When a cold front sweeps across

In the largest observational project ever undertaken in Australian meteorology, atmospheric scientists have gained new insight into the familiar cold front. A cold front, they say, is like a giant broom, sweeping dirty weather ahead for hundreds of kilometres.

When we see a cold front marked on a weather chart, we are inclined to think of it as a single phenomenon: a line marking a sharp transition from warm air to cold. And when a cool change arrives, our response is to equate that with the passage of the cold front.

In fact, the cool change may comprise a complex assembly of meteorological events that precede the final arrival of the front some hours and hundreds of kilometres later.

The front on the chart marks where a wedge of cold air is undercutting warm air. Behind it there may be a day or so of cloud, showers, and generally cooler conditions.

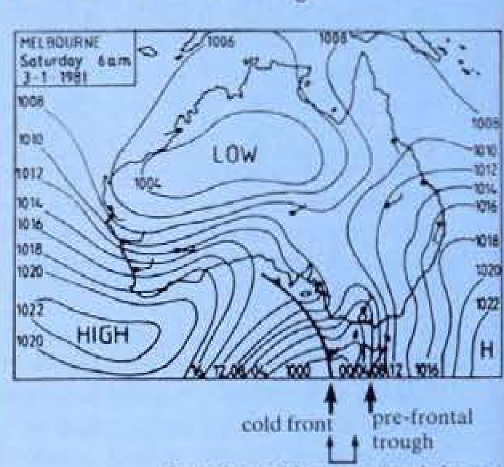
Problems in forecasting temperatures are greatest in summer, and cold fronts are the main reason.

The turbulent weather ahead of the summertime front — sudden cool changes, wind shifts, squalls, and thunderstorms — is more spectacular, and until now it has been little understood.

> *Weather forecasters have had great difficulty in predicting the time of arrival and severity of the cool change.*

More significantly, weather forecasters have had great difficulty in predicting the time of arrival and severity of the cool change. They know a 'pre-frontal trough' often accompanies a cold front approaching south-eastern Australia, but significant weather features such as thunderstorms are too small to appear on most charts. Furthermore, some elements of the cool change are ephemeral, generally intensifying by day and disappearing at night. Its speed of movement, too, fluctuates, and often differs considerably from that of the front that spawned it.

Cold fronts and cool changes



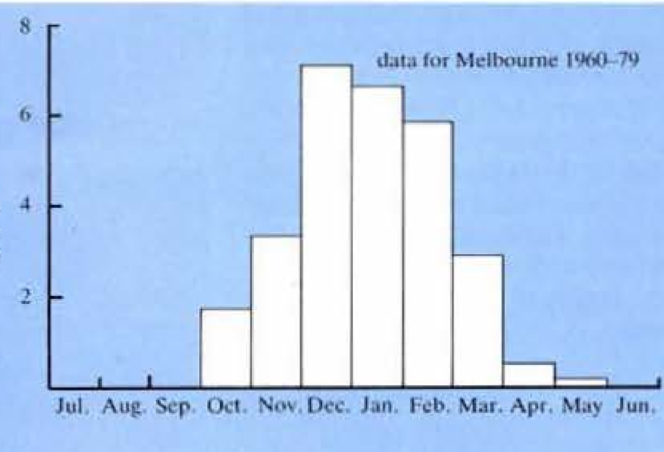
The cool change develops in a 'frontal transition zone' ahead of the cold front.

Yet, in the sweltering heat of summer, a predicted cool change is eagerly awaited by everybody, and a wrong prediction rarely goes unnoticed. A temperature above 40°C delivered by a hot continental northerly can drop 10 or 15 degrees in minutes when a cool south-westerly blows in from the Southern Ocean. As well as comfort, the strategy of fire-fighters can hinge on the correctness of the Bureau's forecast.

On average, 12 cold fronts cross south-eastern Australia during November and December. Sometimes the effects of a cool change can be awesome, such as when it brings in a dust storm, or occurs during the outbreak of a major bushfire. Only about half the changes bring rain, but when they do it can be intense.

As the bar chart shows, most large errors in maximum temperature forecasts (errors of 8°C or more) occur in summer. The main

Cold fronts and forecasting errors



main causes of forecast deficiencies on days of very high fire danger, summer 1981/82

cause	number of occasions
mis-timing, or incorrectly forecasting the effect of, a front or trough line	12
incorrectly forecasting the evolution of the surface pressure pattern (non-frontal)	3
incorrectly forecasting the effect of cloud	3
sea breezes	2
incorrectly forecasting mid-level temperature	1

cause of these errors is failure to predict the correct arrival time, or intensity, of a cool change.

Cold Fronts Research Program

Before the Cold Fronts Research Program began in 1979, no studies had been done, since satellites revolutionized the meteorologist's art, on the nature of the weather activity that precedes a cold front. The Program, proposed by CSIRO, uses the modern facilities and techniques of all Australia's major meteorological institutions. It was launched in the belief that a concerted study of cold fronts would improve forecasting accuracy. Summer presents the strongest mixture of elements, and a solid month's observations in November–December have been obtained for 1980 (Phase I of the Program) and for 1981 (Phase II). The third and final phase, to confirm the general validity of the findings to date, began on November 14, 1984.

The scientists have found there is a distinct pattern in the turmoil.

The main collaborators in the project are the Bureau of Meteorology, the CSIRO Divisions of Atmospheric Research and Oceanography, the Australian Numerical Meteorology Research Centre, the Meteorology Department of the University of Melbourne, the Mathematics Department of Monash University, the Institute of Atmospheric and Marine Science at Flinders University, the Royal Australian Navy, and the Royal Australian Air Force. The resources called upon include instrumented aircraft, ships, and buoys, and an extensive network of meteorological stations recording information on ground-level and upper-air behaviour. The box below gives more detail of the effort going into the Program.

Although there are major differences between Australian cold fronts and fronts that have been extensively studied in the Northern Hemisphere, models of the latter have up to now provided the basis for frontal analysis and forecasting in Australia. Those studied in the Northern Hemisphere originate primarily over water to the west of major land masses, and rarely have a pre-frontal stream of hot, dry air associated with them as in south-eastern Australia. Warm fronts are common in America and Europe, but hardly ever make an appearance here.

A fine observing net

During observation phases of the Cold Fronts Research Program, the imminent arrival of a cold front sets off an intensive 30-hour observing period, with its focus at the Mount Gambier meteorological office.

The normal calm of the office is transformed as it is taken over by the 30 or so members of the research team. The forecasters, analysts, scientists, engineers, and technicians are accompanied by telephones, radios, telex machines, facsimile terminals, and other equipment. Leader of the exercise is Dr Brian Ryan of the Division of Atmospheric Research. His aim is to ensure that a cold front doesn't slip through without yielding all the data the scientists want.

That's unlikely, given the resources of the institutions whose activities during Phase III are summarized below.

BUREAU OF METEOROLOGY

Data come from its routine observing network, and additional observation stations.

Upper-air stations at Ceduna, Mildura, Wagga Wagga, and Adelaide make 6-hourly observations of winds, temperature, and moisture, using radar-tracked balloons (rawinsondes). Other 2-hourly observations come from Mount Gambier and Laverton.

A mobile meteorological station has been transported to King Island, and this also releases rawinsondes every 2 hours.

Pictures come in 3-hourly (or more frequently) from the GMS-3 satellite. These comprise visible- and infra-red-band images.

Radar sets at Adelaide, Laverton, and Mount Gambier obtain patterns of rainfall echoes (when not tracking balloon ascents).

Data come from drifting buoys and commercial planes and ships.

CSIRO DIVISION OF ATMOSPHERIC RESEARCH

The CSIRO F-27 research aircraft is ready and waiting at Mount Gambier airport.

A communication centre links the observing network.

A network of equipment for observing surface winds, pressures, and rain has been installed with the support of volunteer observers.

A computer analyses data on the spot.

CSIRO DIVISION OF OCEANOGRAPHY

The research vessel *Sprightly* patrols the waters off the coast, and releases buoys to measure wind, temperature, and pressure.

ROYAL AUSTRALIAN NAVY

HMAS *Kimbla* is available in the area for observations.

ROYAL AUSTRALIAN AIR FORCE

A reconnaissance aircraft makes first contact with a cool change.

JAMES COOK UNIVERSITY

A coastal radar (COSRAD) is set up at Pelican Point.

MONASH, MELBOURNE, ADELAIDE and FLINDERS UNIVERSITIES

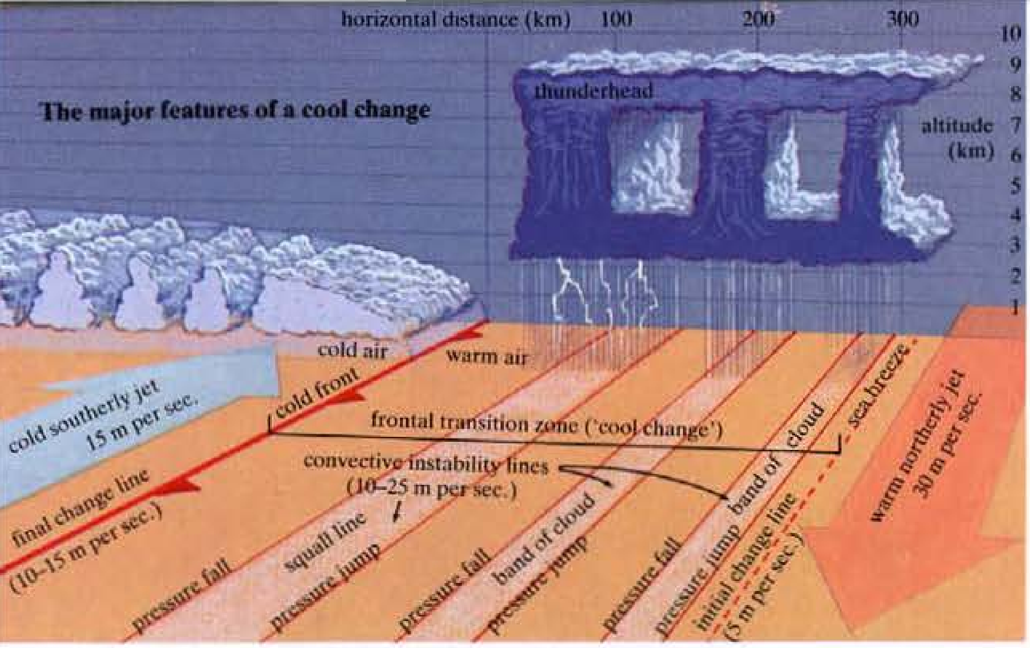
A floating instrumented buoy has been anchored in Bass Strait (Monash); VHF radar measures upper winds near Adelaide (Adelaide); and pilot balloons are released at Peterborough, Lake Bolac, and Inverleigh (Monash, Melbourne, Flinders).

TELECOM

A lightning-detector network monitors thunderstorm activity.

Releasing a balloon for upper air sounding.

A major aim of the Cold Fronts Research Program is therefore to develop frontal models for application by our forecasters. For instance, indices of instability relating to the development of thunderstorms were mostly developed in the Northern Hemisphere, where the warm air ahead of the



The cool change typically begins with a sea breeze and is followed by change lines (colour) of varying severity. A change line is a change in wind or temperature, and is associated with a fall or jump in pressure.

front contains much more moisture. Our relatively dry air makes rain associated with fronts less frequent over south-eastern Australia.

In addition, half of all thunderstorms in this area originate in conjunction with cold fronts, and the interaction of fronts with the coastal ranges leads to a unique phenomenon along the southern coast of New South Wales, the 'southerly buster' (see *Ecos* 18). Forecasting these phenomena is particularly difficult.

The broad goal of the Cold Fronts Research Program is a greater physical understanding of cold fronts, leading to a better forecasting ability. To achieve this required that the researchers:

- find out what a front looks like (in terms of temperature, moisture, and wind), how these quantities vary with height and along and across the front, and how the front changes with time, particularly as it crosses from ocean to land
- clarify the interactions between the front and the much larger weather situation surrounding it
- obtain sufficiently detailed data to enable the verification of regional-scale numerical models of frontal activity

Most of the remainder of this article will focus on the studies that have illuminated the first of these aims, as this is the one that bears most closely on what we experience on the ground. In other words, we will be more concerned with the effects of the 'broom' rather than with the movement of the broom itself. The box on this page gives an outline of the findings relating to the second aim.

Mount Gambier, near the Victoria–South Australia border some 350 km west of Melbourne, was chosen as the central site for the project, and 15 other weather stations in an area 300 km square contributed to the wealth of data. The scientists selected the locality because its relatively flat terrain should not interfere with a front's progress and the town's airport allows unhindered operation of the research aircraft. The meteorological office there has a weather-watch radar, and proximity to the sea allows observations of fronts over the sea, and of how they change as they cross the coastline.

The extensive observational net recorded details of 10 fronts during Phases I and II of the Program. While each of the fronts had features not shared with the others, analysis of the data has allowed the participating scientists to piece together a coherent picture of a cold front and all that goes with it.

The most significant feature, the scientists found, was the way in which the front (the broom) swept turbulent weather 100–300 km in front of it. This weather was organized into a number of discrete lines, roughly parallel to the driving front at the rear. The researchers speak of 'change lines' within a 'frontal transition zone', beginning with an initial change line ('a change has arrived!'), and finishing with the final change line (the passing of the cold front proper).

The broader context

The origins and progress of cold fronts lie in the familiar system of highs and lows seen on the weather map. Meteorologists involved in the Cold Fronts Research Program have examined the larger-scale wind systems in which cold fronts are embedded, and have found a common pattern. The picture that emerges suggests that these systems control the speed of movement of the front and the inflow of moisture (and energy) into the frontal transition zone.

Evidently three distinct air streams surround a cold front, and the two most important are shown in the accompanying diagram.

The first, and most important, is a warm belt of moist air ahead of the front. It originates over the Tasman Sea and subsides into a heat trough over the continent. It is forced to ascend ahead of the front.

This ascent cools the air, giving rise to the characteristic cloud that precedes a front. More importantly, the ascent releases convective instability, producing thunderstorms and the like. Here is the energy source for much of the weather the cold front brings.

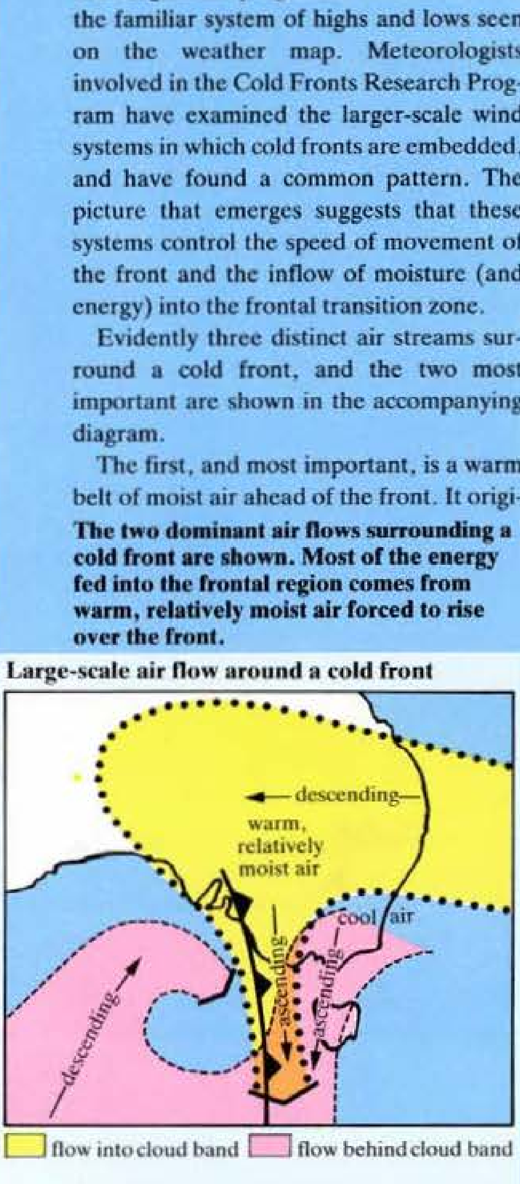
Underneath the cloud lies a stream of cool air, which also has to ascend to cross the front. It does this obliquely while travelling generally towards the south. Part of it curves around the front and subsides into the region behind. The eastern arm continues to move slowly to the south.

Above the clouds can be found the third flow of air — a high-level flow from the north-west that weakly ascends over the front and continues on to the south-east.

While the larger-scale processes exert their influence on the cold front, the reverse effect no doubt also occurs. However, at this stage models are too simple to be able to deal with how the front itself influences synoptic-scale events.

The two dominant air flows surrounding a cold front are shown. Most of the energy fed into the frontal region comes from warm, relatively moist air forced to rise over the front.

Large-scale air flow around a cold front



The Australian summertime cool change: synoptic and subsynoptic scale aspects. K.J. Wilson and H. Stern. *Monthly Weather Review*, 1984, **112**(in press).
(Both of these authors are with the Bureau of Meteorology in Melbourne.)

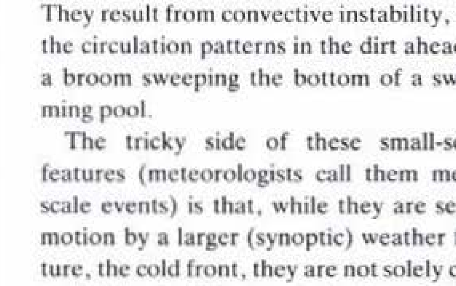
Melbourne's dust storm of February 1983. The dust makes visible an avalanche of cold air spilling out from a squall line.

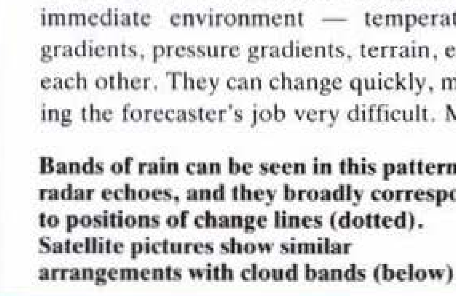
The change lines may be detected and followed as changes in pressure, temperature, or wind direction, and are evident as the edges of cloud bands in satellite pictures, and on radar screens as echoes from rain. They result from convective instability, like the circulation patterns in the dirt ahead of a broom sweeping the bottom of a swimming pool.

The tricky side of these small-scale features (meteorologists call them mesoscale events) is that, while they are set in motion by a larger (synoptic) weather feature, the cold front, they are not solely controlled by it. What controls them is their immediate environment — temperature gradients, pressure gradients, terrain, even each other. They can change quickly, making the forecaster's job very difficult. Melbourne is only about 6 hours away from Mount Gambier as the cool change flies, but this can alter a lot in that time and a forecast for Melbourne based on observations at Mount Gambier may not be very accurate.

Bands of rain can be seen in this pattern of radar echoes, and they broadly correspond to positions of change lines (dotted). Satellite pictures show similar arrangements with cloud bands (below).

Change lines, and bands of rain and cloud





While synoptic weather features occupy dimensions of thousands of kilometres, have lifetimes of a day or so, and are dominated by Coriolis effects (the result of the earth's spin), mesoscale processes span only tens to hundreds of kilometres and exist for a few hours at most, and the effect of the earth's spin can mostly be neglected. How can one hope to forecast such an ephemeral disturbance?

The pressure fluctuations ahead of a cold front, when recorded, look like the trace of a seismograph during an earth tremor (see the illustration on this page). Each of the major excursions of the recording pen corresponds to the passage of a change line. Usually, at least one of these is a major squall line, accompanied by up to three other change lines. The pattern changes with time, since the speeds of individual change lines differ. The initial line may, at one particular instant, move at 5 metres per second, and intermediate lines at 15, 10, and 25 m per sec. — all driven ahead of a cold front (the final line) moving at 12 m per sec. Difficult to forecast indeed.

But the scientists have found there is a distinct pattern in the turmoil. The convectively unstable atmosphere and the wind shear give rise to lines of thunderclouds, evaporative cooling, outflows of cold air, and — *voila!* — change lines.

The broom

Let us go back to the father of it all — the wedge of cold air that constitutes a cold front moving into warm air. The wedge typically has a slope of 1 in 100, and warm air slides up and over it, producing the high and middle-level cloud-bank typical of cold fronts.

The cold wedge is held together by a wind (called a geostrophic wind) that blows at right angles to the direction of motion of the front. In the Southern Hemisphere, this cold wind comes from the south. Balancing it, a warm wind blows from the north ahead of the front.

Such winds are shown on the diagram (page 24), and during the observing program their maximum speeds ahead of the cold wedge were about 25 m per sec. at a height of 1 km.

These side-by-side jets give rise to a considerable amount of shear, both horizontally and vertically, leading to a breakdown in the stability of the atmosphere. The air mass ahead of the front is prompted to form into lines of convective instability — the broom has swept too fast for streamlined flow.

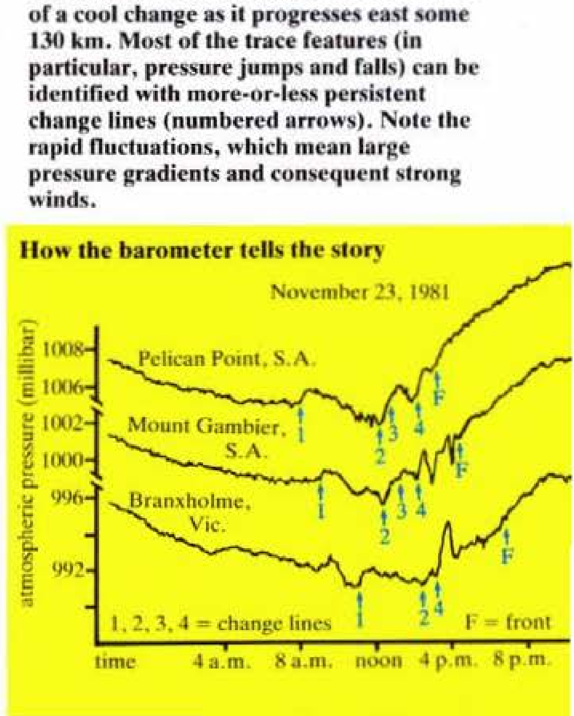
Although the scientists are uncertain about the actual mechanism involved, the result is clear — the formation of distinct lines of convection cells. One or more may intensify into what is called a squall line — a row of thunderclouds that can be clearly seen by eye or on radar.

Enough information was gathered during the first two phases of the Cold Fronts Research Program to piece together the essential elements of a vigorous squall line. A low-level inflow of air occurs at the forward edge, and an outflow ahead at upper levels (the anvil). Also important is an inflow of relatively dry air at middle levels from behind the squall. This augments the squall line's evaporative cooling ability; it appears that rain from the thunderstorms falls into the dry air, evaporates, and creates a pool of cold air up to 70 km across just below the cloud base.

As the temperature and pressure of a parcel of air are physically related, a small high-pressure cell should be observable beneath

These barometric traces show the evolution of a cool change as it progresses east some 130 km. Most of the trace features (in particular, pressure jumps and falls) can be identified with more-or-less persistent change lines (numbered arrows). Note the rapid fluctuations, which mean large pressure gradients and consequent strong winds.

How the barometer tells the story



the cold pool associated with each squall line. Indeed it is, as the data clearly showed.

In fact, the data revealed a further remarkable phenomenon: the heavy cold air pours out from beneath the thunderstorm and spreads out on the ground like spilt milk (see the diagram on this page). Because the spill progresses forward due to density differences — in the same way as an avalanche — it is an example of what are known as 'gravity currents'. Another common meteorological gravity current is the familiar sea breeze.

The leading edge of an expanding spill of cold air is observed as a gust front (a type of change line). If the air becomes loaded with dust, then the gust front becomes dramatically visible, as it did in February 1983 when such a creature blew in over Melbourne.

Because of the link between the air's temperature and pressure, the arrival of a gust front coincides with a sudden jump in pressure. The size of the jump reflects the thickness and temperature of the spreading spill.

Measurement of the speed of movement of these gust fronts has confirmed that the gravity current explanation is broadly correct. After allowing for the speed of the bank of thundercloud, scientists can predict the speeds of the leading and trailing edges of the gust front fairly well from the temperature of the cold air and that of the warmer air into which it flows.

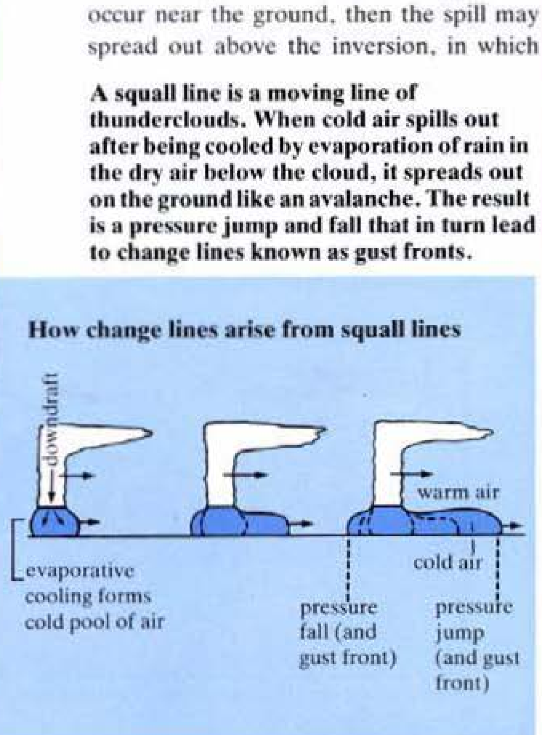
The leading edge, or change line, moves faster than its parent squall line, and sometimes overtakes the lagging change line associated with a squall line ahead. In this way, change lines can merge and intensify, or can disappear. The nature of the interaction between the various lines requires further investigation, and this aspect will be looked at during Phase III of the Program.

If a temperature inversion happens to occur near the ground, then the spill may spread out above the inversion, in which case the pressure jump and associated wind gusts will be detected on the ground, but not the temperature drop.

Why should the spreading perimeter of the outpouring cold air give rise to strong wind gusts? The explanation lies in the very abrupt pressure jumps that are associated with squall lines: a pressure change of several millibars can occur over a distance of only a few kilometres. The resulting pressure gradient can be five times greater than that associated with cyclones! Luckily, the forces that this pressure gradient produces act only for a few minutes in a small region, and so cyclone-force winds don't have time to build up. Nevertheless, the wind can be severe, and it changes direction rapidly as the pressure jump passes.

A squall line is a moving line of thunderclouds. When cold air spills out after being cooled by evaporation of rain in the dry air below the cloud, it spreads out on the ground like an avalanche. The result is a pressure jump and fall that in turn lead to change lines known as gust fronts.

How change lines arise from squall lines



On the tarmac at Mt Gambier, CSIRO's F–27 aircraft awaits the arrival of a cold front.

Towards Phase III

The research team has come close to explaining most of the features of a cool change. Of the change lines (of temperature, pressure, or wind shift), the first is sometimes simply a wind shift due to a forewarning sea breeze and the last marks the arrival of the cold front proper. The rest are associated with either the leading or trailing edge of an outflow of cold air from a squall line or other line of convective instability.

The conceptual model that the scientists have built up explains what goes on and provides information on the likely sequence of weather changes and the approximate timing and position of them. However, it gives no indication of their severity; in particular, the appearance of cloud and rain needs closer attention — where will it rain, for how long, and how much?

Phase III of the Cold Fronts Research Program should help answer questions like these. Other important information gaps include the effects of the coastline, local topography, and time of day on the passage of cold fronts. The model was derived from observations near Mount Gambier, and its applicability to other locations remains to be confirmed.

Andrew Bell

A regular mystery

Living in Melbourne, you'd soon get the impression that cool changes hit in the afternoon. Indeed, the statistics bear this out.

Why should that be? The mystery is deepened upon recognizing that the same preference for afternoon arrival holds for everywhere else as well!

Not enough data have been gathered yet to give a conclusive answer, but observations are consistent with the suggestion that the front speeds up considerably in the afternoon. Evidently it tries to make the eastern coast by night-fall, and if it's behind schedule it hurries up.

On hot summer days the sun heats the land to considerably higher temperatures than the sea; and the result, by the afternoon, can be a substantial atmospheric pressure gradient between parts of the continent and the coastline. This is probably the main cause of the front's acceleration.

Local topography also must have a significant effect on a cool change's arrival time.

More about the topic

The Australian summertime cool change: mesoscale aspects. J.R. Garratt, W.L. Physick, R.K. Smith, and A.J. Troup. *Monthly Weather Review*, 1984, **112** (in press).
(The first two authors are with the CSIRO Division of Atmospheric Research at Aspendale, near Melbourne. Dr Smith is in the Geophysical Fluid Dynamics Laboratory at Monash University. Dr Troup, who contributed much to cold fronts research in his years with the Division of Atmospheric Research, died in 1983.)

The Australian summertime cool change: subsynoptic and mesoscale model. B.F. Ryan and K.J. Wilson. *Monthly Weather Review*, 1984, **112** (in press).
(Dr Ryan is with the CSIRO Division of Atmospheric Research; Mr Wilson is with the Bureau of Meteorology.)

Low level wind response to mesoscale pressure systems. J.R. Garratt and W.L. Physick. *Boundary-Layer Meteorology*, 1983, **27**, 69–87.

Mesoscale observations of a pre-frontal squall line. W.L. Physick, W.K. Downey, A.J. Troup, B.F. Ryan, and P.J. Meighen. *Monthly Weather Review*, 1985, **113** (in press).
(The authors already named are with the Division of Atmospheric Research; the other two are with the Bureau of Meteorology.)