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Forecasting applications of radar-derived precipitation echo velocities in the vicinity of polar lows

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ABSTRACT

Precipitation data derived from radar are shown to provide an operationally useful indication of the speed and direction of movement of two cyclonic vortices. For the particular kind of event studied, it is shown that by following the track of individual convection cells, a good indication of the strength of the gusts in exposed locations can be obtained.

1. Introduction

Maps of precipitation derived from single radars or networks of several radars are now available to operational forecasters in many countries. Conventionally, these data are used for locating and tracking precipitation. However, such data may also be used to estimate winds appropriate to the steering level of discrete precipitation cores and on some occasions where marked differential motion is present, a sequence of radar images displayed in time lapse may yield information on the track of an apparent centre of rotation within the precipitation field.

In general, the steering level of precipitation is several kilometres above the surface (e.g., Ligda and Mayhew, 1954; Parsons and Hobbs, 1983; Browning and Mason, 1981), and data obtained from tracking precipitation has little relevance to the surface wind. However, Bond et al. (1981), stimulated by the Fastnet storm which caused serious loss of life during the Fastnet yacht race on 14 August 1979, used radar data to track a number of weak but rapidly moving shower cells that were observed within the boundary layer by a radar at Camborne in southwest England. The showers occurred in a very strong southwesterly airstream, following the passage of a cold front from the west. The top of the precipitation as inferred from radar, satellite cloud top data and radiosonde ascents was no higher than 2.5 or 3 km.

Bond et al. found that the speed of these shallow showers was very closely related to the speed of maximum gusts observed at adjacent exposed coastal locations. They extended their study to a number of other occasions when shallow showers were present within range of the Camborne radar in strong southwesterly airstreams and found that with only a single exception maximum gusts at exposed locations were within ± 5 m s^{-1} of the velocities of nearby showers. The Bond et al. study was limited to cases where showers lay within marked baroclinic zones, such that, had the showers been deep with a consequently higher steering level they would have had very different velocities. In this paper, we present observations from the United Kingdom radar network of cyclonic systems which lay entirely within regions of polar air where only limited baroclinicity was present. Two case studies are discussed, a mature depression and a polar low, where, although the precipitation is somewhat deeper than in the cases studied by Bond et al., the speed of movement of convective radar echoes nevertheless gave good indications of peak gusts at exposed surface locations. In addition time lapse sequences of radar data enabled the vortex centres and their movement to be located. This information is of considerable practical value to the bench forecaster.

2. Case 1: 22 December 1983

2.1. *Synoptic background*

The first case study is of an old Atlantic depression which re-developed as it approached the British Isles from the west, and became exceptionally intense. The operational surface analysis at 12.00 GMT (all times GMT) shown in Fig. 1a indicated a low immediately west of Ireland with central pressure of 975 mb. Although observations along the west coast of Ireland were not inconsistent with the analysis, only 2 h later sudden pressure falls and increasing winds suggested the arrival of a deep, very

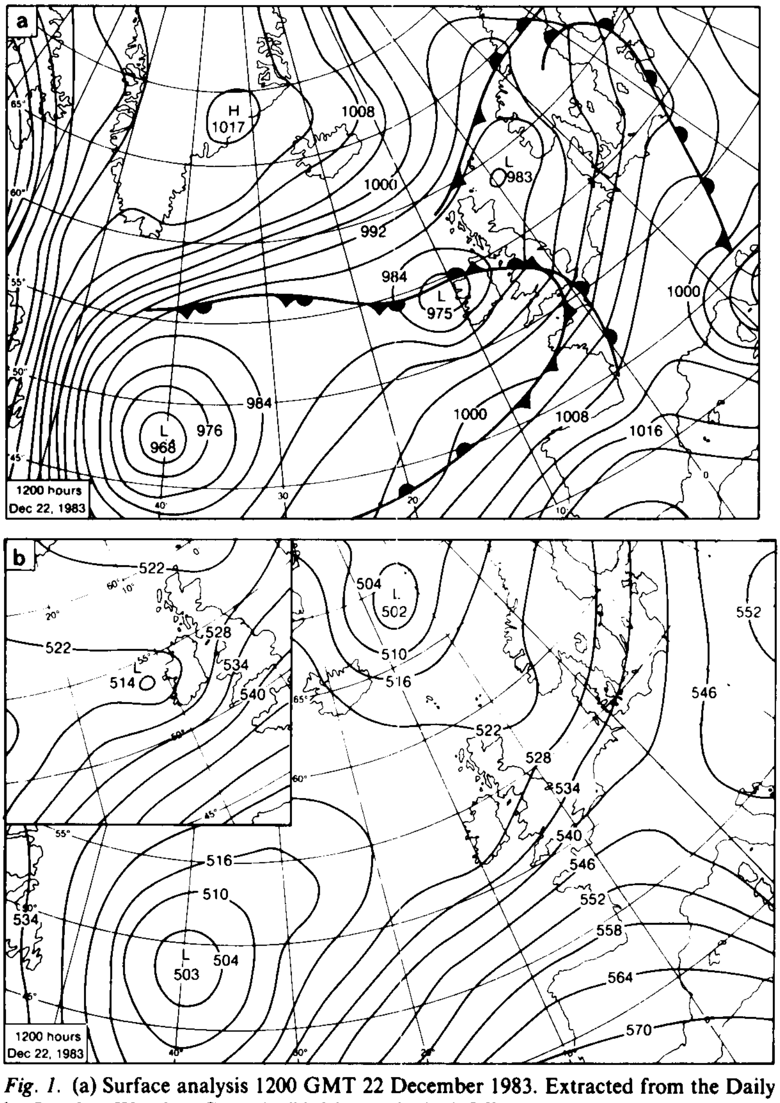

Fig. 1. (a) Surface analysis 1200 GMT 22 December 1983. Extracted from the Daily Weather Summary (prepared by London Weather Centre). (b) Meteorological Office coarse mesh 500 mb contour analysis at 1200 GMT 22 December 1983. The inset shows a manual reanalysis performed in the vicinity of the surface low immediately west of Ireland, taking particular account of soundings from Long Kesh (Northern Ireland), and Valentia (Republic of Ireland).

vigorous depression. The Meteorological Office coarse mesh (resolution 150 km) model 500 mb height analysis shown in Fig. 1b failed to resolve any circulation in association with the

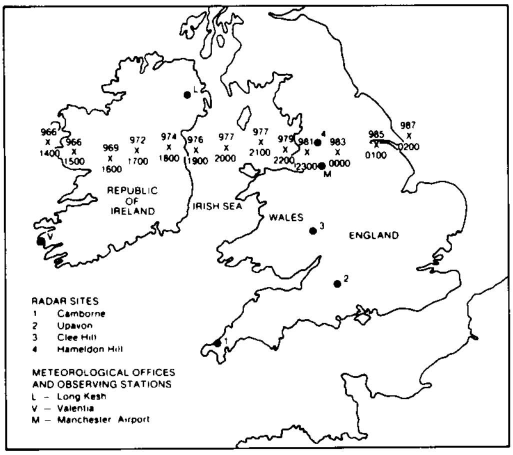

Fig. 2. Track and depth (in mb) of the depression on 22 December 1983. Places mentioned in the text are labelled, as are the positions of the 4 radar sites that composed the radar network in 1983.

low. However, a hand analysis performed for this study, indicated that had the two radiosonde soundings over Ireland (at Valentia and Long Kesh) been adequately analysed by the model, a small 500 mb low would have been apparent as shown in the inset to Fig. 1b. Thus, only 3 hours before landfall this low was inadequately analysed both at the surface and aloft. Surface charts were re-analysed for the period the low travelled across the British Isles. The track and depth of the low shown in Fig. 2 indicates an eastward track and progressive filling of the low, although with only slow filling whilst over the Irish Sea. A remarkably sharp isobaric gradient was present immediately south of the centre, which led to very strong winds particularly on windward coasts where gusts of 30–35 m s^{-1} were reported. The surface charts for 1500 and 2100 shown in Fig. 3 also indicate progressive weakening of the pressure gradient to the south of the low, leading to a narrowing of the zone in which gales occurred and that the depression was of small scale, being only about 500 km in diameter.

Sequential METEOSAT pictures displayed in time-lapse after the event indicated rapid forma-

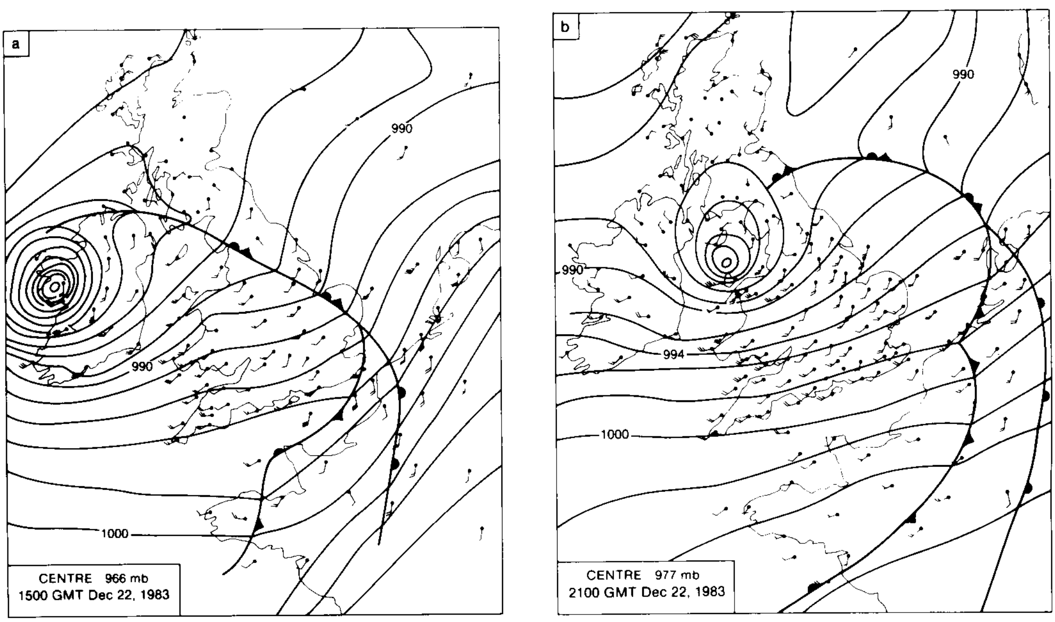

Fig. 3. Surface analyses at (a) 1500 and (b) 2100 GMT 22 December 1983. Observations of wind speed and direction are shown in m s^{-1} where each full feather represents 5 m s^{-1}, and pendants represent 25 m s^{-1}. So as not to obscure the chart, the central pressures of the low are shown bottom left.

tion of a new cloud vortex during the morning of 22 December, suggesting that the cyclonic development was taking place (Junker and Haller, 1980). Although historically a mature mid-latitude depression, in several respects, its structure was not dissimilar to that which may be expected within a polar low. It was a small, intense vortex lying within a cold air mass, which filled rapidly over land, and contained a narrow band of very strong winds. Although upper air data within the circulation of the low as it crossed the British Isles were sparse, a largely barotropic vertical structure was suggested. A slight warm anomaly may have been present within the vortex, particularly between 700 and 500 mb. Synoptic data failed to resolve the feature before it reached the coast of the Republic of Ireland, and only the sequential METEOSAT pictures suggested the formation of a new vortex. We now discuss how radar precipitation data may be exploited to supplement conventional analyses and geostationary satellite cloud data.

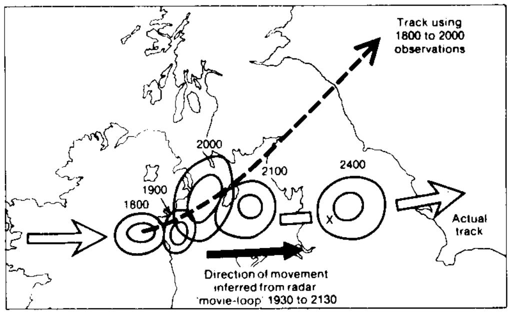

Fig. 4. Positions of low between 1800 and 2400 GMT 22 December 1983 according to the analyses of the Central Forecasting Office at Bracknell. Each position is defined by the innermost 2 isobars (2 mb intervals) irrespective of the actual pressure values. The possible track inferred from analyses between 1800 and 2000 is shown by the dashed arrow, whilst the direction of movement suggested by radar data up to 2130 is shown by the bold solid arrow. The 2130 radar picture (available within 2 minutes), was available before the 2100 surface chart. The position of the Hameldon Hill radar is shown by a cross.

2.2. *Operational use of radar data*

Forecasters analysing hourly surface observations over the British Isles had difficulty in correctly locating and tracking the low centre. This was due to the exceptionally tight isobaric gradient immediately south of the low, a relatively weak gradient north of the low, and to marked ageostrophic winds. Particularly where there was no observation immediately north of the low centre, the analysis tended to be smoothed resulting in the low being drawn too far north. This was particularly apparent as the low entered the north Irish Sea between 1800 and 2000 (Fig. 4), when it appeared that the low was curving cyclonically. As is shown clearly by the narrowness of the zone of strong winds in Fig. 3, the exact track of the depression was vital in forecasting the area of gale force winds associated with this low. Forecasters at Manchester airport, responsible for aviation forecasts for northern England, initially issued gale warnings (at 1630) to airfields over northwest England that lay both north and south of the actual depression track, i.e. the warnings were issued over a too broad an area. However, in the late evening, when the low centre reached the UK radar network and the issue of gale warnings for north-east England was being considered, evidence derived directly from radar data led to the forecaster (the lead author) correctly pinpointing the places likely to experience gales.

Radar pictures derived from PPI data are displayed at UK forecast offices using systems capable of replaying short sequences of the most recent data. On the evening of 22 December, most of the rain within coverage of the radar network occurred within range of the Hameldon Hill radar in northern England (see Fig. 2) and forecasters at Manchester had the facility to display a sequence of 9 pictures at 15 minute intervals from Hameldon Hill. The rain associated with the low was first observed between 1900 and 2000 and by 2200 it covered much of nothern England. Rapid replay in time-lapse of the sequences between 1900 and 2200 suggested an eastward movement of the precipitation system as whole. However, the motion of both the precipitation pattern as a whole and of individual convective cells embedded within the precipitation field exhibited cyclonic rotation. Furthermore, soon after 2100, a centre of rotation could be defined within the display area corresponding to the position of the cyclonic vortex at the steering level of the precipitation. The radar defined vortex appeared to move due eastwards (Fig. 4). This information was used directly in nowcasting the position of the surface low due eastwards across England, and in consequence correctly re-assessing which airfields over the north-east of England were likely to experience a gale.

2.3. *Further analysis of radar data*

All Hameldon Hill archived radar data tapes relevant to this case study were accessed for further analysis off-line. The precipitation area as a whole was composed of a generally eastward moving amorphous area, but with a number of embedded convection cells. Individual cells were tracked using 2 and 5 km horizontal resolution PPI data with temporal resolution of 5 minutes. Some difficulty was experienced in following cells due to a combination of orographic effects and to the presence of a very marked radar bright band. However, the velocities of cells that could be tracked for more than half an hour were calculated and are shown together with the overall rainfall pattern at 2150 and 2250 in Fig. 5. A close correspondence between maximum surface winds and speed of movement of the cells in the region immediately south of the track of the depression is apparent at coastal locations. Even at a normally sheltered inland location, Manchester Weather Centre, a gust of 27 m s^{-1} was recorded, a speed only 5 m s^{-1} lower than the speed of movement of adjacent shower cells. Radar data indicated convection tops to be between 3 and 4 km, somewhat higher than those analysed by Bond et al., but still quite shallow.

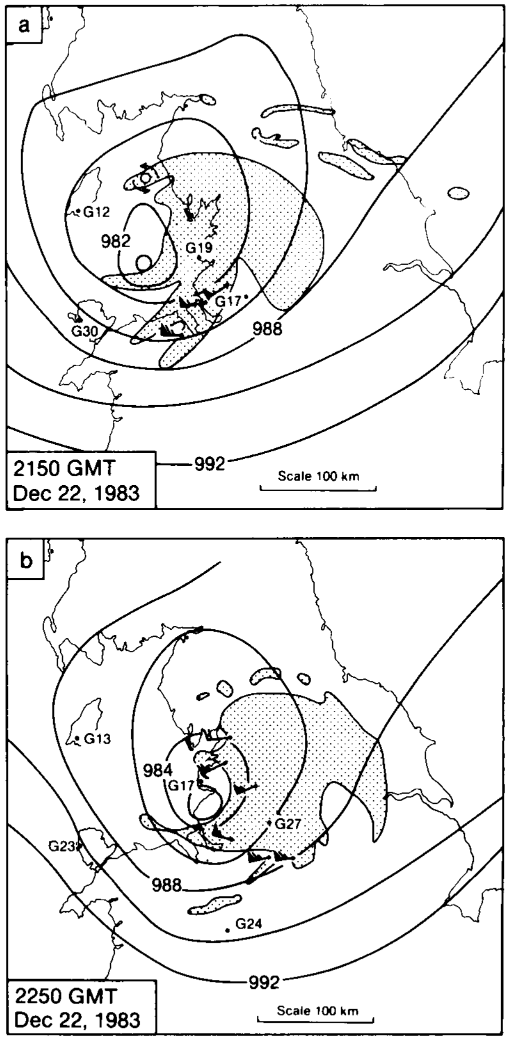

Fig. 5. Area of precipitation (stippled) and cell velocities as derived from radar, and maximum surface gusts for a selection of surface observing stations at (a) 2150 and (b) 2250 GMT 22 December 1983. The velocities derived from radar are shown according to the convention described in Fig. 3. Surface gust reports are prefixed by the letter G.

3. Case 2: 26 December 1984

A small, shallow cold air vortex moved southeastwards across western districts of the British Isles about 24 hours after the eastward passage of an occluded frontal system across the British Isles. The front was associated with a large complex region of low pressure which lay south of Iceland on 25 December. By the 26th, part of this low complex persisted near Iceland, but a small low moved southeastwards across the British Isles in association with an extending upper trough. This polar vortex was evident throughout the 26th. It was centred immediately off the west coast of the Republic of Ireland at 0600, moving southeastwards at 14 m s^{-1} to reach southwest England at 2100 (Fig. 6). Although it was filling, the vortex lay within a large scale field of rising pressure; thus maintaining a similar size and intensity of circulation throughout the 26th. There were isolated observations of gale force winds on the southwest flank of the depression such as at Scilly Isles (off southwest England) at 2400, where the observer reported a mean wind

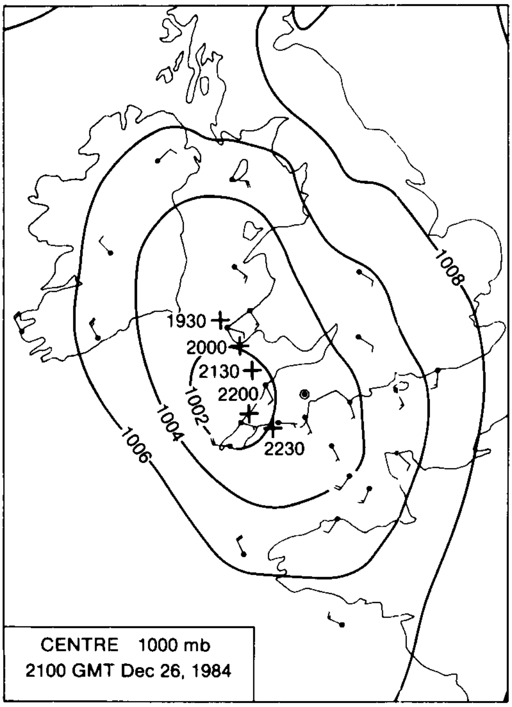

Fig. 6. Surface analysis at 2100 GMT 26 December 1984. The crosses refer to apparent centres of rotation inferred from sequences of four radar network pictures displayed in time lapse, centred on the times shown.

of 20 m s^{-1} with a hand-held anemometer. However for the most part the region of strong winds lay over the sea. Precipitation associated with the vortex was composed entirely of convective cells or clusters of convective cells. Radar network data available at 15-minute invervals were used to track individual cells of area of order 100 km^2 sometimes for longer than 3 hours whilst infrared satellite data from METEOSAT available half hourly were used to identify and track clusters of cumulonimbus clouds an order of magnitude larger in area, a number of which persisted more than 6 hours. Both satellite and radar derived motions are shown together in Fig. 7, at 1800 and 2100. Despite the difference in size between the cells tracked by radar and the cluster of cells tracked by satellite, Fig. 7 shows good agreement between the winds derived by these two methods.

Sequences of four radar network pictures were displayed in time-lapse for the period in which the low crossed SW Britain. A well-defined south-eastward moving centre of rotation was observed, which has been plotted in Fig. 6. The data were obtained prior to detailed cell tracking analysis, and have not been smoothed. Between 2000 and 2130, the rotation centre apparently moved only slowly south-eastwards and intermediate positions are not shown. The deceleration may have been real or possibly due to incorrect visual interpretation of the data between 1930 and about 2030 when the apparent

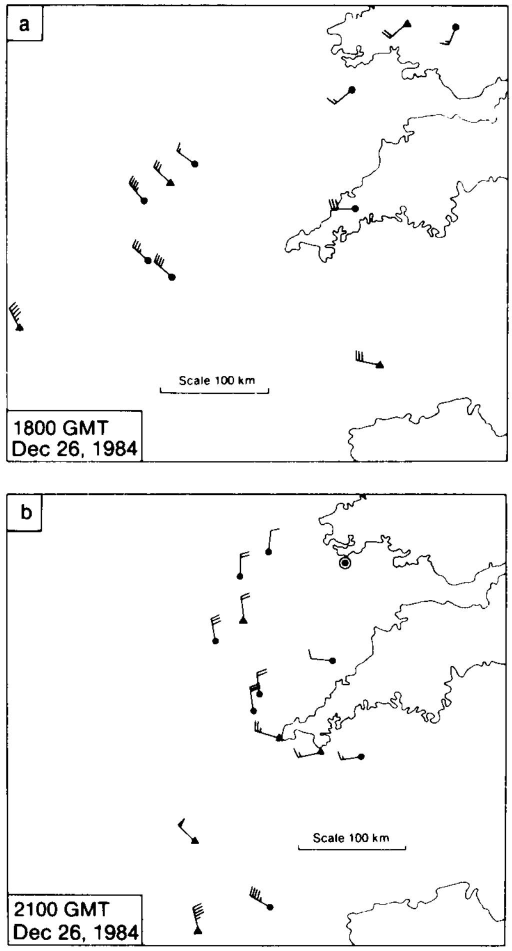

Fig. 7. Shower velocities derived from radar and satellite at (a) 1800 and (b) 2100 GMT 26 December 1984. The values derived from radar are distinguished by the small circle at the observation point, whilst observations derived from satellite are marked with a triangle.

rotation centre was near the boundary of radar network.

Radar data indicated the precipitation to be deep, whilst METEOSAT infra-red imagery indicated that cloud top temperatures of a number of cloud clusters were below −40°C, which according to local upper air soundings occurred near the tropopause, at a height of 6–7 km.

4. Discussion

In the presence of low-level convection, whether or not convective cloud occurs, maximum surface gusts at exposed locations tend towards the gradient wind at the top of the friction layer (approximately 900 mb) (Meteorological Office, 1975). Bond et al. (1981) found that the speed of shallow showers, which probably had steering levels close to 900 mb gave good indication of maximum surface gusts. Where deeper showers are present, with a consequently higher steering level, it becomes less likely that the shower velocities will give useful information on maximum surface gusts, since air originating within a deep convection cell far above the top of the friction layer, may well penetrate to the surface as local gusts, and additionally in vigorous cumulonimbus convection, organized downdrafts and gust fronts are likely. An exception to this might be in a barotropic or weakly baroclinic atmosphere where weak vertical wind shear leads to geostrophic winds at the steering level being similar to those at the top of the friction layer. We believe this to hold in the case studies presented in this paper and moreover to hold in the vicinity of many polar vortices, not only within regions of weak baroclinicity, but also where convection has produced a well-mixed convective layer with relatively weak vertical wind shear. Such regions of weak vertical shear tend to inhibit the formation of well-marked downdrafts and associated gust fronts. Caution is therefore required in applying the relationship to regions of weak low-level flow, in the presence of deep cumulonimbus clouds, such as may occur near the centres of or within the circulations of shallow polar lows.

The position and movement of an observed centre of rotation within a field of precipitation cells also yields an operationally useful indication of the velocity of the surface centre in weakly baroclinic situations. In the two cases described above, the apparent centres of rotation of the rainfall field, and of the surface low centre as drawn by isobars were not co-located. In both cases a displacement of about 50 km was observed. However, the relationships between the two centres (in both cases) remained unaltered whilst within radar range. Inspection of sequences of radar data in the UK near the centres of a number of mature mid-latitude depressions and polar lows indicates that velocities of the systems may be obtained from the radar data, even when convection is relatively deep, with the steering level of the precipitation well above the boundary layer.

Experience with the UK radar network, has indicated that often as few as 4 pictures at 15 or 30-minute intervals can be sufficient to give a useful impression of regions of strong winds from the speed of movement of small convective echoes, although a slightly longer sequence may be necessary when the echoes are embedded within amorphous regions of precipitation. Sequences of geostationery satellite cloud images have also been used for determining low-level winds. However, detailed tracking of cells and precise determination of cell velocities may be performed accurately using only a series of data sets at intervals of 5 minutes or less (Rodgers et al., 1979; Bond et al., 1981), and cannot be carried out in real time except where an objective tracking procedure such as that described by Browning at al. (1982) can be used. Scrutiny of objectively tracked echoes is necessary, since occasionally it may recognize areas of permanent or semi-permanent echoes (e.g., sea clutter) and extract erroneous velocities.

5. Conclusions and implications for operational polar low forecasting

Radar precipitation data displayed in real time as a short sequence in time lapse, enabled forecasters to nowcast the track of an intense depression that possessed characteristics of a polar low, and to nowcast its associated zone of gale force winds. From a 2-hour sequence of pictures at 15-min intervals, a centre of cyclonic rotation was observed within the field of precipitation, and its direction of travel diagnosed. The direction of movement of the overall field of precipitation echoes was the same as that of the surface low centre. In a second case, a simple precipitation field composed of discrete deep convection cells was clearly seen to have rotated about an easily defined point located near the surface centre of a small polar low when only 4 pictures at 15-minute intervals were displayed. Successive sequences of only 4 pictures suggested that the centre of rotation moved at the same velocity as the low, although there was some confusion when the true centre of rotation was near the edge of the area of radar coverage. Inspection of sequences of data near a number of other cyclonic circulations suggests general applicability of the method in the vicinity of mature mid-latitude depressions and polar lows, providing convective precipitation originating at the surface is present.

Detailed tracking of radar echoes carried out after the event using data with a horizontal resolution of 2 or 5 km at intervals of 5 minutes enables velocities of discrete convective cells to be calculated. They were found to be well correlated with peak surface winds especially at exposed locations. The relationship may well be widely applicable in the vicinity of polar lows, except where deep cumulonimbus with organized downdrafts and gust fronts are present. Given radar hardware and software tailored towards identification and tracking of precipitation echoes in real time, cell velocities may be calculated from which operationally useful estimates of peak surface gusts may be obtained.

With continued expansion of weather radar networks (e.g., ECC, 1986), and the possible exploitation of weather radar in data sparse northern oceans, we see radar derived wind information and polar vortex location and movement as a unique and valuable data source. High temporal resolution geostationary satellite data enabled the formation of the intense vortex described in case 1 to be observed. However, in extreme northern latitudes such data are not available, in which case precipitation data from a single radar or network of radars could perform equally valuable functions in observing the movement of a polar low and in identifying cyclogenesis from increasing rotation of the precipitation field and hence alerting the forecaster at an early stage to warning of possible severe weather.

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