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A comparison of satellite sounding data and aircraft measurements within a mature polar low

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ABSTRACT

The value of satellite temperature sounding data in polar lows research is investigated through a comparison of satellite temperature profiles produced using radiances from the TIROS Operational Vertical Sounder (TOVS) and in-situ measurements from the first aircraft observations made within a mature polar low. The soundings are also compared to the ECMWF analyses to see how they represent the broadscale thermal field. The TOVS 1000–500 mb thickness data were found to be capable of resolving the main thermal features associated with the system including a warm core at the centre of the vortex. The 1000 and 500 mb temperature fields and thermal gradients were comparable in the two forms of data. A low-level temperature bias was found in the TOVS retrievals and was thought to have been caused by the small signal of the near surface adiabatic lapse rate in the TOVS channels.

1. Introduction

Over the last 25 years, satellite observing systems have been amongst the most important tools in increasing our understanding of synoptic and mesoscale weather systems. In the data-sparse regions of the world their impact has been particularly important and they have often provided the only means of investigating many of the phenomena observed. With the current operational system of polar orbiting and geostationary satellites, it is now possible to obtain frequent, high horizontal resolution data from any region of the world for use in research studies or operational forecasting. Satellite instruments offer many significant benefits in meteorological studies through the provision of data with a high horizontal resolution and a global consistency, as a single instrument is used over the whole area observed by the satellite.

In the high latitude areas, polar lows and other mesoscale cyclones that occur in, or at the leading edge, of polar airmasses have been studied extensively for a number of years with satellite imagery. These data have been used to produce climatologies of the occurrence of mesoscale vortices and to carry out case studies of their evolution and structure (Rasmussen, 1985; Reed and Blier, 1986; Businger, 1985, 1987; Rabbe, 1987). Surprisingly, satellite sounder data have only recently received attention in this work (Steffenson and Rasmussen, 1986; Turner and Warren, 1988). However, these early studies indicate that the temperature profiles may be of value, provided that they have sufficient resolution to identify the mesoscale detail. One of the main problems in using sounder profiles is that few detailed validation studies have been carried out on data from the polar regions so that their value in case studies is not known. Of the comparisons undertaken, most have been concerned with validating the soundings against collocated radio sonde ascents (Lachlan-Cope, 1991). These studies yielded statistics on the general characteristics of the satellite data and highlighted biases in the profiles. They also allowed an indication of the vertical resolution of the soundings to be obtained. To date, no comparisons of satellite-sounding data with high horizontal resolution in-situ thermal observations have been carried

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out, because of the lack of major data gathering campaigns in the polar regions.

The first flight by an instrumented aircraft through a polar low (Shapiro et al., 1987, hereafter referred to as SFH) on 27 February 1984 was made as part of the Arctic Cyclone Expedition. A very comprehensive data set on the thermal, moisture, precipitation and motion fields within a mature polar low was collected. These data provide a unique opportunity for investigating the capabilities of atmospheric sounder data and determining their value in mesoscale studies. This paper presents a detailed comparison of the thermal data obtained by SFH with temperature profiles derived from radiances measured by the TIROS-N/NOAA polar orbiting satellites (Schwalb, 1978). The horizontal resolution of the soundings from the TIROS Operational Vertical Sounder (TOVS) is assessed and the value of these data in case studies is considered. Analyses of the Microwave Sounder Unit (MSU) brightness temperatures are also carried out as they provide a coarse resolution picture of the thermal field without the many problems associated with inverting the radiances into vertical profiles.

2. Satellite data and processing

2.1. Data availability

During early 1984 the US NOAA 7 and NOAA 8 polar orbiting satellites were operational and giving Advanced Very High Resolution Radiometer (AVHRR) imagery and TOVS data. The University of Dundee tracking station (Baylis, 1983) takes selected broadcasts from passes of the TIROS-N/NOAA series satellites for use in meteorological, oceanographic and other environmental studies. The ground station can receive data for much of the Atlantic Ocean, North Africa, Europe and as far north as Jan Mayen. Data for the period under consideration were therefore available in the Dundee archive. At Dundee there is only a single TIROS-N/NOAA tracking antenna available so it is impossible to take all the satellite passes visible from the site. However, for this case study the University were able to provide computer tapes of NOAA-7 data for 03:40, 13:42 and 15:22 GMT on the 27 February and one pass of NOAA-8 data at 08:25 GMT. Unfortunately, the two NOAA-8 passes at 07:25 and 10:05, which occurred during the development phase of the system, were not taken. NOAA/NESDIS were able to provide the 4 km Global Area Coverage (GAC) imagery for these passes from their global archive, but reported that the TOVS data were not available in their archive for this day.

2.2. The TIROS-N/NOAA satellites and the TOVS

The polar low was investigated using data from the TOVS instruments aboard the US TIROS-N/NOAA series of meteorological satellites. The satellites are in a sun-synchronous, near-polar orbit and have an orbital period of about 100 minutes. Two operational satellites are usually in orbit at any one time and, with the 2000 km wide swath of the TOVS, global coverage of sounder data can be obtained twice each day from each satellite. The TOVS consists of three instruments.

(a) The High Resolution Infra-red Sounder (HIRS). A scanning radiometer with one visible and 19 infra-red channels. The HIRS is the primary sounder for use in clear or partly cloudy conditions and has a resolution of about 40 km at nadir.

(b) The Microwave Sounder Unit (MSU). A four channel radiometer making measurements in the 5 mm oxygen band. The MSU has a coarser horizontal resolution of about 120 km and is used to detect and remove cloud contamination in the HIRS radiances and to produce soundings in completely cloudy conditions, when the HIRS data cannot be used.

(c) The Stratospheric Sounder Unit (SSU). The SSU has three channels in the 15 micrometer CO_2 band and uses a pressure modulation technique to measure radiation emitted by the lower and middle stratosphere. As we are concerned solely with the troposphere no SSU data have been used in the present study.

2.3. Processing of the imagery and sounder data

The tapes of raw AVHRR data were processed on the British Antarctic Survey ARAMIS remote sensing system (Turner, 1987) and converted into calibrated, earth-located digital images which could be merged with coastline information, a latitude/longitude grid or other satellite or in-situ observations. The data were calibrated using the technique of Lauritson et al. (1979) and re-mapped onto a polar stereographic projection using a simple nearest neighbour technique.

The raw TOVS data were converted into atmospheric profiles of temperature and humidity using version 3 of the International TOVS Processing Package (ITPP) provided by the Cooperative Institute for Meteorological Satellite Studies at the University of Madison-Wisconsin (Smith et al., 1985). This is a simultaneous physical retrieval scheme producing atmospheric temperature and humidity profiles by solving the radiative transfer equation in its perturbation form. No modifications were made to the retrieval package from the form used in mid-latitudes since the case examined here occurred over the ice-free ocean where no particular problems should be experienced in the cloud detection procedure. The method of solving the equation requires an atmospheric temperature profile for use as a priori (initial guess) data. This can be either a radiosonde ascent, a three dimensional climatological field or an analysis from a numerical forecasting system. We did not use any of the SFH data as a first guess since one of our goals was to access the capabilities of the sounding data when no additional data were available. For this case we therefore used the 12 GMT 27 February 1984 radio sonde ascent from Jan Mayen as the first guess across the whole area. The ITPP-3 package allows near-surface (screen level) temperatures, when available, to be used as additional a priori data. As this case occurred over the ocean no near-surface observations were available and as the use of the Jan Mayen screen temperature would have resulted in this temperature being given a high weight in the retrieval process, the decision was taken to impose no surface temperature on the scheme and allow it to compute its own low-level temperature field. Some retrieval schemes can make use of a priori skin temperatures (cloud or surface), however, the ITPP-3 calculates this parameter from the HIRS window channels (channels 8, 10 and 18).

In clear or partly cloudy conditions, the soundings are produced using radiances from both the HIRS and the MSU. In very cloudy areas (such as those often encountered in this case study), the soundings below the cloud top are derived using MSU data only. Above the cloud both HIRS and MSU radiances are used.

The HIRS instrument is a scanning radiometer producing lines of 56 scan points across the track of the satellite. Each of these lines of fields of view is separated by 42 km in the along track direction (Schwalb, 1978). In principle a retrieval can be produced at every HIRS instantaneous field of view (IFOV), however, because of the need to remove the effects of clouds it is more usual to use the data from several IFOV in the production of each sounding. In this case 2 by 2 IFOV boxes were used so that the final field of retrievals had a horizontal resolution of approximately 80 km (although the distribution of soundings is not uniform). In completely cloud covered areas, where little HIRS data could be used, the scheme still gave soundings every 80 km, however, these were produced essentially from interpolated MSU data. To investigate the effectiveness of the cloud detection procedure the MSU channel 2 brightness temperatures, which give an indication of the mean temperature of the mid to upper troposphere, were also examined to see if the thermal structure was apparent in the brightness temperature field.

The retrieval scheme produces temperatures at the standard meteorological levels of 1000, 850, 700, 500, 400, 300, 250, 200 and 100 mb. Humidity mixing ratios are also computed at the standard levels below 300 mb when cloud cleared HIRS data are available. However, these were not used in the comparison with aircraft data as there was extensive cloud cover around the polar low. As noted in many studies of TOVS temperature retrievals (Turner et al., 1985) the soundings have poor vertical resolution because of the limited number of sounding channels and the extensive vertical depth of their weighting functions. This results in an ill-posed inversion problem. Rather than use single level temperature fields many workers have found it preferable to use integrated quantities, such as fields of 1000–500 mb thickness, which give a better representation of the information contained in the TOVS data. These quantities are difficult to use directly in the present generation of numerical forecasting systems, but are very valuable in case studies. The following analysis will largely be based on lower tropospheric thickness fields with only the occasional use of temperatures for comparison with the aircraft observations and the numerical analyses.

Although the MSU measurements are not significantly affected by cloud, heavy precipitation can scatter some of the upwelling radiation giving depressed apparent brightness temperatures. SFH made precipitation measurements using an airborne Doppler radar and reported heavy precipitation on the mesoscale frontal zones. However, this was mostly below the 2 km level (approximately 800 mb) whereas the peak of MSU channel 2 (the channel for which we produced analyses of the brightness temperatures) is at around 650 mb, so minimizing the affect on the satellite measurements. The impact is also limited by the fact that the heavy precipitation areas were found to be less than 10 km in width, which is well below the 110 km horizontal scale of the MSU IFOV. Careful manual analysis of the MSU 2 brightness temperatures did not show any marked steps at the boundaries of the precipitation areas so confirming our belief that the precipitation did not have any significant effect on this channel. MSU channel 1 peaks at the surface and will be affected by heavy precipitation resulting in depressed brightness temperatures. But as discussed above the small horizontal scale of the precipitation areas will minimize this effect and manual analysis of the retrievals did not show any marked anomalies.

3. The evolution and structure of the polar low

3.1. Synoptic development

The formation and development of the polar low has been described in detail by SFH and only a brief summary will be given here. A general account of the development and structure of the polar low is presented with more detailed information on the thermal field, which is relevant to assessing the TOVS soundings.

The polar low developed south of Jan Mayen, between Iceland and Norway, on 27 February 1984. During the period of the formation and development of the system, the upper level synoptic-scale environment over the Norwegian Sea was dominated by a quasi-stationary, cold-core low situated over the centre of Greenland. This gave predominantly westerly flow over southern Greenland and Iceland, with southwesterly winds over the area south of Jan Mayen. During the 26 February, an upper-level short wave trough was located south of the Greenland low and this moved east over the Denmark Strait. By early on the 27 February, the trough was lying to the west of Iceland where 500 mb temperatures had dropped by 10 K over the previous 24 h as the thermal

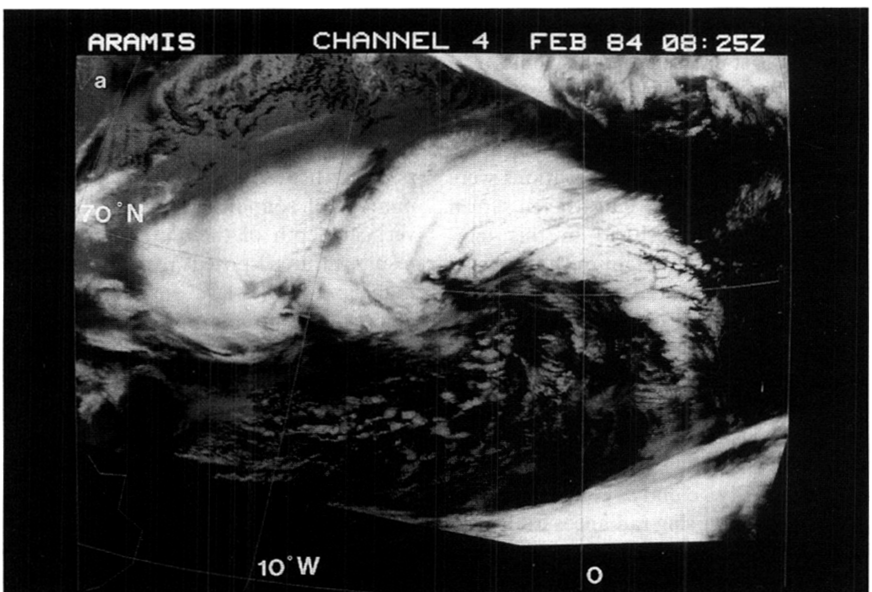


Fig. 1. AVHRR 1 km horizontal resolution infra-red imagery for (a) 08:25, (b) 13:42 and (c) 15:23 GMT 27 February 1984.

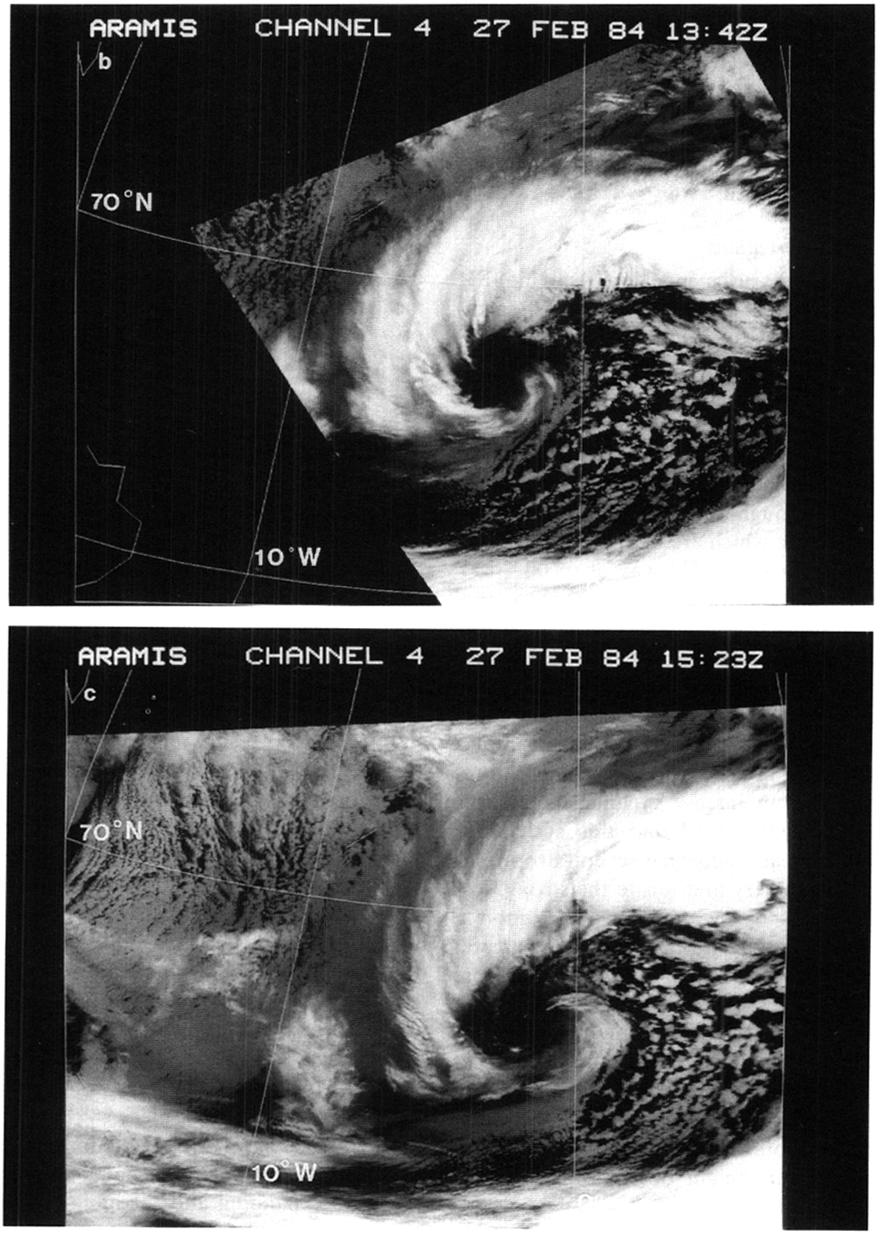


Fig. 1 (cont'd).

trough propagated eastwards. This motion continued during the 27 February so that the trough lay well to the northeast of Iceland by 12:00 GMT, giving a strong baroclinic zone between Iceland and Northern Norway. The upper trough had a region of strong ascent at its leading edge which, by the 27 February, lay over the eastern Norwegian Sea in the area where the polar low developed.

The surface analyses for 12:00 GMT on the 26 February had a synoptic-scale area of low pressure located to the east of Greenland, within a region of strong low level baroclinicity over the Denmark Strait. During the following 24 h, the low moved east so that by 12:00 GMT 27 February it lay ahead of the upper level short wave trough to the west of northern Norway. It was within the western sector of the surface low that the polar low developed.

3.2. *Aircraft observations*

The aircraft measurements described in SFH were made as part of the Arctic Cyclone Expedition organised by the National Oceanic and Atmospheric Administration (NOAA), National Aeronautical and Space Administration (NASA), the US Navy and research scientists from Iceland, Norway and the USA. The NOAA WP-3D (P3) aircraft made a number of flights as part of the project, although it is only the data from 27 February 1984, which are of interest here. This flight began from Bodö, Norway at 08:00 GMT when the aircraft flew towards Spitsbergen to carry out ice-edge studies, as no clouds with polar low characteristics were visible on the satellite imagery. However, by mid-morning the scientists at Oslo, who were monitoring the real-time satellite data, suggested a flight alteration towards the area south of Jan Mayen to investigate some cloud features which indicated an intense cyclonic circulation. The aircraft attempted to find this system for about two hours and deployed several dropwindsondes in order to try and locate the strong, low level circulation. A few minutes after noon a dropwindsonde reported 150 m winds of greater than 30 ms^{-1} from the north, indicating the core of the polar low.

The polar low was studied using measurements from in-situ sensors carried by the aircraft, profiles from dropwindsondes, precipitation observations from an airborne radar, sea-surface temperature measurements from a downward-looking radiometer and pressure-height observations from an airborne radar altimeter.

The data from all these observing systems were combined into a space-time adjusted analysis for 13:40 GMT 27 February 1984.This gave the polar low a central surface pressure of 979 mb located at 69°N, 3°W, with a radial pressure gradient of 17 mb per 200 km. The analysis of 300 m wind velocities showed that the system contained a confluent asymptote to the southwest of the low centre which corresponded to a baroclinic zone where the heaviest precipitation was found. A second confluent asymptote was located to the northeast of the centre, but was not extensively investigated by the aircraft.

On the synoptic scale, the system developed on the Arctic front at the leading edge of an outbreak of very cold air which had tracked down the eastern side of Greenland. The aircraft measurements indicated considerable small-scale thermal detail within the low including a tongue of warm air at the 300 m level with temperatures in excess of -3°C and a warm core in the derived 580 to 1013 mb thickness field.

3.3. *Satellite imagery*

The 1 km horizontal resolution AVHRR infrared imagery over the area where the polar low developed is shown in Fig. 1. Images for 08:25, 13:42 and 15:23 GMT on 27 February 1984 are considered since these show the cloud structure when the low was forming and in its mature phase.

At 08:25 GMT 27 February 1984 there were two convective cloud clusters located just to the south of Jan Mayen. The infra-red imagery allowed the cloud top temperature to be determined as approximately -55°C. This temperature can be assigned to around 400 mb using the Jan Mayen radiosonde ascent.

The satellite imagery from the passes during the late morning (not shown) indicate that the easternmost cloud cluster developed into the polar low considered here. By 13:42 GMT (Fig. 1b) the western cloud cluster had all but disappeared and the polar low had formed an 80 km diameter cloud-free core surrounded by high clouds. The cloud to the east of the centre, along the tail of the comma, had shown considerable development and it was in this area that a new polar low development subsequently took place.

By 15:23 GMT (Fig. 1c) the imagery indicated that the polar low was declining with the cloud-free core expanding and the major developments taking place further to the east.

4. Analysis of the sounding data

4.1. *Synoptic scale features*

The capability of the TOVS data to represent the synoptic-scale environment around the polar low will be considered via the analysed 1000 and

500 mb temperature fields produced from the 03:40, 08:25, 13:42 and 15:23 GMT passes on the 27 February 1984. These are shown in Figs. 2a–d and will be compared with the ECMWF analyses at the main synoptic hours illustrated in SFH as Figs. 2 and 4.

The 03:40 GMT data in Fig. 2a shows the 500 mb temperature gradient from northwest to southeast between Jan Mayen and Norway. This is caused by the cold, upper-air trough extending southeastwards from the cold core upper vortex located over the centre of Greenland. The thermal pattern corresponds well with the ECMWF analysis for 00 GMT 27 February. At the 500 mb level, the cold air has extended a little further to the east in the TOVS data, but this can be accounted for by the satellite observations being nearly four hours later than the model analysis time. The field of TOVS 1000 mb temperatures also have the correct shape for the low level thermal field, but the actual temperatures are several degrees colder than in the numerical analysis. This cold bias will be discussed in detail in Section 6.

The second pass of TOVS data at 08:25 GMT

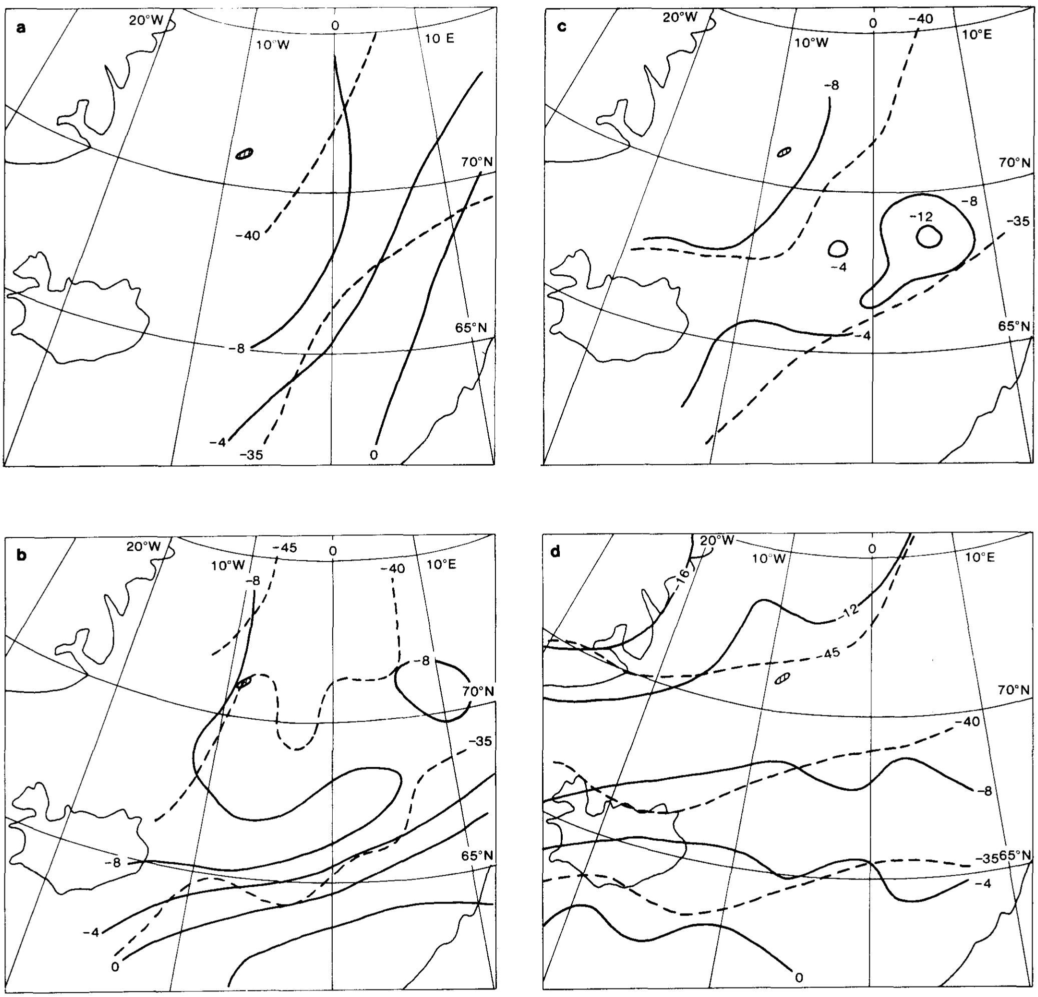
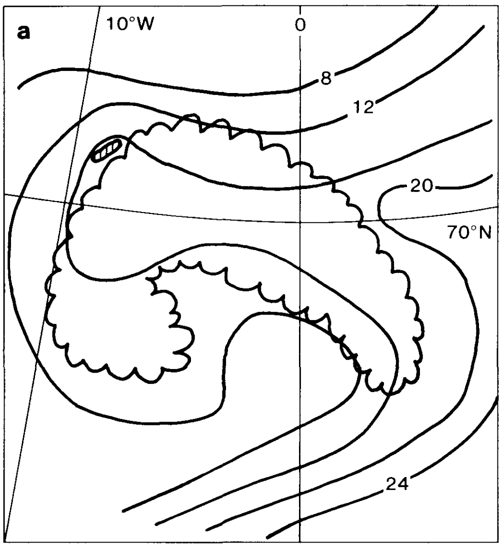
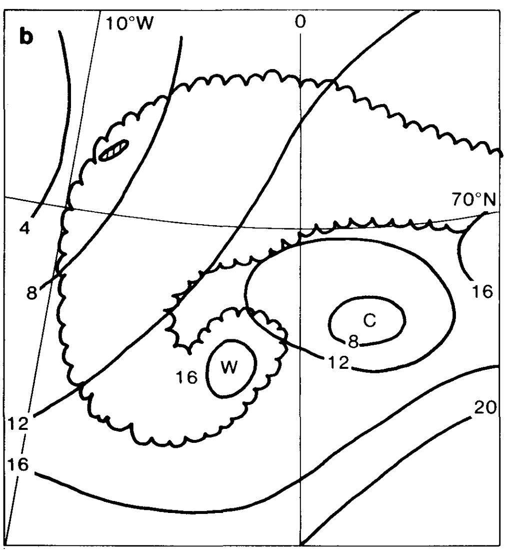


Fig. 2. Analysed TOVS 1000 mb (solid) and 500 mb (broken) temperature fields (°C) at (a) 03:40, (b) 08:25, (c) 13:42 and (d) 15:23 GMT 27 February 1984.

shows little change in the 500 mb temperature field with only slight southeastwards progression of the cold trough. The major changes since the previous satellite pass are at the 1000 mb level where the thermal field shows considerably more structure. Between 65 and 67° N a tongue of cold air has penetrated eastwards to around 7° E with, at the same time, warm air moving anti-clockwise around the top of the low along the 70° N line of latitude. South of 65° N, the north-south thermal gradient has strengthened considerably as air with temperatures above 4°C moved northwards to almost 64° N. By this time, there were large differences between the ECMWF 1000 mb analysis and the TOVS data. This is felt to be because the numerical analysis scheme is designed to represent the synoptic-scale flow while the TOVS data are showing mesoscale information.

The 13:42 GMT TOVS 500 mb temperatures indicate further southward movement of the cold air, especially around 70° N, 10° W. However, the major changes since the previous pass are near the surface where further structure is apparent in the 1000 mb temperatures (Fig. 2c). This figure can be compared with the ECMWF analysis in SFH Fig. 4b. Both show the cold low-level trough near 10° W, but the detail between 0° and 10° E is very different. The ECMWF data have a warm ridge in this area while the TOVS temperature field has a cold pool. This is further evidence of the TOVS resolving mesoscale structure within the polar low which was not present in the ECMWF analyses. This will be discussed in detail in the following section.





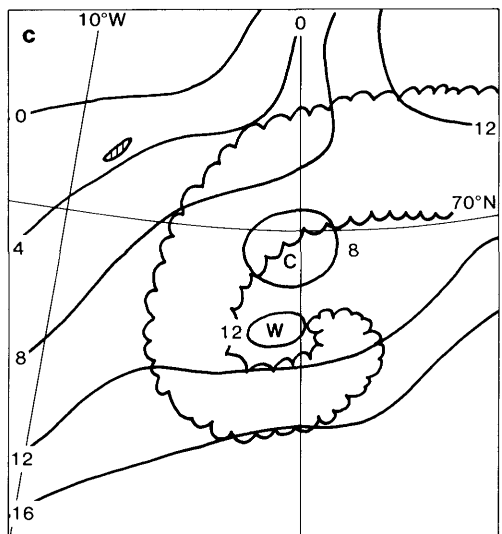


Fig. 3. Analysed TOVS 1000–500 mb thickness fields (gpm/10 minus 500) with the main cloud features superimposed over the immediate area of the polar low at (a) 08:25, (b) 13:42 and (c) 15:23 GMT 27 February 1984.

The last satellite pass at 15:20 GMT shows the isotherms with a much more zonal orientation at both 1000 and 500 mb. At the upper level there has been further southward movement of the cold air with the $-40°$ and $-35°C$ isotherms about one or two degrees of latitude further south than at 13:42 GMT. The 1000 mb temperature field is much simpler by this time with a predominantly north-south gradient and no cut-off warm or cold pools.

On the synoptic scale the sequence of four charts in Figs. 2a–d show very clearly the eastward movement of the upper level cold trough and the cooling that it brought to the regions east of 10° W. The TOVS temperatures were in broad agreement with the ECMWF analyses, but suggested additional mesoscale structure. There was general agreement between the ECMWF and TOVS 500 mb temperatures, although the strength of the thermal gradient was less in the satellite data. At 1000 mb the satellite data had a significant negative bias.

4.2. *Mesoscale features*

The mesoscale structure within the heart of the polar low was examined using the 80 km horizontal resolution TOVS profiles from within the immediate area of the polar low.

Firstly, the lower tropospheric thermal field is examined with the analysed 1000–500 mb thickness fields presented in Figs. 3a–c. These cover the immediate area of the polar low development and are for the satellite overpass times of 08:25, 13:42 and 15:23 GMT on 27 February 1984. The major cloud features, as determined from the satellite imagery, have been superimposed.

By 08:25 GMT there was considerable structure in the thermal field with a pronounced warm ridge ahead of the polar low and thickness values greater than 5200 gpm north of 70° N. Along this line of latitude warm air was being advected around the top of the low with a suggestion of warm air moving southwards around the back of the low. The figure also shows cold air advection around the base of the system into the cloud-free slot on the Greenwich meridian. The warm air moving southwards in the western sector of the low had already begun to isolate the cold air on the Greenwich Meridian forming a cold pool. The strongest gradient at this time was to the south of the low, although the warm advection ahead of the system had increased the gradient above 70° N.

The 13:42 GMT (Fig. 3b) thickness field indicates that rapid development had taken place

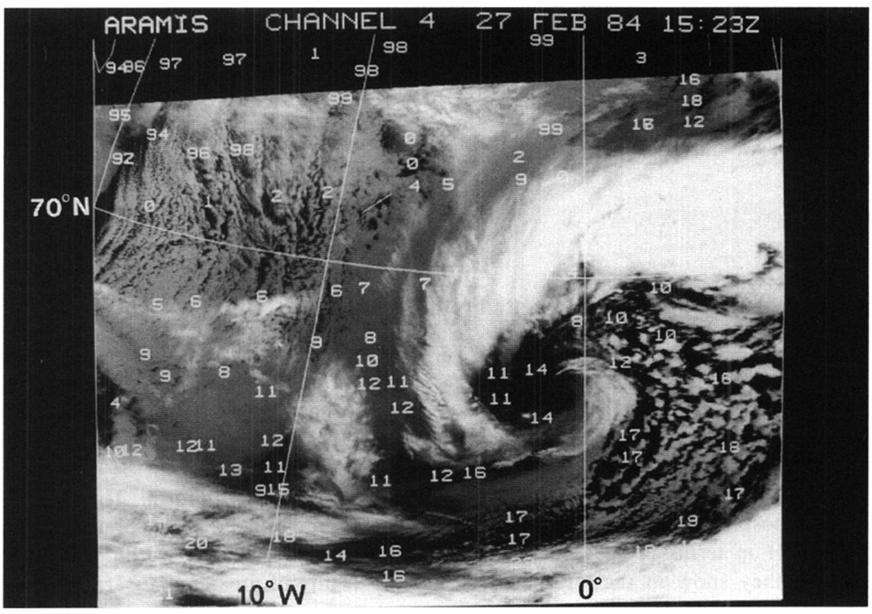


Fig. 4. AVHRR infra-red imagery for 15:23 GMT 27 February 1984 with superimposed TOVS 1000–500 mb thickness values (gpm/10 minus 500).

since the 08:25 GMT satellite pass. On the western side of the polar low there had been advection of cold Arctic air with thickness values near 10° W as low as 5040 gpm. By this time, the warm air that had been drawn into the circulation from the east had become isolated near the centre of the low as a small warm pool with thickness values above 5160 gpm. Cold air brought around the base of the low has also become isolated from its source as a cold pool in the area of broken cloud in the "dry slot" east of 0°. The changes in thermal structure between the two satellite passes suggest a very rapid advection of warm air anti-clockwise on the eastern side of the system with cold air also moving rapidly round the base of the circulation. The cold pool marks the leading edge of the cold air.

The last of the satellite passes processed was for 15:23 GMT 27 February 1984 (Fig. 3c) when the centre of the cloud vortex had moved to just west of the Greenwich Meridian. The warm and cold pools in the 13:42 GMT pass are still apparent, but the centre of the remaining cold air had moved onto the Greenwich meridian with the warm pool staying in the same location. To illustrate the distribution of soundings produced by the ITPP-3 package we have included Fig. 4 which shows the 15:23 GMT AVHRR channel 4 imagery overlaid by the field of 1000–500 mb thickness values.

The sequence of thickness fields add weight to the proposal made in SFH that the warm core was the result of a "seclusion" process in which the warm air becomes isolated in the centre of the vortex as the cold air moved around the base of the system.

5. Comparison of the aircraft and satellite data

The data from the 13:42 GMT satellite pass collocated well, both in time and space, with the aircraft observations and allowed an intercomparison to be made between the two forms of data.

The lower tropospheric thermal structure was examined by SFH in terms of the 580–1013 mb thickness which they show in their Fig. 15. The most comparable field obtained from the TOVS data was the 1000–500 mb thickness which is shown in our Fig. 3b. In terms of the overall thermal structure the two forms of data both have the general pattern of the field but differ slightly in the strength of the thermal gradients that are present. Both have the coldest air over Jan Mayen with strong warming towards the centre of the polar low. The aircraft observations give a marked warm pool at the centre of the low with a suggestion of colder air to the east. While the thermal gradient from Jan Mayen to the warm core was 140 gpm (9°C) in the aircraft data (580–1013 mb thickness), the TOVS had a gradient of 100 gpm (5°C) in the 500–1000 mb thickness field. In the satellite data the centre of the warm core is about 50 km northeast of the location determined by the aircraft. To the east of Greenwich the TOVS had a cold pool with thickness values below 5080 gpm. SFH had a suggestion of this cold pool in their Fig. 15, but the area is at the very edge of the figure and is where they had less aircraft data. Whereas SFH give the central mean 1013–580 mb temperature as −15°C the satellite data had a value of −19°C over the 1000–500 mb layer.

The SFH composite analysis of 300 m temperature (Fig. 12 of SFH) shows a general increase in temperature from Jan Mayen towards the centre of the polar low, but with a very marked tongue of warm air extending southwestwards from the centre of the low. Within the warm pool temperatures were in excess of −3°C over an elliptical area about 300 km long, with the maximum temperature measured being −0.5°C. This occurred about 100 km to the southwest of the centre of the low. The strongest temperature gradient was on the southeastern edge of the warm air where a mesoscale frontal zone was encountered. The lowest TOVS temperature field that can be computed is at 1000 mb and these data (Fig. 5) are compared to the SFH analysis. To the northwest and southwest of the polar low the thermal field is very similar to the SFH data, although the TOVS temperatures are about one or two degrees colder. The strong gradient between Jan Mayen and the warm pool of about 8°C is well reproduced in the TOVS data, although the distribution of the gradient is more uniform. The TOVS analysis correctly identified a warm pool to the southwest of the vortex centre and within this the maximum temperature of greater than −4°C occurred. The warm pool was about 70 km to the northeast of the warmest point in the aircraft data, but considering the coarse horizontal resolution of the satellite data greater accuracy cannot be expected. The strongest gradient found by SFH was on the southeastern edge of the warm pool. This feature, however, was on a horizontal scale of about 10 km which is well below that which can be resolved by the TOVS instruments. To the east of the vortex centre the aircraft observations have a fairly slack thermal gradient with temperatures between -3 and -4°C. The satellite temperatures, on the other hand, are several degrees colder than this, and there is a suggestion of further cooling to the east. As this is an area of broken cloud, the TOVS processing scheme will attempt to remove the effects of cloud and determine the radiances that would have been obtained in cloud-free conditions. This is a difficult procedure in all TOVS processing packages (Eyre and Watts, 1987) and can often introduce large errors into the derived temperatures (Turner et al., 1985). On occasions when cloud is not correctly detected the cold temperatures measured from the cloud tops will be assumed to have come from the clear atmosphere and will introduce cold biases into the retrieved temperatures in the lowest layers. This is considered the most likely reason for the negative bias in this area.

To assess the ability of the TOVS retrievals to resolve thermal detail in the vertical, the sounding nearest to the centre of the polar low was compared to a profile taken from SFH Fig. 18. The retrieval was just to the north of the warm axis shown in SFH Fig. 18. Our Fig. 6 shows the SFH data, the nearest retrieval and the Jan Mayen first guess profile on one tephigram. It can be seen that the retrieval produced is within about 1°C of the SFH data above 850 mb. At lower levels there is a cold bias which has a maximum of almost 7°C at 1000 mb. This is felt to be caused by the limited amount of HIRS data that could be used in the cloudy conditions at this location. The processing scheme correctly detected the cloud and used a cloud top pressure of 620 mb and only MSU data below this level.

As a control, Fig. 6 also shows a comparison of the Jan Mayen first guess and the final retrieval produced near to the island. This shows that the processing scheme has not significantly modified the profile at that location.

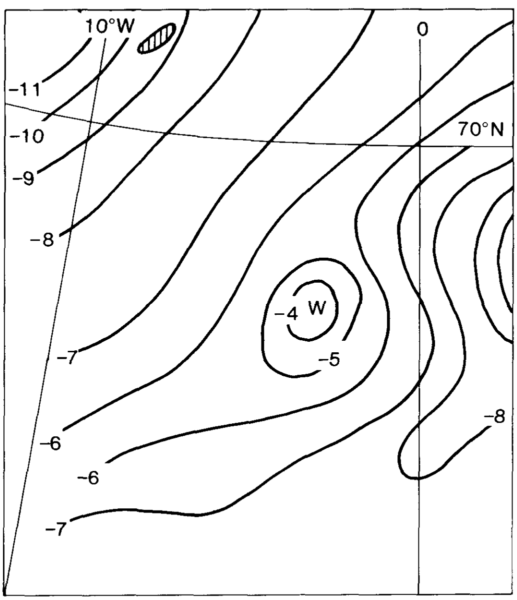


Fig. 5. Analysed TOVS 1000 mb temperature field (°C) over the immediate area of the polar low at 13:42 GMT 27 February 1984.

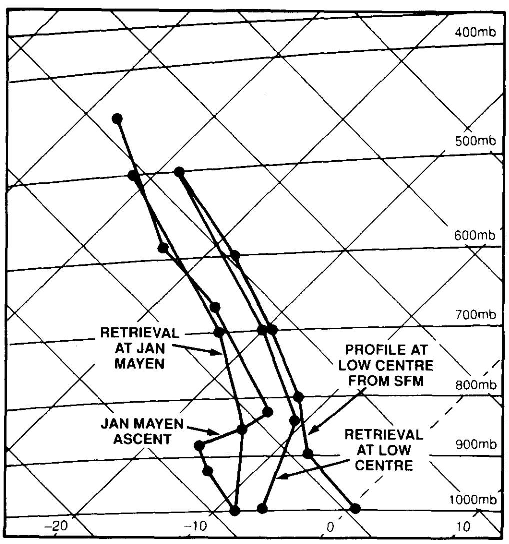


Fig. 6. A tephigram showing the Jan Meyen first guess profile, the retrieval at Jan Meyen, the SFH vertical profile near the centre of the low and the TOVS sounding at the same location.

6. Discussion

The TOVS group of instruments are flown on the operational meteorological satellites to provide atmospheric soundings for use in the preparation of numerical analysis in remote regions of the world. The TOVS processing algorithms give soundings on the scale of the numerical analyses schemes which have a resolution of the order of 100–200 km in the horizontal and 100 mb vertically. Mesoscale atmospheric structure is not required by these models and a limited horizontal and vertical resolution can be accepted when using the data in numerical analysis schemes. Nevertheless, there has been concern amongst many of those using the data operationally that the lack of vertical resolution and in particular the inability to resolve the tropopause and boundary layer structure correctly in the TOVS retrievals may at times degrade the analyses when good forecasts from earlier analysis times (background fields) are available and data from in-situ observing systems are present. The current numerical analysis schemes are also still essentially optimised for in-situ data, such as radiosonde ascents and have difficulty in assimilating satellite sounding data. Much research is taking place into how to make the best use of TOVS data through more direct use of the satellite measurements, such as assimilation of the raw radiances.

In case studies, the poor vertical resolution can be partially compensated for by using integrated quantities, such as thickness fields, and as shown in the previous sections, the 1000–500 mb field was able to resolve much of the thermal structure detected by the aircraft on scales above about 40 km. It was only the meso-beta-scale (≈ 10 km) features such as the narrow frontal zone to the southwest of the low centre that could not be identified in the satellite observations.

The comparison with the aircraft measurements brought to light a number of differences between the two sets of observations. Some of these may be because of problems in taking into account the contaminating effects of cloud on the infra-red radiances (cloud clearing). In this case there was extensive cloud cover associated with the polar low, resulting in limited use of HIRS channels with weighting functions peaking at low level. Exceptions to this were the cloud free area at the centre of the low and the dry slot where there was broken cloud. Because of the different number of channels that could be used in the cloud covered and cloud free areas there is a danger that the resultant soundings could be significantly biased in these two areas. As there is no jump in the characteristics of the soundings across the edges of the cloud this does not appear to be the case. However, it is possible to examine the impact of cloud by comparison of the lower tropospheric thickness field with the MSU channel 2, limb-corrected, calibrated brightness temperatures. This is the lowest level MSU sounding channel and the IFOV brightness temperatures and an analysis of the data for 13:42 GMT are shown in Fig. 7. The normalised weighting function computed for this area from the 12 GMT 27 February 1984 Jan Mayen radio sonde ascent is shown in Fig. 8. It can be seen in Fig. 8 that although there is a contribution from the surface the channel gives the largest response over the lower troposphere and the brightness temperatures will represent the mean temperature over this layer. The brightness temperatures will not be affected by cloud and will provide a means of detecting cloud-clearing

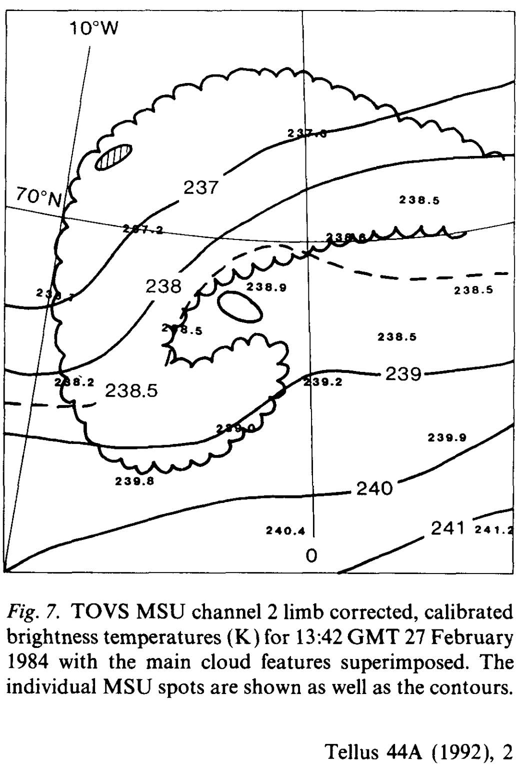


Fig. 7. TOVS MSU channel 2 limb corrected, calibrated brightness temperatures (K) for 13:42 GMT 27 February 1984 with the main cloud features superimposed. The individual MSU spots are shown as well as the contours.

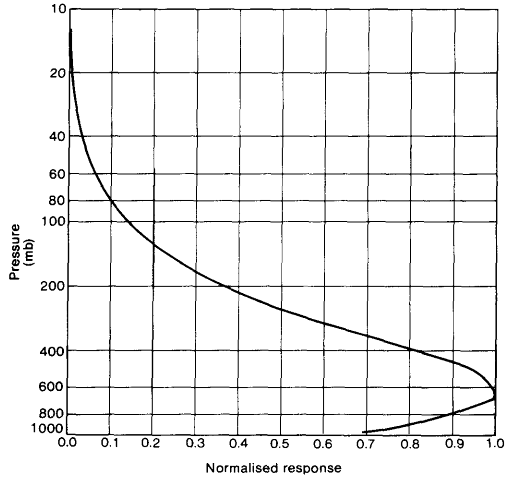


Fig. 8. Normalised MSU channel 2 weighting function (showing the contribution to the total radiation seen at the satellite from each atmospheric layer) derived from the 12 GMT 27 February 1984 Jan Mayen radio sonde ascent.

problems in the TOVS soundings. Comparing the brightness temperatures in Fig. 7 with the 1000–500 mb thickness field for the same time (Fig. 3b) it can be seen that they generally indicate the same thermal structure, but have significant differences in the area of broken cloud to the east of the Greenwich Meridian. This would suggest cloud clearing problems in this area. From the sequence of TOVS thickness fields and the aircraft data it is clear that a pool of cold air was present. However, the cloud clearing difficulties have given thickness values which are too low. Over the main cloud band and in the southernmost part of the region the general thermal structure in the two fields is similar, suggesting few problems with thick cloud. Near the centre of the low the location of the warm core is about 100 km further north in the brightness temperature field. This is, however, only about one MSU scan point and is at the limit of what can be determined with MSU data.

As noted earlier the TOVS 1000 mb temperature field (Fig. 5) exhibited a negative bias of several degrees when compared to the aircraft 300 m observations. In comparison with the Jan Mayen surface data the temperature was also about one degree too cold. Although TOVS temperature profiles are poor at low levels and often have a negative bias because of cloud clearing problems (Turner et al., 1985) in this case the bias is felt to be caused by the particular conditions where the polar low formed. As noted by SFH, intense low-level heating was occurring with fluxes of up to 1000 W m^{-1} resulting in adiabatic conditions over the lowest few hundred millibars of the atmosphere. The a priori information available to the inversion scheme consisted of only the Jan Mayen 12 GMT radio sonde ascent, which did not have such extreme conditions in the lowest layers. The inversion process was therefore totally reliant on the TOVS low level channels to indicate the near-surface warm air. The vertical resolution of the channels is poor in the lowest layers and in this particular case proved unable to provide enough information to resolve the exceptional boundary layer conditions.

7. Conclusions

The temperature soundings derived from the TOVS radiances resolved the broad-scale thermal structure of the polar low and allowed the tracking of individual thermal features over the lifecycle of the system. To the southwest of the vortex centre the low level warm pool was correctly analysed, although the meso-beta-scale frontal zone could not be identified. The temperature biases in the TOVS data were fairly small, although there was a negative bias near the surface because of the near adiabatic lapse rate. This study has shown that TOVS temperature retrievals can be of great use in the study of mesoscale phenomena, such as polar lows, when few in-situ observations are available.

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