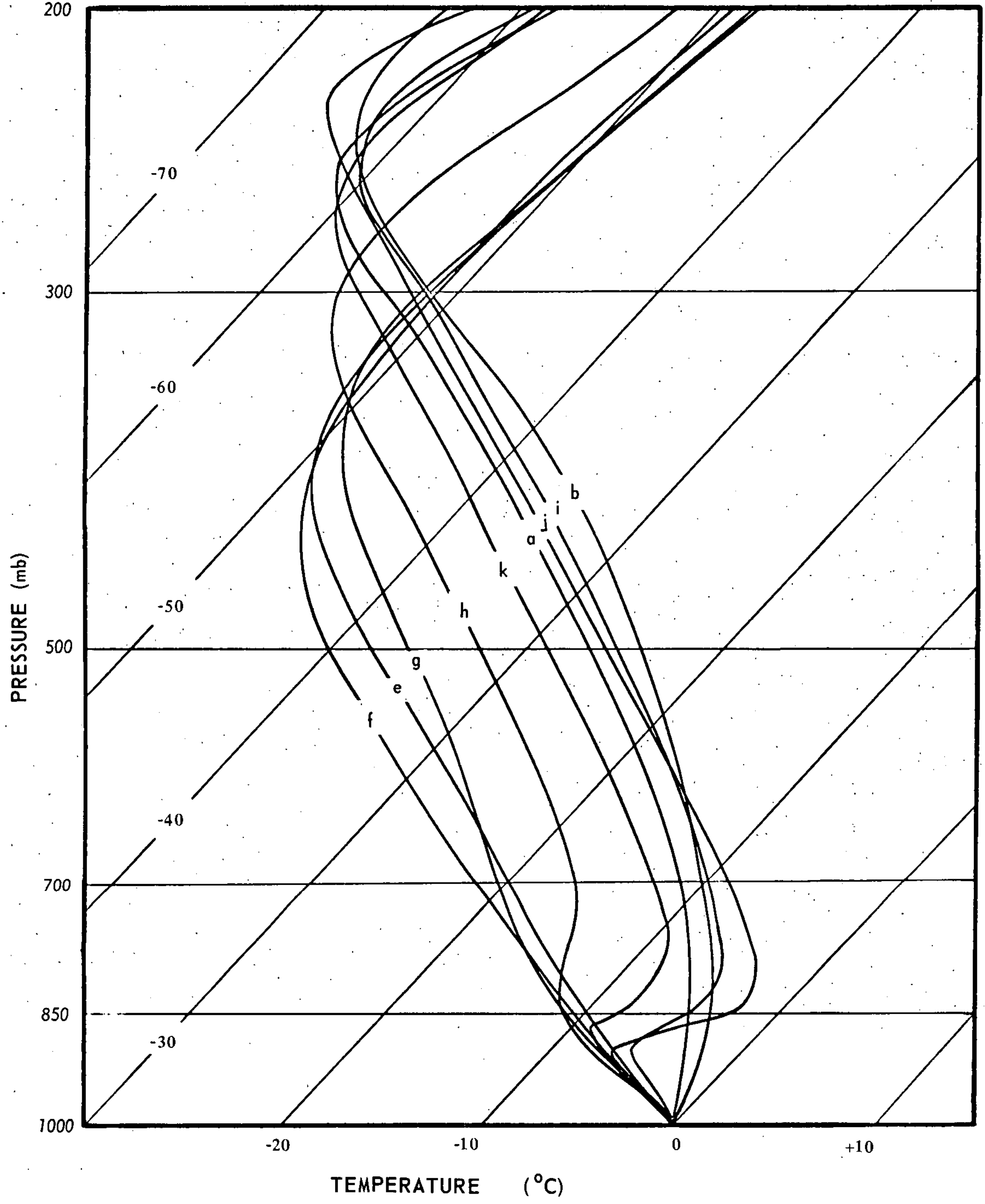

Fig 4 Model profiles for cloud categories a, b and e to k described in the text. All profiles are are referenced to a common surface air temperature.

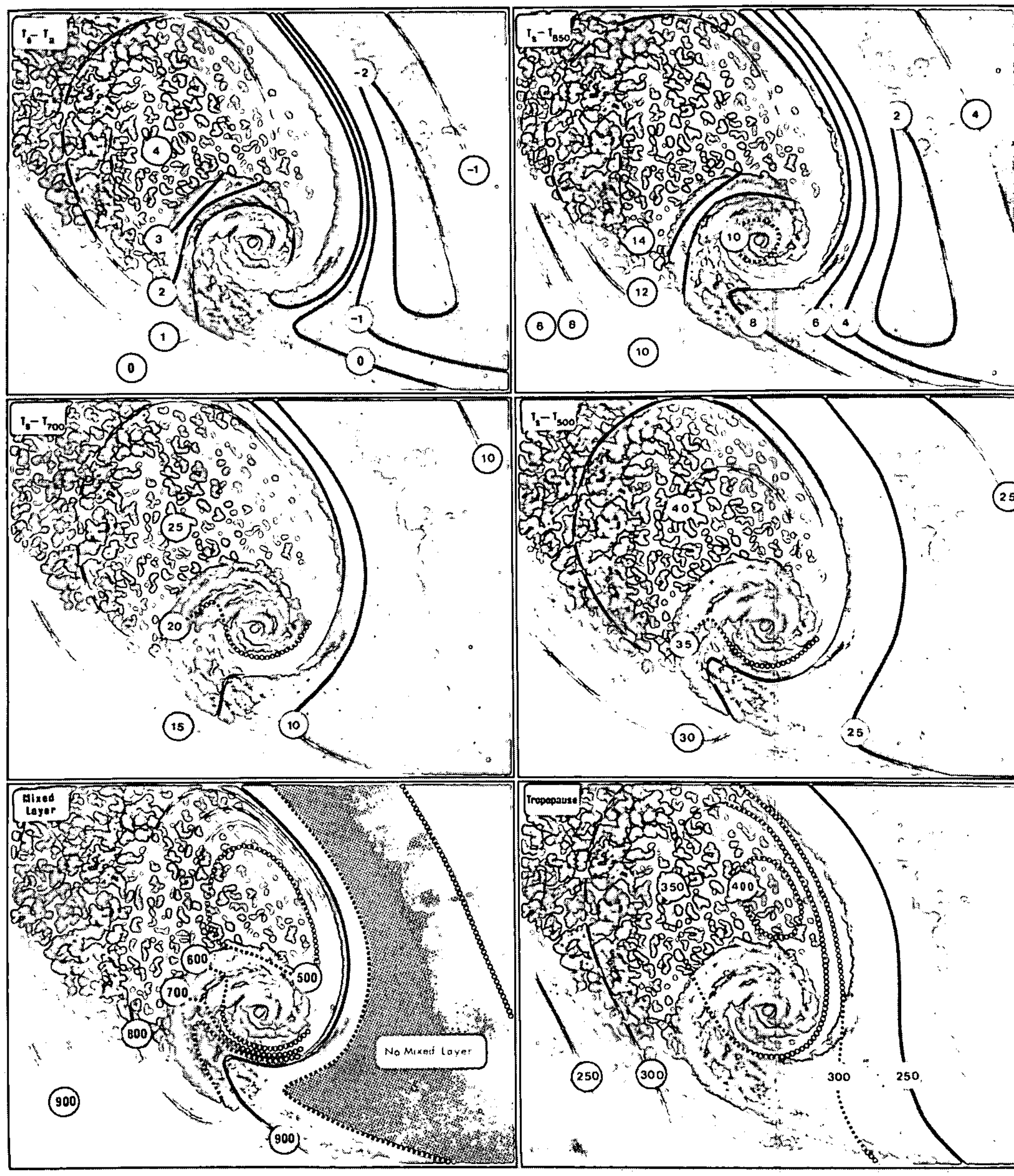

Fig 5 Idealised three-dimensional structure of the mature oceanic cyclone synthesised from model profiles and sea-air temperature difference statistics:

(a) Sea-air temperature difference, $T_s - T_a$ (°C)

(b) Sea surface - 850 mb temperature difference, $T_s - T_{850}$ (°C)

(c) Sea surface - 700 mb temperature difference, $T_s - T_{700}$ (°C)

(d) Sea surface - 500 mb temperature difference, $T_s - T_{500}$ (°C)

(e) Pressure at the top of the mixed layer (mb)

(f) Tropopause pressure (mb)

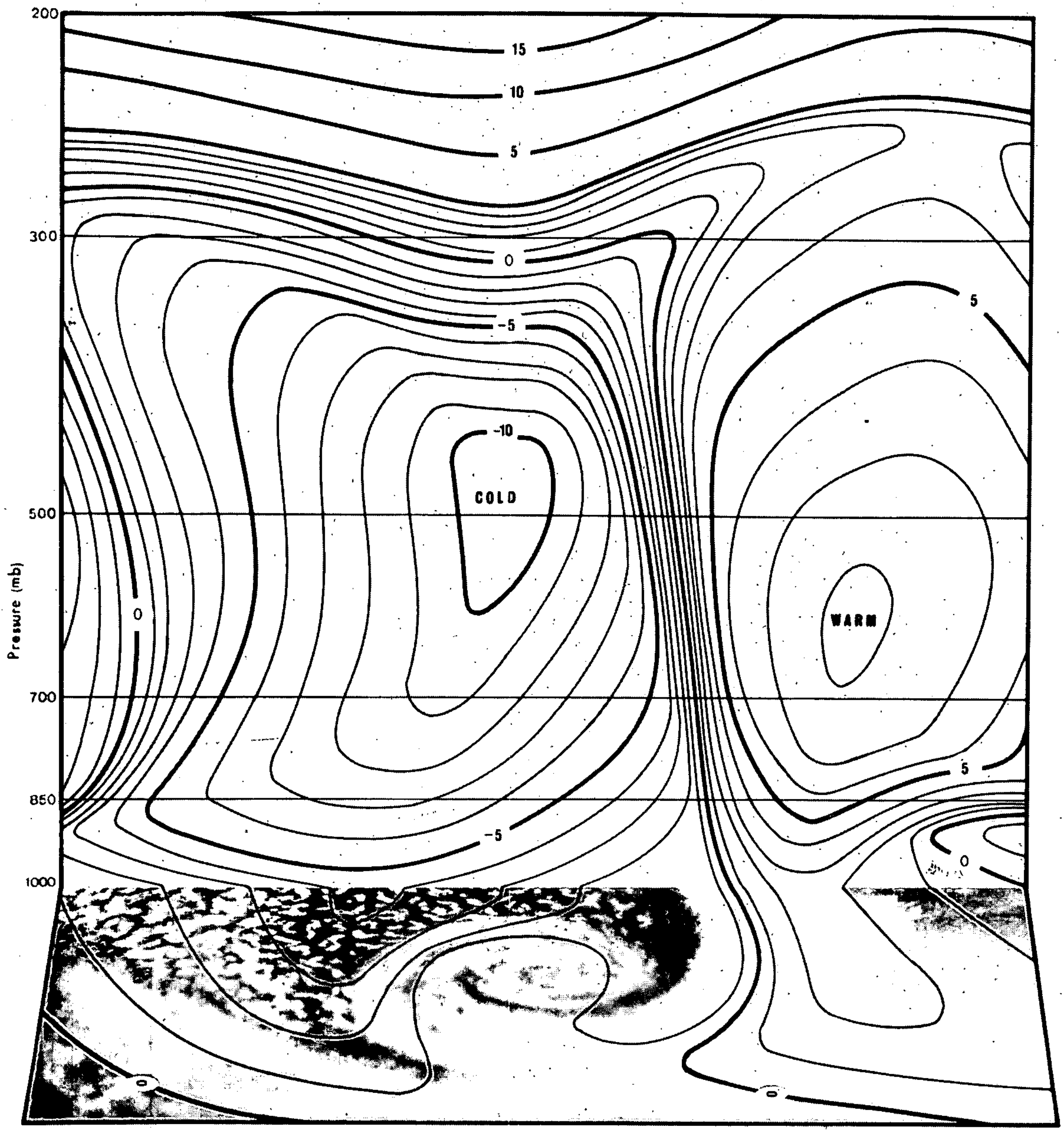

Fig 6 West-east cross section of temperature departures from a reference atmosphere just equatorward of the core region of the idealised vortex. The reference atmosphere has a 74°C logarithmic temperature decrease from the sea surface temperature to 200 mb, thus approximating the climatological normal in the troposphere.

DISCUSSION AND CONCLUSION

Apart from several obvious limitations in the model of Fig 5, there are others which to a degree invalidate the approach. One concerns the neglect of the temperature variation of the moist adiabatic lapse rate implicit in combining data where the same physical process (saturated ascent) may be operating but at different temperatures. Another is concerned with averaging temperature differences over varying pressure intervals (dependent on surface pressure) rather than averaging lapse rates. The discrepancies, however, are largely negligible in the context for which the model of Fig 5 may be used.

The purpose of the model is to provide an aid to indirect aerology in the environs of mature high-latitude oceanic cyclones. All that is needed to specify an approximate thermal structure is an actual (or in its absence a climatological) sea-surface temperature field. For constant pressure analysis the simplest procedure consists of sketching a pattern of (say) $T_s - T_{500}$ over a map-projection of the satellite photographs and graphically subtracting this from a sea-surface isotherm field. To proceed further and derive the topography of the various constant pressure surfaces *via* differential analysis, the topography of one at least must be known. Conventionally this has been the lowest level, though the development of the miniaturised balloon-borne radio altimeter and techniques relating constant pressure topography to upwelling radiation in various infrared bands may shift the emphasis to the upper troposphere or stratosphere within the next decade. A rule of thumb which has been used as a guide in the absence of any conventional data is that the sea level central pressure anomaly in mb (referenced to the seasonal normal) of a mature, regularly shaped vortex between 40°S and 60°S is $1\frac{1}{2}$ times its east-west diameter measured in degrees of latitude. Vortex diameter for this purpose should be measured according to the scheme of Nagle and Hayden (1971).

The tentative nature of the model thermal patterns here described should not be overlooked. The desirability of refinement by further sub-categorisation is obvious: this has in fact been carried through to distinguish for example between the thermal structure of the mature stages of 'wave' and 'comma cloud' types of development. The data samples involved were, however, not judged adequate to warrant the reproduction of additional profiles or variants of Fig 5. Instead the following qualitative observations are offered:

(i) Vortices which develop to maturity from an initial (inverted) comma formation are usually several degrees colder at all levels particularly in the 'band poleward of vortex' sector than their counterparts which develop in association with pre-existing bands

(ii) When the cellular convection field (f) shows extreme development, 700 and 500 mb temperatures may be up to five degrees colder than the mean. Conversely when the open cellular cloud area shows only weak development a tendency towards closed cellular appearance and/or significant shear, 700 and, in particular, 500 mb temperatures will usually be considerably warmer than suggested by Fig 5

(iii) When the stratiform areas ahead of a vortex and band are extensive and uniform in texture, surface and 850 mb temperature tend to be warmer than implied for the mean in Fig 5. On the other hand with any evidence of cellular cloud ahead of a major band, $(T_s - T_a)$ values should be increased to zero or slightly positive.

Final comment is reserved for the hitherto largely avoided question: what relation does the structure of Fig 5 bear to the classical Norwegian model of the occluded polar front cyclone? The polar front models have been applied, at times with great skill and insight, in Southern Ocean synoptic analysis and forecasting for almost half a century; but as diagnostic tools for data-void areas, they are essentially qualitative in character. Also much has been learned in the past fifty years concerning the dynamical processes involved in the development of the extratropical cyclone. Not only have diagnostic studies revealed the operation of far more complex processes than the wedge-like undercutting and upgliding of cold and warm air masses, but the theoretical foundation of the classical models in instability of a sloping interface has not yet fulfilled its initial promise. Writing in 1948 Godske, Bergeron, Bjerknes and Bundgaard (1957) declare that "the results of the theory of frontal cyclone formation have hitherto been very modest." In spite of the strenuous efforts devoted to this subject by Bjerknes and, in particular, by Solberg, we are still far from anything resembling a real 'wave theory' of cyclogenesis. There is little evidence that the situation has improved substantially since then. The synoptic application and interpretation of the Norwegian models in the southern hemisphere has also been the subject of considerable controversy (Taljaard *et al*, 1961). The view was expressed in the opening paragraphs that there is considerable need for quantitative models of cyclone structure based, not on envisaged kinematic or dynamic processes, but on data. Accordingly:

(i) the model structure of Fig 5 is purely diagnostic; there are no consciously built-in preconceptions concerning the physical processes which produced this structure. Frontal symbols are thus absent but their absence implies no lack of belief in the existence, in many cases, of extremely sharp temperature discontinuities or of sloping zones of transition between regions of more homogeneous characteristics.

(ii) Fig 5 and 6 attempt to provide *quantitative* estimates of temperature contrasts, measures of instability and strength of inversions in the cold air, tropopause pressure and the like under the particular geographic conditions of the Southern Ocean - information which does not emerge from the classical models. Data-based models of this kind (not necessarily this one - it applies to only one stage of evolution and the limited data base has already been stressed) may be used to supplement or replace the array of conventional frontal paraphernalia, depending upon the purpose and philosophy of the analyst.

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