Part 7

Dropsonde observation and modelling experiments in IOP 16: an example of dynamical and microphysical interaction

by
Sidney A. Clough

Joint Centre for Mesoscale Meteorology, United Kingdom Meteorological Office, Reading, United Kingdom.

7.1 An overall assessment of the UKMO C-130 dropsonde data

The FASTEX C-130 dropsonde data are the most comprehensive set of mesoscale sounding data on middle latitude weather systems in existence, and the combination with airborne Doppler radar data provides a powerful and unique resource. They show many structures previously unrecorded across a wide range of frontal wave types.

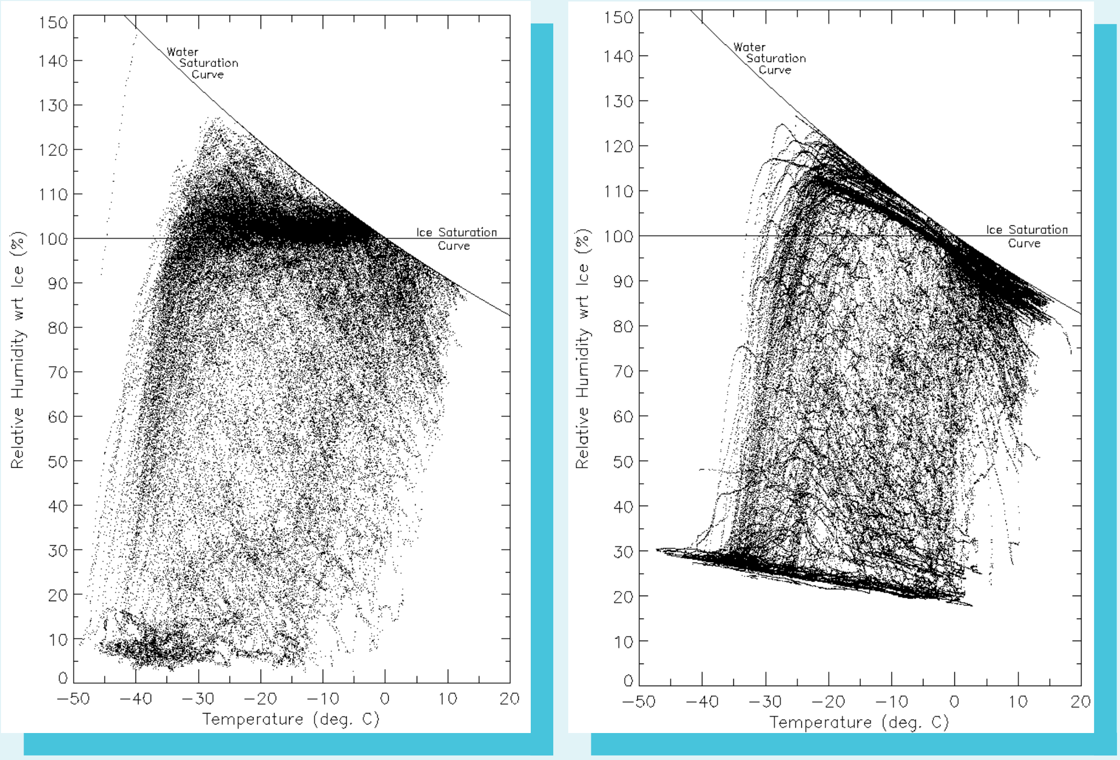


Figure 7.1: *Distribution of all the dropsonde observations taken during the IOP 16 of FASTEX (left panel) and during FRONTS 87 (right panel) in Temperature – Relative Humidity with respect to ice space.*

In particular the data are an improvement on earlier sounding data in two particular respects. Firstly, from IOPs 10 onwards GPS winds are used, which have better resolution and accuracy than the best previously available soundings from LORAN sondes. (GPS wind-finding uses Doppler shift measurements to give instantaneous winds rather than position information time-differenced.)

Secondly, the sondes use the Vaisala unheated humidity sensor which is proving to be a considerable improvement upon the earlier Meteorological Office dropsonde's carbon hygristor. Aside from better response in the dry part of the range it shows indications of a clear quantitative response near ice saturation. Figure 7.1(left) shows a scatter plot of the relative humidity vs temperature for all C130 FASTEX GPS dropsondes while Figure 7.1(right) presents the equivalent for the Fronts 87 experiment dropsondes (Clough and Testud, 1988). The former show a clear tendency of values to cluster near ice saturation which is not evident in the latter. The clustering behaviour is a natural property to expect of the atmosphere because of operation of the Bergeron-Findeisen process of precipitation growth causes it to relax towards a state of saturation with respect to ice in active weather systems. This appears to occur both because of the evaporation of water droplets but also the sublimation of ice crystals increasing humidity in sub-saturated conditions.

Figure 7.1 is also interesting in that the soundings also show, though in only one event (IOP 16), water saturation being achieved at temperatures as low as −23°C in the strong ascent ahead of a deepening low. Since these observations are isolated and not part of a continuously varying pattern, though they occur in several soundings, it seems most likely that they are valid an indicate a significant microphysical feature.

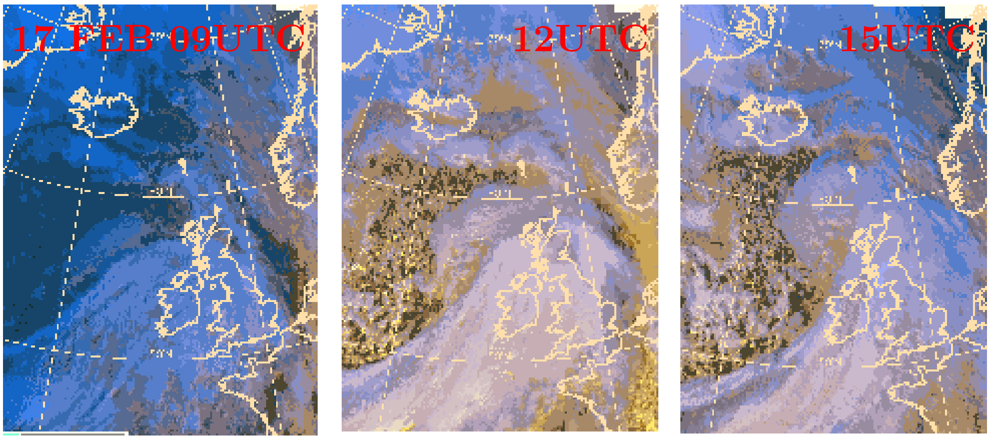
This derived diagram thus represents a very important observational result. Such plots seem likely to prove a useful discriminant of the accuracy of NWP and climate model microphysical parametrization schemes to produce realistic distributions in a range of situations.

One reservation, however, is necessary regarding these observations. There are indications that the humidity near and above ice saturation may be too high. Attempts are currently being made to conduct a comparison between these measurements and other sondes and aircraft to check and perhaps correct the calibration, but to date without success.

7.2 Evidence of dynamical effects driven by sublimation of precipitation in IOP 16

Studies of dropsonde observations from the earlier Anglo-French FRONTS'87 experiment led to theoretical calculations and the proposal of a mechanism by which

Figure 7.2: *METEOSAT composite images showing the devlopment of Low 39A during IOP 16 that shows through the expansion of the cloud head. The images combine, whenever possible, the 3 channels of the METEOSAT radiometer in a way that help materializing the cloud types. Images courtesy of EUMETSAT, processed by the Centre de Météorologie Spatiale of Météo-France.*



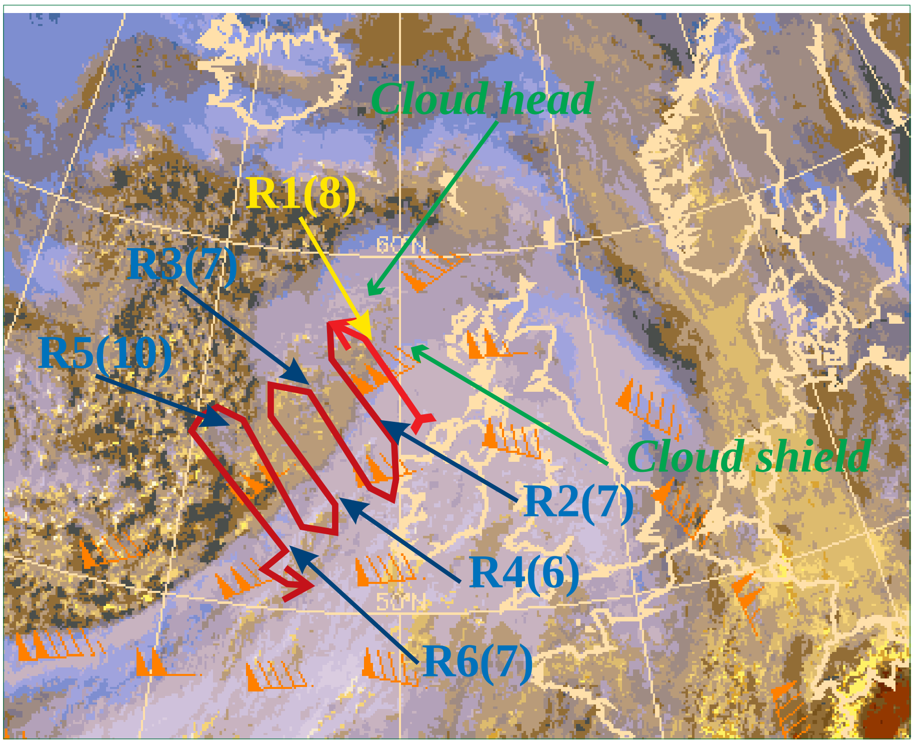


Figure 7.3: *METEOSAT composite satellite image similar to Fig. 7.2, but at 12UTC superimposed to the ARPEGE analysis of upper-level wind (orange arrows) showing Low 39A and the jet-stream. The flight plan of the C-130 on 17 February is superimposed. Legs are labelled Rn, the number of dropsondes within each leg is shown in parentheses.*

the sublimation of ice precipitation might lead to descending mesoscale circulations important to the dynamics of weather systems (Clough and Franks, 1991; Thorpe and Clough, 1991). One of the important scientific goals of FASTEX is to confirm and quantitatively refine that hypothesis and investigate the role of precipitation in weather systems and Numerical Weather Prediction (NWP) more generally.

An observational and modelling study has been carried out on one of the events, Intensive Observing Period (IOP) 16, which has led to confirmation of the earlier results and the possibility of more quantitative results for modelling. The results have important implications for understanding the mesoscale structure of frontal waves.

A quick-look summary of IOP 16 is shown in section 3.19 of Part 3, page 116 of this Report. The frontal wave studied in this IOP formed from a weak trough on the main baroclinic zone in the western Atlantic (Fig. 7.2). The rearmost of two troughs, it passed Newfoundland around 06–12UTC on 16th February 1997 and travelled rapidly (30–40 ms^{-1}) across the Atlantic, deepening to form a low pressure centre in the first half of 17th February.

Figure 7.3 shows a satellite image during the flight with dropsonde run locations marked in a system-relative frame. The observations for the first run, highlighted in red, contain particularly interesting symptoms, which are discussed below. This first run crossed the upper cloud shield and the region immediately ahead of the forming cloud head. It can be seen that the upper cloud shield is broken up by the occurrence of bands, which formed in the few hours before the start of observing.

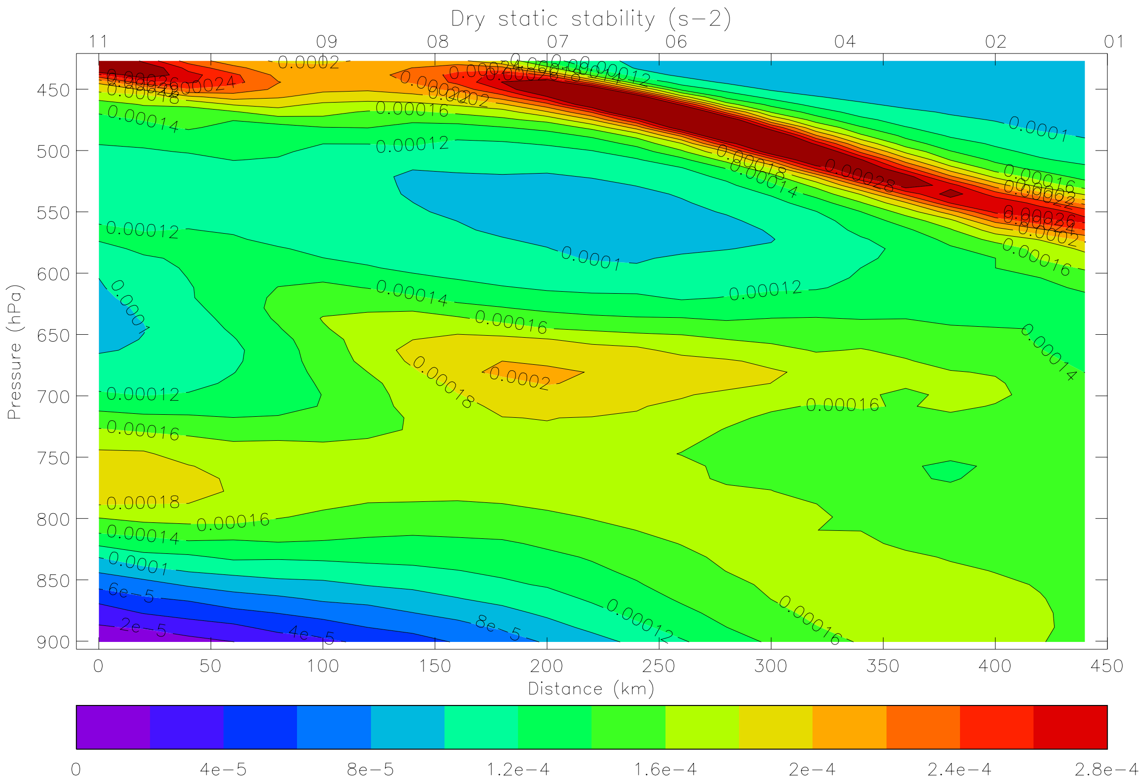


Figure 7.4: *Vertical cross-section of dry static stability N^2 derived from the dropsondes. The plane of the cross-section is shown on Fig. 7.3.*

The flight plan executed in this case is the best example carried out of the systematic survey pattern, which lends itself well to model comparison over a wave domain, and the system is the early stage of a well-forecast wave development. Both of these are well suited to the Cloud System Study project, where the ability to compare observations and models is vital.

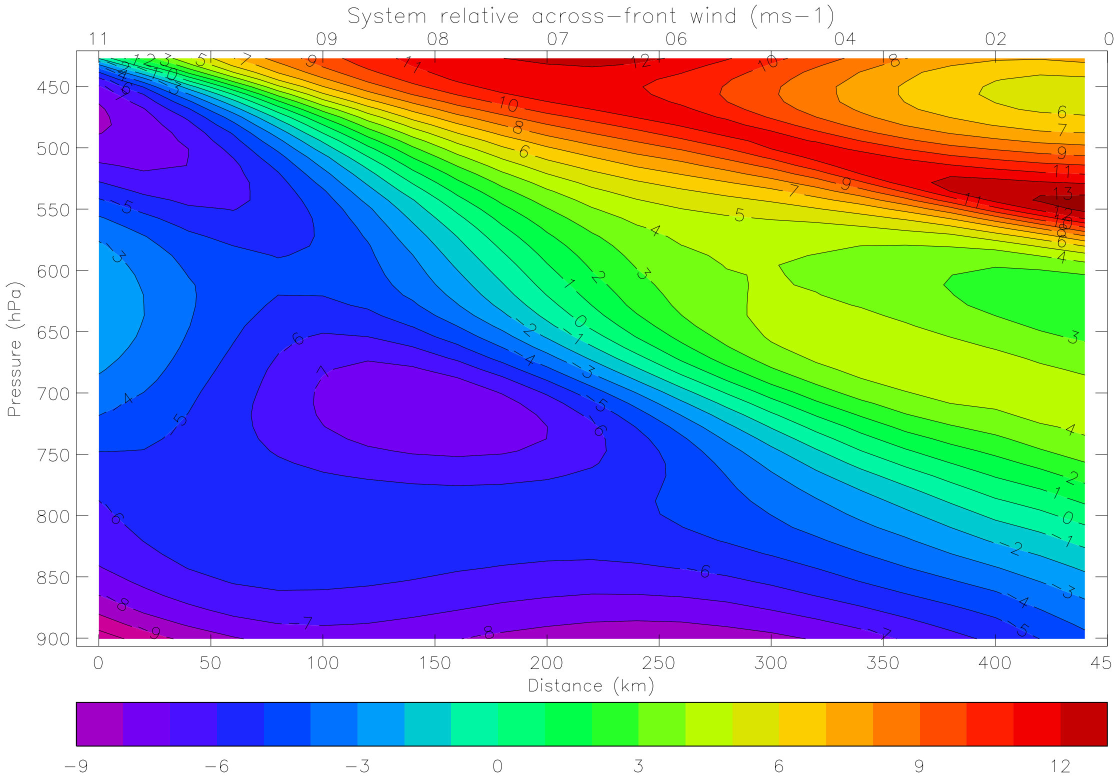
Vertical cross-sections have been objectively analysed from individual dropsonde runs to characterise the internal mesoscale structure of the systems observations. The 1.5 s sounding data of basic parameters (temperatures, scalar wind components and humidity) were objectively analysed as 2-dimensional vertical cross-sections for each of the runs as indicated in Figs. 7.3(c) and 7.4 in log-pressure vs distance coordinates using successive correction algorithms developed by Pedder (1993) to produce the cross-section illustrations. It should be noted that the parameters of the analysis have been subjectively defined to maximise the vertical resolution while avoiding a break-up of differentiated features because of the limited horizontal resolution. This was achieved by using 15 s sampling of the data and filtering with a vertical scale of 25 s (corresponding to 250 m) and horizontal scale of twice the mean sounding separation of 50–90 km in the successive correction algorithm. Horizontal distances are shown as the projected distance onto the plane chosen to resolve vector quantities.

Figure 7.4 shows the analysed static stability in the form of the Brunt-Vaisala frequency N^2. The dropsondes used to prepare the cross-section are numbered along the top axis. This clearly shows the presence of a frontal surface, the sloping stable layer around 500 hPa. A very important feature, however, is the deep layer of weakly stable air beneath the frontal surface. In fact at full data resolution soundings 8, 9 and 11 possess shallow dry adiabatic layers immediately beneath the inversion, a typical symptom of sublimation cooling highlighted by Harris (1977). The extent of the feature is striking, crossing the whole 440 km section and θ_w values from 10 to 13°C, suggesting that it may be formed by a process operating over the system's extent. It is suggested that sublimation from the upper cloud shield makes an important contribution to the presence and amplitude of such a structure.

The cross-frontal flow also shows particularly interesting structure (Fig. 7.5). A shallow layer of strong forward flow coincides with much of the stable zone of the upper front. The pattern in mid-troposphere shows a pair of forward-rearward flow near 500 hPa and another weaker pair at 650–700 hPa, with maxima of relative humidity (not shown) above the peak forward flows. This pattern, of forward descending motion where precipitation is subliming, qualitatively matches that predicted by the Clough-Franks mechanism.

The Clough-Franks mechanism is as follows. Ice crystals sublime very efficiently in sub-saturated environments because of their low fall rate and long residence time, as well as their large effective surface area. The sublimation cools the surrounding air, which descends. Descent increases the subsaturation, which further increases the sublimation until all the precipitation has evaporated. This can occur in a depth scale of a few hundred metres or less. Normally the atmosphere is statically stable and

Figure 7.5: *Vertical cross-section of along-plane wind velocity derived from the dropsondes, in the same plane as Fig. 7.4, shown on Fig. 7.3.*



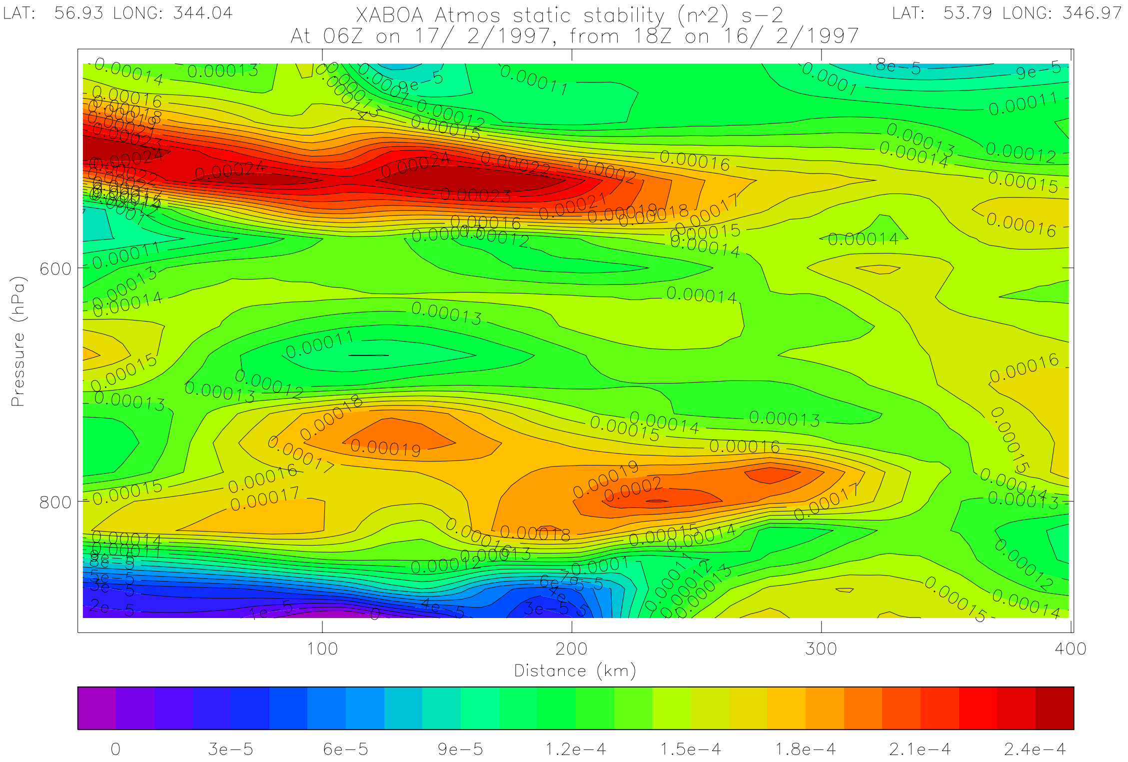


Figure 7.6: *Vertical cross-section of dry static stability N^2 derived from the Unified Model reference simulation, to be compared to Fig. 7.4.*

so descent can only occur in sloping trajectories towards the warm air mass, though Harris (1977) demonstrated that static instability can also be caused by sublimation of intense precipitation. The depth and strength of this circulation are sensitive to the microphysical parameters and so are significant to accurate prediction of weather system structure. For practical NWP and climate simulation sublimation raises some difficulty because of the high vertical resolution necessary to simulate the atmospheric behaviour accurately, which is as yet not well achieved in practice.

The overall forward flow in the warm sector aloft is associated with the anticyclonic flow into the ridge strengthening downstream of the main latent heating zone near the low centre. This probably corresponds to the reduction of potential vorticity above and downstream of the level of maximum heating. The local maximum in the frontal surface corresponds to a direct circulation driven by local sublimation cooling, and the fact that the maximum coincides with the lower part of the saturated region is consistent with moist adiabatic descent occurring where precipitation is sufficient to support it. The layer is shallow because the available precipitation sublimes efficiently but is insufficient to support a deep layer of descent, hence the structure degenerates into finer scales because of the moisture distribution.

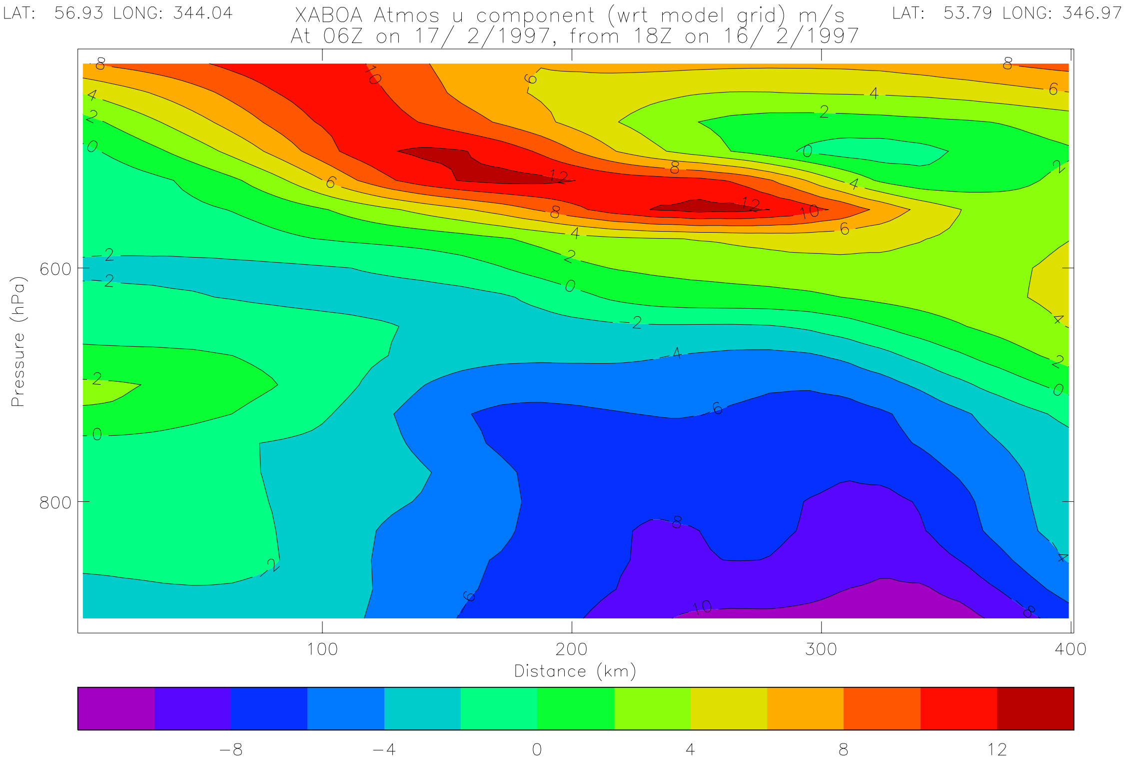
7.3 Model results: quantitative assessment of the impact of sublimation

The event was simulated with the UK Meteorological Office's Unified Model, using versions with both conventional forecast resolution and mesoscale resolution. The models were initialised at 21UTC on 16th February and integrated to 12UTC on 17th February. Although it was a comparatively short integration period, significant mesoscale structure was evolved even by the time of the first run at 06UTC.

The forecast model, the Limited Area Model (LAM), had resolution 50 km and 19 levels and produced a good forecast used to plan the observations. Despite this the model failed to reproduce the above front and associated circulation, presumably because the vertical resolution was insufficient to simulate the sublimation accurately.

Figure 7.6 shows a cross-section of the static stability located near run 1 in a mesoscale model simulation. Compared to Fig. 7.4 it reproduces qualitatively well the upper front and reduced stability beneath the front. Figure 7.7 shows the corresponding cross-frontal wind component, which may be compared to Fig. 7.5. A forward flow occurs in the frontal surface, which corresponds to the circulation inferred from the observed structure. Figure 7.8 shows the actual descent in the model, thus confirming the applicability of the assumption made in analysing the observations that the forward horizontal flow does in fact correspond to descent.

Figure 7.7: *Vertical cross-section of dry static stability N^2 derived from the Unified Model reference simulation to be compared to Fig. 7.5.*



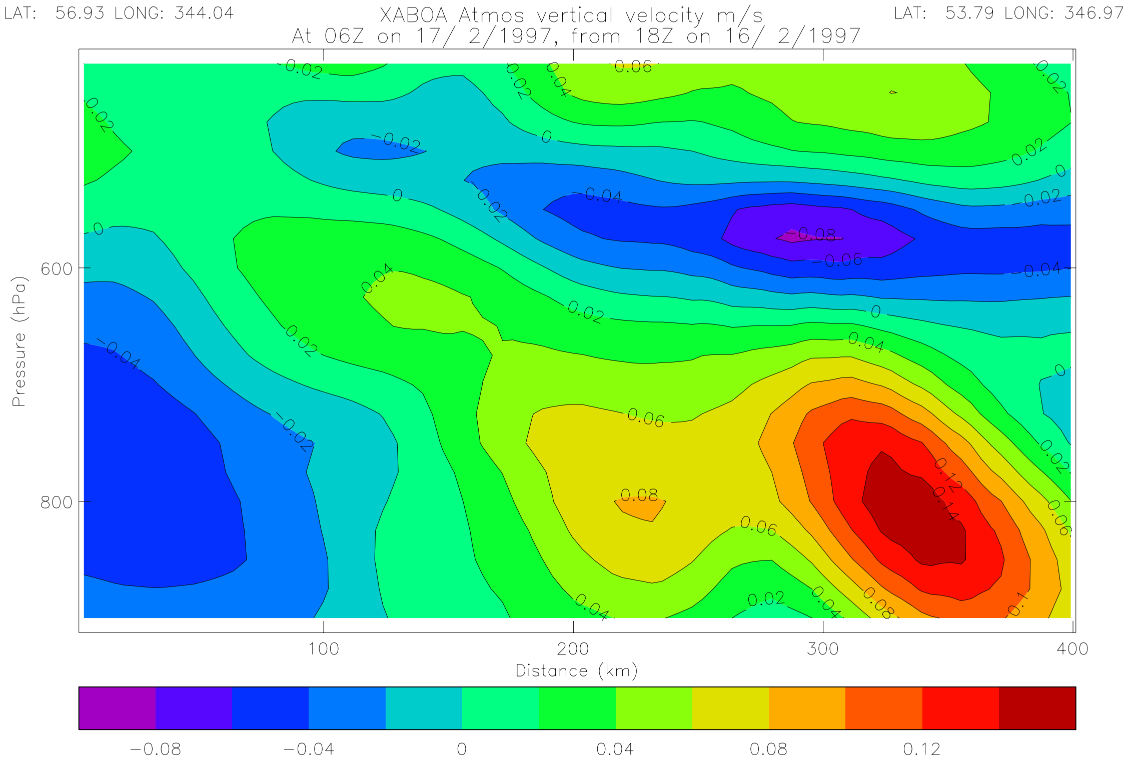


Figure 7.8: *Vertical cross-section of vertical velocity w derived from the Unified Model reference simulation, which, together with the wind shown on Fig.* 7.7*, materializes the cross-frontal circulation, in particular the descent of the upper-level front.*

In the model environment more information is available than in the dropsonde observations because complete 3-dimensional fields are available, including ascent/descent and potential vorticity.

Thus the link between the circulation and stability has been confirmed by omitting from a model simulation the sublimation cooling. This modifies both the stability and flow in the predicted manner, weakening the observed signatures. Figure 7.9 shows the vertical velocity from this integration, which also confirms numerically an aspect of the Clough-Franks mechanism, that the sublimation mechanism acts primarily to amplify descent for which forcing may be already present, through the shallow depth scale permitted by the presence of ice precipitation.

7.4 Concluding remarks

The integrations have also shown a strong interaction between the sublimation and the potential vorticity. A region of low potential vorticity (PV) is normally associated with the upper part of the diabatically heated region of a frontal wave. In the presence of sublimation in the numerical model, however, the low PV is amplified to strongly negative values, the circumstances in which symmetric instability or conditional symmetric instability (SI or CSI) is present.

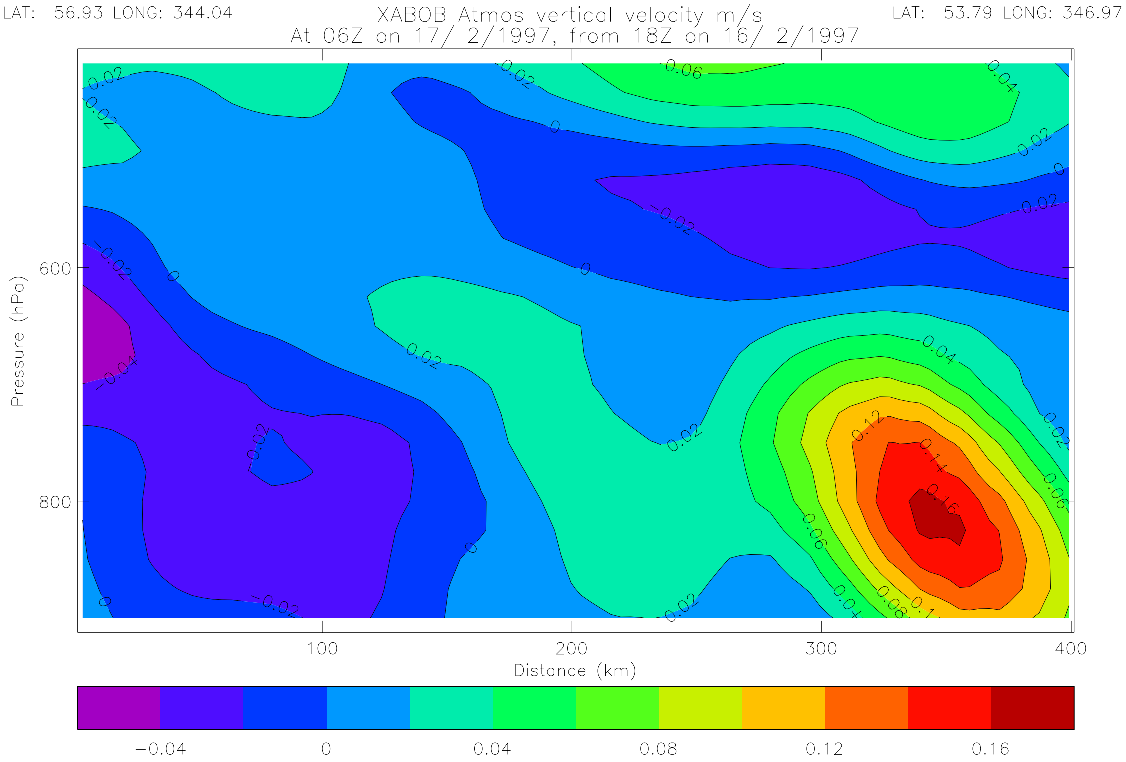


Figure 7.9: *Vertical cross-section of vertical velocity w derived from the Unified Model simulation* without sublimation. *Compared to Fig. 7.8, this figure shows the quantitative impact of Clough-Franks mechanism.*

This result strongly suggests that the combination of sublimation and negative potential vorticity is associated with the occurrence of strong mesoscale circulations and probably the formation of broad mesoscale cloud and precipitation bands.

It is hoped in future work to combine analyses of Doppler radar cloud-mesoscale motions and aircraft microphysical and other data in order to test existing models and to develop more sophisticated parametrizations of mesoscale processes associated with cloud and precipitation on the basis of this and other cases.

7.5 References

Clough and J. Testud, 1988: The FRONTS-87 Experiment and Mesoscale Frontal Dynamics Project. WMO Bulletin, **37**, 276–281.

Clough S.A. and R.A.A. Franks, 1991: The evaporation of frontal and other stratiform precipitation. *Quart. J. Roy. Meteor. Soc.*, **117**, 1057–1080.

Harris F.I., 1977: The effects of evaporation at the base of ice precipitation layers: theory and radar observations.
J. Atmos. Sci., **34**, 651–672.

Pedder M.A., 1993: Interpolation and filtering of spatial observations using successive corrections and Gaussian filters.
Mon. Wea. Rev., **121**, *(10),* 2889–2902.

Thorpe, A.J. and S.A. Clough, 1991:
Mesoscale dynamics of cold fronts - Part I : structures described by dropsoundings in Fronts 87.
Quart. J. Roy. Meteor. Soc., **117**, 903–941.