# TEPHRA

KIA TAKATŪ TAHI TĀTOU

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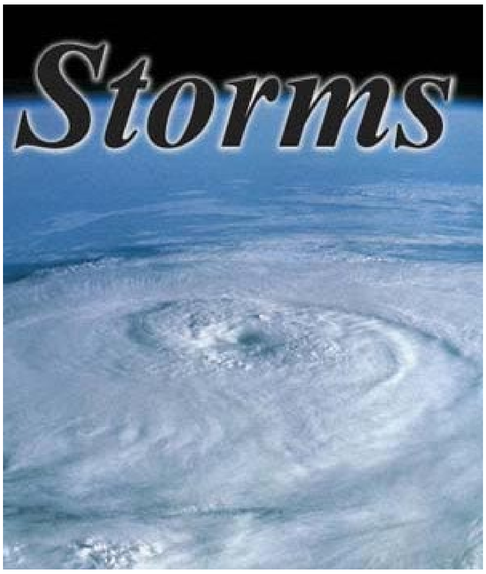



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# Foreword - Hon Jack Elder

Civil Defence was very much in the glare of media scrutiny over the summer, with a run of events demanding the mobilisation of Civil Defence staff. It also provided me with a hectic introduction to the job of Minister of Civil Defence, which I took up last December. Along with most other New Zealanders, I was surprised by the appearance here of two tropical cyclones in rapid succession over the Christmas period, and a third cyclone in March. While Fergus and Drena washed out the holiday plans of many people, the country was very lucky that the damage was not more extensive. Cyclone Gavin also caused disruption to normal activities as well as outdoor and travel pursuits, especially in coastal regions. The cyclones also put the work of the Ministry of Civil Defence in the public limelight, and gave me a chance to see the staff in action.

I travelled to Thames after waves breached the sea wall, flooding low-lying residential areas. The work being done by the Civil Defence volunteers was most impressive, and they can be extremely proud of their achievements. The collapse of the Opuha Dam, which had the potential to cause a significant loss of life, again demonstrated the skill and commitment of Civil Defence staff. I cannot stress enough the importance of the volunteer spirit in New Zealand, and these dedicated people that make up our emergency services are the backbone of the community. It is the job of the Government to ensure staff have the organisational structure and resources to enable them to carry out their mission, and for this purpose there is currently an extensive review of the entire field of emergency services being carried out which will considerably improve the ability to prepare, respond and recover from large scale emergencies particularly in large urban areas. Although no decisions have yet been made, I expect that there will be movement towards a transition period in the next few months. Again, I want to express my admiration for the people who work on behalf of the community, and I look forward to doing what I can to help their task.

Hon Jack Elder
Minister of Civil Defence

# Foreword - Paul Officer

In October 1995 we devoted an issue of Tephra to volcanic hazards. Previously these hazards had been underrated, but more recently given prominence by the Ruapehu eruptions. This present issue focuses on storms, a more common hazard in New Zealand but one which gained special attention this past summer, with three storms of tropical origin reaching us within three months.

New Zealand is affected by two different sets of storms those drifting south in the summer months in the shape of transformed tropical cyclones such as Fergus and Drena, and those generated in the expanses of the Southern Ocean and sweeping around the "roaring forties". The latter can occur at any time and caused the summer emergencies of 1993 94 which affected Kaikoura, Southland and South Canterbury over a period of several months.

The damage from storms can be great. Cyclone Bola damage in 1988, one estimate suggests, was in excess of $200 million. The recent storms Fergus, Drena and Gavin caused nowhere near those losses, but on the holiday industry of Northland and Coromandel the impact was, nevertheless, severe. This reminds us that the financial or economic impact of emergencies is only part of their effect. The failure of expectation, whether of a family holiday or of business volume, has psychological consequences which may in some cases prove highly disruptive of personal relationships at a considerable distance from the physical events, and for a significant time after them.

Mitigation, preparedness, response and recovery from storms depends firstly on the quality and timeliness of advice available from the MetService. I am deeply appreciative of the highly responsible position taken by the Service and by the positive relationships which they have fostered with the Ministry of Civil Defence, regional councils and others with a direct role in emergency management. Those at MetService are to be congratulated again.

I am also heartened by the involvement of the National Institute of Water and Atmospheric Research (NIWA). Some of our most scenic and tranquil areas, such as the coastlines adjacent to the Firth of Thames and Nelson, are vulnerable to storm surge as well as the direct effect of wind and rain. Estimating such complex phenomena involves close partnership between MetService and NIWA and this was very evident last summer. Through working parties of its Scientific Advisory Committee on Hazards, the Ministry of Civil Defence is promoting and financially supporting inter-agency studies which will increase our understanding of potential events and so enable plans to be developed to deal with such eventualities.

In this Tephra we present authoritative articles by scientists from the two institutions. I am sure they will be read with interest, and I thank those who have taken time from busy schedules to provide us with them.

Finally I would reflect that the hazardscape is only part of the equation. Personal and community vulnerability is an equally important factor. Civil defence is about self reliance and mutual support, about social relationships, about interdependence, about the untiring willingness of volunteers and the development of robust communities. These principles are often tested under bleak and frightening circumstances. Whatever the origin of an emergency, its successful management and outcome depends always on people helping people being prepared to display the appropriate measure of good grace, generosity and humility of spirit in offering and accepting help. Whilst we should take great pride in the way we have adhered to these principles during times of adversity, stoicism and resilience can never be taken for granted. We still have much to learn in these social aspects of emergency management.

P N Officer
Director
Ministry of Civil Defence

# ANATOMY OF A storm

**by M.R. Sinclair**
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In the Southern Hemisphere, a cyclone is any region of clockwise rotation about a low pressure area. Meteorologists divide cyclones into two classes tropical and extratropical. While the terminology reflects their regions of occurrence, tropical and extratropical cyclones have fundamentally different structure and formation mechanisms, and derive their energy from different sources, as we shall now see.

## TROPICAL CYCLONES

A tropical storm is an intense cyclonic storm of tropical origin. The same type of storm is given different names in different parts of the world. The term hurricane is most commonly used over the North Atlantic and eastern North Pacific regions, while the term typhoon is used for western North Pacific storms. Tropical cyclone is used for storms in our region (southwest Pacific) and in the Indian Ocean. Born over warm tropical oceans and nourished by an abundant supply of water vapour, the tropical cyclone can grow into a ferocious storm that causes widespread devastation from huge waves, heavy rain and winds that can exceed 250 km/h.

### Structure

When viewed from space, a typical mature tropical cyclone comprises a central region of dense, active cloudiness averaging 500 km in diameter (Fig. 1). The eye of the storm, a region of little cloud and light winds around 20 50 km across, is located near the middle of this dense overcast region. Surface winds rotate clockwise (counterclockwise in the Northern Hemisphere) about the centre of lowest pressure located within the eye. Central sea level pressures below 900 hPa have been recorded within mature hurricanes. (Air pressure at sea level normally ranges from 980 1035 hPa over New Zealand.) The air within the eye is markedly warmer than outside, especially in the mid- to upper troposphere (6 km 15 km), giving the cyclone a warm-core structure. This warmth derives from the release of huge quantities of latent heat as water vapour condenses out as heavy rain in the surrounding clouds. Latent heat is the exact reverse of the heat energy used to convert a volume of liquid water to vapour (e.g. boiling a pot of water dry), and is a major energy source for the tropical cyclone.

The inner edge of the cloud lining of the eye is termed the eye wall, because an observer within the eye sees an impressive wall of rotating thunderclouds (cumulonimbus). These clouds may extend vertically for more than 15 km. The heaviest precipitation and strongest winds are found within the eye wall and are typically located less than 60 km from the storm centre, making the area of extreme winds quite small. Looking down the track of the cyclone, the strongest winds are found to the left of the track (right in the Northern Hemisphere). Outside of the eye wall cloud, the winds fall off slowly with increasing radius from the centre, and cloud and precipitation are predominantly stratiform layer cloud. While tropical cyclones have a predominantly circular structure, there are generally one or two spiral arms of cloud that give the mature hurricane its beautiful pinwheel appearance. As these active cumulonimbus cloud bands spiral in toward the centre, they feed heat and moisture to the system.

**<u>How they work</u>**

Near the Earth's surface, the air that flows clockwise around the cyclone has a component of motion toward low pressure (Fig. 2). As this air spirals inwards (converges), it rotates faster, just like an ice skater spins faster when she pulls her arms close to her body. As this air moves toward lower pressure, it expands and cools, similar to air leaving a compressor or flowing into an engine inlet manifold. Because of the cooling, this fast-moving air becomes even more efficient in picking up huge quantities of heat and moisture from the underlying ocean. As this near-surface air converges into the eye wall cloud, it is forced to rise to preserve mass continuity, just as compressed plasticine "rises" between the fingers.

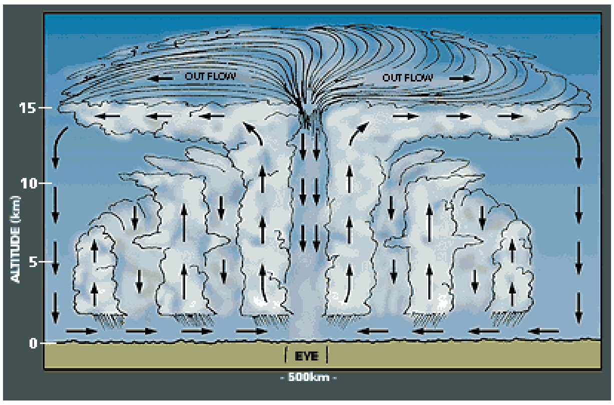


**FIGURE 2**
Verticle slice through a tropical cyclone

As the air rises, it cools and condenses, releasing latent heat. In the tropical cyclone, this condensation and consequent precipitation is continually fuelled with new moisture picked up from the ocean.

As the air rises into the eye wall cloud, it is rapidly warmed by the heat released during condensation, further accelerating its rate of ascent. The latent heat released in a single hurricane in a single day is equivalent to the energy from several hundred atomic bombs. If this energy were converted to electricity, it would supply the needs of New Zealand for about 25 years. As the air continues to ascend, it eventually encounters the upper boundary of the troposphere and spreads out, or diverges (Fig. 2), removing air from the column above the cyclone and producing an anticyclonic (counterclockwise) circulation aloft. This air spirals outward in the region above about 12 km elevation. Below this level, the air is convergent and rotating cyclonically.

Formation and maintenance of the tropical cyclone is by means of a positive feedback effect. The near-surface air spiralling in to the centre of the low picks up heat and moisture from the sea to fuel new thunderstorms that release huge quantities of latent heat. Driven by this heating, the air accelerates upward and outward in the anticyclonic outflow region at the top of the troposphere, giving rise to a net loss of air mass from the column above the cyclone. As a consequence, the surface pressure in the cyclone falls, leading to an even stronger cyclonic wind circulation. This results in even greater pick-up of heat and moisture from the sea to fuel heating in the eye wall cloud and increased upper-level outflow, leading to further pressure falls in the cyclone, and so on.

If any of these processes is inhibited, the cyclone will start to weaken. Vertical wind shear that displaces the upper-level anticyclone from its location directly above the lower cyclonic circulation will inhibit the efficient removal of air from the cyclone core and will rapidly tear the cyclone apart. This symmetric, concentric organisation is a crucial aspect of tropical cyclone structure. If the cyclone moves over cooler water, the heat and moisture supply that fuels the storm will be reduced. In general, tropical cyclone maintenance requires a sea surface temperature (SST) in excess of 27 C.

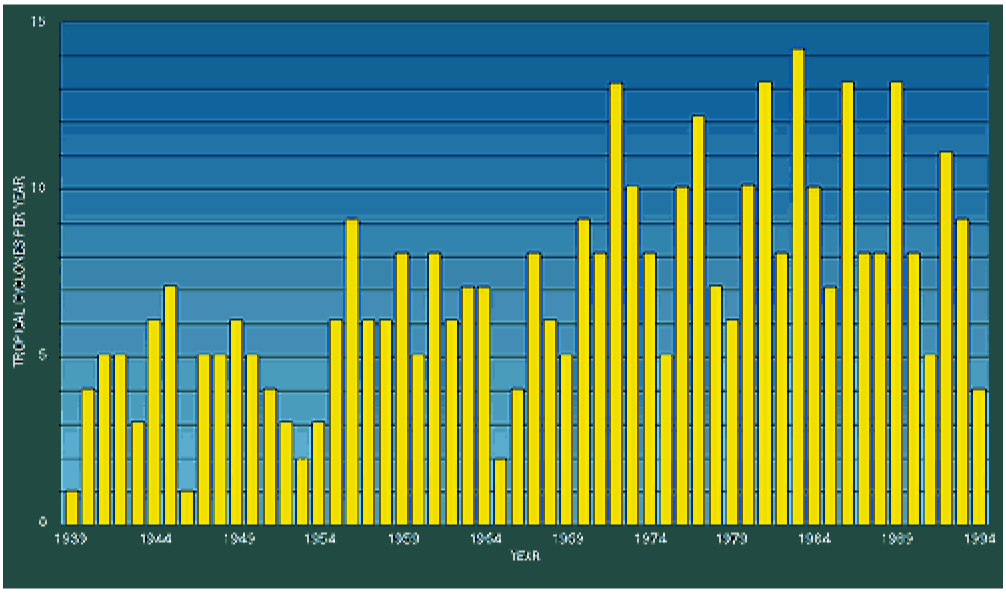



**FIGURE 3**

Annual numbers of tropical cyclones in the southwest Pacific ocean basin. While there was an increase in the numbers of tropical cyclones detected since the advent of meteorological satellites in 1969, there is no clear evidence that tropical cyclones _have been changing in number or intensity over the years.

**Effects**

Although the high winds inflict considerable damage, huge waves and excessive flooding cause most loss of life and property. Heavy rain often exceeds 500 mm per day, particularly on the upwind side of mountains, flooding rivers and low-lying areas. Low-lying coastal areas can be inundated by storm surge. This is an abnormal rise of sea level by as much as several metres, caused by a combination of wind pushing water toward the shore and the lessened air pressure in the storm that allows the sea to rise. Tropical cyclones can also spawn tornadoes and waterspouts.

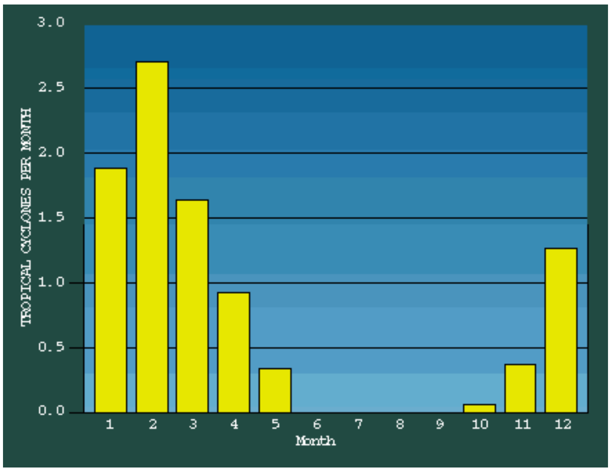



**FIGURE 4**
Annual variation of tropical cyclones, using data since 1970 when cyclones were reliably spotted from satellite

**Occurrence**

In the southwest Pacific, an average of ten tropical cyclones can be expected to form during any one year (see Fig. 3). The peak month is February, although cyclones can form any time between December and April (Fig. 4). Tropical cyclone formation generally occurs in the region between Australia and 170 W in the 8 20 S latitude band. On average, newly-formed cyclones move toward the southwest, but they subsequently generally curve southeastward and accelerate. Of course, individual cyclone motion is highly erratic and difficult to predict, as many tropical cyclones meander in a haphazard fashion for several days. Overall, the seas north of New Caledonia experience the greatest number of tropical cyclone transits (Fig. 5).

# EXTRATROPICAL CYCLONES

Extratropical cyclones (sometimes called mid-latitude depressions, or lows) form in middle and high latitudes, within the belt of westerlies encircling the globe between 30 and 70 S. They generally move from west to east, bringing a period of generally unsettled weather, with wind, cloud and precipitation, particularly near fronts.

## How they work

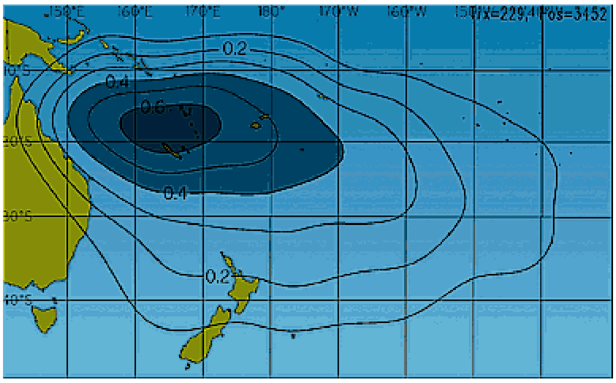



**FIGURE 5**
Geographic occurrence of tropical cyclones. Contours are the numbers of cyclones per month passing within 555 km of each point. Data for Figures 3-5 are from MetService archives.

Unlike their tropical counterparts, extratropical cyclones do not require heat and moisture input from the sea. Instead, the cyclone feeds on potential energy contained in horizontal temperature contrasts. These temperature contrasts are continually building as a result of the solar heating imbalance between the equator and the poles. The cyclone forms as a result of the redistribution of air that occurs when contrasting air masses are brought together.

If one considers a container having warm water on one side and colder, more dense water on the other, it is apparent that the cold water will immediately sink and slide under the warm water, resulting in warm water overlying cold water, with no further motion possible without input of external energy. In other words, there is something inherently unstable about horizontal temperature contrasts.

In the atmosphere, a similar process of warm air rising and cold air sinking occurs, transforming potential energy into kinetic energy. An additional complication is that moving air parcels are acted upon by forces associated with the Earth's rotation. As the cyclone develops, the region of thermal contrast organises itself into cold and warm fronts, giving the mature cyclone a highly asymmetric structure (Fig. 6). The warmest air is found about and east of the low, while the coldest air occurs to the rear (west) of the cyclone in the equatorward-moving air. In addition, most of the cloud and precipitation occurs in the rising warm air about and ahead of the cyclone, in contrast with the symmetric annular rainband structure of the tropical cyclone. Extratropical cyclones generally intensify with height and comprise a cold and amplifying low pressure trough aloft, just to the west of the surface centre. In contrast, the tropical cyclone consists of a cyclonic vortex that decreases with height, with a warm anticyclone directly above.

Jet streams near the top of the troposphere (around 10 km above the Earth's surface) are implicated in the formation of extratropical cyclones. These ribbons of very strong wind sometimes in excess of 300 km/h are responsible for the regions of divergence that remove air from the column above the cyclone, making the central pressure fall. As winds approach the jet stream core, they speed up, and then slow down when they leave.

These accelerations and decelerations, along with flow curvature and wind shear effects, cause regions of convergence and divergence along the jet stream axis. Jet streams are inherently linked to the horizontal temperature contrasts on which the cyclone feeds. Although extratropical cyclones can and do form in dry air, latent heat release in the cloudy region ahead of the cyclone can invigorate the system. Thus, extratropical systems featuring low-level inflow of moist subtropical air can be quite active

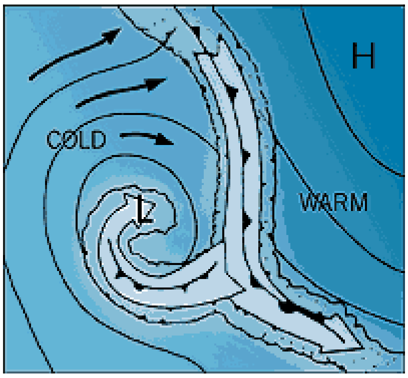



**FIGURE 6**
Extratropical cyclone, showing region of ascent and cloudiness, cold and warm fronts and temperatures.

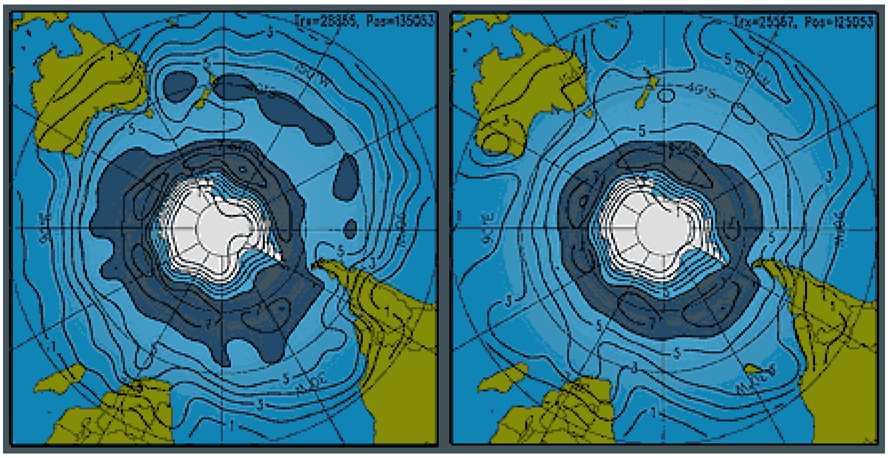
**Occurrence**

Most extratropical cyclones form and develop within middle latitudes, and migrate eastward and poleward during their lives. The warm current running down the east coast of Australia provides additional heat and moisture input to the atmosphere in winter, making that region particularly susceptible to cyclone development, as seen in Fig. 7. In summer, however, the main storm track retreats south of 55 S. Most extratropical cyclones move from west to east; however, many cyclones originating in subtropical regions to the north or northwest of New Zealand track southeastward or even south, and can bring particularly heavy precipitation because of their enhanced moisture content.

Occasionally, extratropical cyclones intensify more rapidly than usual, generating storm-force winds and torrential rain, often within hours of initial storm formation. The terms explosive cyclogenesis or bomb are used to describe these storms. The Tasman Sea and the waters northeast of New Zealand are home to many of these bombs, which require particularly intense horizontal temperature gradients, plentiful moisture and powerful upper-level jet streams coming together in just the right arrangement. Explosive cyclogenesis events pose a particular forecasting challenge because of their rapidly evolving nature.

# TROPICAL CYCLONES ENTERING NEW ZEALAND WATERS

Of the ten or so tropical cyclones that form in the southwest Pacific each year, an average of around two can be expected to migrate poleward of 30 S into the New Zealand sector (between 165 E and 175 W). However, actual annual numbers finding their way into New Zealand waters are highly variable. During 19831, 1987 and 1991, tropical cyclones avoided our region altogether, while in other seasons, up to four occurrences were observed.



**WINTER CYCLONE FREQUENCY | SUMMER CYCLONE FREQUENCY**

**FIGURE 7**

Extratropical cyclone frequency for (a) winter and (b) summer. Contours are numbers of cyclones per month per 555 km radius area.

The El Niño-Southern Oscillation (ENSO) phenomenon influences the likelihood of storms of tropical origin hitting New Zealand. During its positive phase (La Niña), tropical cyclone activity occurs west of its usual position, with more cyclones than usual in Australia and New Zealand longitudes. However, during the opposite (El Niño) phase of the ENSO cycle, tropical cyclone activity extends well to the east of the dateline, with decreased incidence near New Zealand. For example, during the 26 El Niño summer months between 1970 and 1994, just six tropical cyclones entered New Zealand waters, compared with 12 during the same number of La Niña months. This summer (weak La Niña), three ex-tropical cyclones (Drena, Fergus and Gavin) crossed northern New Zealand.

As tropical cyclones track poleward, they weaken as their heat and moisture supply is reduced over cooler water or land. Peak summer season SSTs near New Zealand, ranging from around 22 C in the far north to less than 14 C further south, are somewhat shy of the 27 C needed for the storm to maintain hurricane intensity. The extratropical westerlies also contribute to tropical cyclone demise in our latitudes. The stronger vertical wind shears associated with these westerlies literally tear the symmetric warm-core tropical cyclone structure apart.

The structure changes that accompany tropical cyclone transition into mid-latitudes are qualitatively well known. There is a loss of the symmetric hurricane structure depicted in Fig. 1 as the storm takes on an extratropical structure. During the transformation, the organised cumulonimbus eye wall cloud vanishes as drier air becomes entrained into the inner storm circulation, which typically expands to cover a wider area. There is also a progressive loss of the distinctive concentric anticyclonic upper-level circulation and symmetric warm core structure. Often, the cyclone takes on a hybrid character in New Zealand latitudes. Typically, the cloud structure is asymmetric, with the most active cloud and precipitation to the south or southeast of the centre, but with the warmest low-level air near the centre remaining concentric with the low, as depicted in Fig. 8 for Cyclone Bola. As a rough rule, the cyclone moves toward the region of most active cloud, although its southward passage is often blocked by a developing anticyclone to the south. When this occurs, the moist easterly flow about its poleward side can intensify and remain over the same region for several days, as occurred with Cyclone Bola.

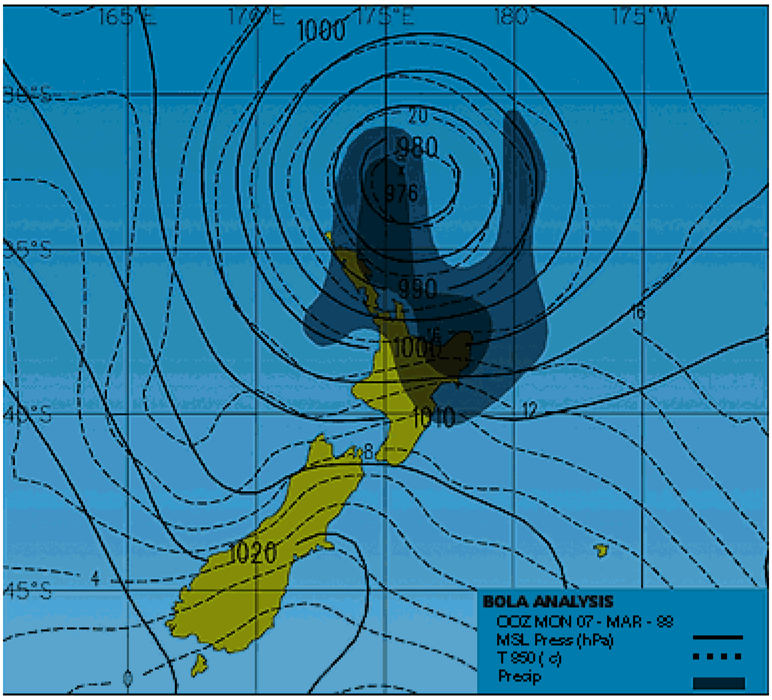



**FIGURE 8**
Sea level pressure chart for Cyclone Bola. Regions of precipitation (shaded) and temperatures at 850 hPa (around 1500 m) are added.

Despite the weakening that occurs as the storm centre moves poleward, strong winds and torrential rain can still occur with these tropical cyclone remnants. Many of New Zealand's most memorable weather events are associated with storms of tropical origin. Even after the cyclone is cut off from its heat and moisture supply, the intense vortex will take a few days to spin down. Large amounts of moisture are often retained in the circulation of the old tropical cyclone. When poleward motion is especially rapid, the vortex will retain much of its original strength when it arrives on our shores. Occasionally, when a tropical cyclone is captured by a particularly active trough in the westerlies, mid-latitude regeneration will occur. A combination of rapid southward motion and extratropical redevelopment accounted for the unusual intensity of Tropical Cyclone Gisele (the Wahine storm) as it crossed New Zealand in April 1968.

## FORECASTING DIFFICULTIES

One difficulty for weather forecasters is that many of the structure and motion changes as the cyclone moves out of the tropics can occur quite rapidly (over a few hours). Even predicting whether a tropical cyclone will migrate out of the tropics is a major forecasting problem. In most cases, a close encounter with a migratory trough in the mid-latitude westerlies provides the major impetus for motion into higher latitudes. As the cyclone is "captured" by the approaching trough, it moves rapidly poleward, embedded in the northerly airflow ahead (east) of the trough. However, another common scenario is for the trough to sweep past the cyclone, destroying its symmetric hurricane structure in the process, but then stranding the decaying cyclone in the tropics. Unfortunately, it is often difficult to discern in advance which of these scenarios will occur as a trough approaches. The forecasting problem is further hampered by the sparse observational network in the subtropical region north of New Zealand. In addition, the atmosphere is inherently less predictable in the vicinity of precipitating tropical air masses because of the huge, but not directly measurable, amounts of latent heat released into the atmosphere during condensation.

## PRECIPITATION AND FLOODING

Precipitation forms in rising air masses, as air parcels cool and condense out excess moisture. The uplift responsible for precipitation formation tends to occur in conjunction with cyclones, usually within organised cloud bands that are clearly visible in satellite imagery. However, rising motion is greatly augmented where air is forced to ascend over elevated terrain. This occurs when a persistent, humid airflow impinges at right angles to the ranges, with rainfall amounts rising with increasing cross-mountain wind speed.

Flooding of rivers and other waterways is dependent on catchment properties as well as on rainfall intensity. Rain water will quickly run off steep alpine catchments devoid of vegetation, with rivers rising quickly (within three hours) from the onset of heavy rain. Flooding can be heightened if snowmelt also occurs, or where the ground is already saturated from a previous storm. In cooler air masses, some of the precipitation may remain on the ground as snow, reducing and delaying runoff.

Precipitation will fall as snow to very low levels in sufficiently cold air. There are two main classes of snow bearing storm. When an extratropical cyclone or front originating over the Southern Ocean moves rapidly northeastward onto New Zealand, snow and small hail typically occurs in shower form. More widespread and heavy snowfall can occur in association with the warm front of a more active cyclone centred near New Zealand that has entrained very cold air at low levels.

The overwhelming majority of all natural hazards insurance claims arise from flooding. There is now a good prospect to supplement commonly used monitoring strategies with quantitative heavy rainfall warnings days in advance of a storm to obtain valuable improvements in flood forecasts. These improved rainfall forecasts are now possible through advances in global computer models of the atmosphere. Mesoscale (small scale) models can now refine forecasts from global models to give more detailed information for individual catchments.

Precipitation (heavy rain and snow) is described in more detail in August Auer's article on page 20.

## WINDSTORMS

Windstorms commonly occur in association with intense cyclones, especially where the isobars are squeezed together by the close proximity of an adjacent high pressure system.

Local topographic effects can modify the airflow field considerably. Contrary to intuition, winds are often stronger to the lee of major mountain chains as air forced to ascend on the upwind side of the barrier rushes down the other side, augmented by air sinking out from higher levels. These downslope wind storms produce the record wind gusts in New Zealand. Where air impinges on a particularly steep alpine barrier, it sometimes deviates to flow along rather than over it, producing a low-level barrier jet. Southwesterly gales along the Kaikoura and Wairarapa coasts and northeasterlies along the South Island west coast are common manifestations of barrier jets.

Strong winds are also common near the ends of major topographic barriers (southern Fiordland, Cook Strait, East Cape), while topographic funnelling can give rise to extreme winds in such places as Cook Strait, Manawatu Gorge and inland valleys. Recent advances in computer technology make it now possible to realistically model the airflow over New Zealand's rugged terrain on scales down to a few kilometres, increasing the potential for improved forecasts of these phenomena.

Windstorms are described in more detail in Steve Reid and Richard Turner's article on page 24.

# Storms from the Tropics

by Erick Brenstrum
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**After a number of relatively quiet summers the visits of two decaying cyclones to the North Island in quick succession last summer has focused attention on just how destructive cyclones can be.**

Cyclone Fergus, coming between Christmas and New Year, brought torrential rain and damaging winds to parts of the North Island and triggered a major exodus from coastal camping grounds as thousands of people got out of its way. Over 300 mm of rain fell in 24 hours over Coromandel causing flooding and landslides. Heavy rain also fell over Northland and Auckland and a large slip closed State Highway 1 in the Brynderwyn Hills. The wind was at its worst near East Cape where a house was destroyed. Fortunately, there was no loss of life, in part because of timely warnings about the ferocity of the storms.

A fortnight later, Cyclone Drena hit the North Island causing more wind damage than Fergus but bringing less rain. The combination of wind and extremely high tides caused millions of dollars of damage at Thames, where the waves came over a seawall and inundated houses on a reclamation. Easterly winds of 90 km/h the day before had helped pile up water against the coast near Auckland. Without losing much of its strength, the wind swung around to the north, pushing the excess water southwards into the Firth of Thames and dangerously increasing the sea level there. The waves on top of the higher-than-normal sea did the rest.

**CYCLONE SHELTER** *Photo: New Zealand Herald.*
Evacuees pass time in emergency accommodation during Cyclone Fergus, in the Coromandel.

Cyclone Drena claimed one life in Auckland, when a man was electrocuted. He had grasped a fallen power line in order to pull himself up a bank.

During the summer the Pacific was influenced by a weak La Niña event which caused the airflow over the North Island to be from the northeast more often than normal. This helped steer Fergus and Drena over the North Island.

**CYCLONE DRENA** *Photo: New Zealand Herald.*
Huge waves lash container wharves in Auckland, during Cyclone Drena.

Tropical cyclones are revolving storms, about half the size of a mid-latitude depression of the sort commonly experienced in New Zealand, but with a pressure gradient about ten times greater. If you drew all the isobars around a tropical cyclone on the weather map, they would be so close together near the centre that they would touch, leaving just a blob of black ink on the page.

When tropical cyclones move away from the tropics towards New Zealand they gradually weaken as the cooler seas provide less heat to sustain them.
However, occasionally they have a second burst of development if they meet a cold front in an active trough in the westerlies near New Zealand, which transforms the tropical cyclone into an intense mid-latitude depression.

During this change the cyclone loses its eye wall and the belt of extreme winds surrounding it weakens. However, the area of gale and storm force winds becomes larger sometimes by a factor of four. Consequently, although the strongest winds associated with the cyclone may now be weaker than before, they are often 500 km or more away from the centre of low pressure. Usually with a tropical cyclone the damaging winds are within about 100 km of the centre, and the maximum winds within about 30 km.

This is one reason these storms are not referred to as hurricanes, or even tropical cyclones, once they reach New Zealand's latitudes. In the tropics these storms are small enough for ships to be able to take evasive action and get out of their way if given sufficient warning, but in our part of the world the area of strongest winds is usually too large to be sidestepped and ships just have to ride it out, unless they can shelter in the lee of the land.

When winds of hurricane force are expected in New Zealand latitudes they are described in a storm warning, with the actual wind speed expected given in knots. Using the term hurricane carries the risk that it may be interpreted to mean that the only danger is close to the centre of lowest pressure.

The worst of these storms to affect New Zealand often occur in the second half of summer or in autumn. This is because sea surface temperatures remain high in autumn, allowing the tropical cyclones to retain intensity for longer as they travel away from the tropics, and the chance of encountering an outbreak of cold air surging up from the Antarctic increases as autumn progresses.

## NEW ZEALAND'S WORST STORM THIS CENTURY

Cyclone Bola caused extensive flood and wind damage in March 1988, and Cyclone Gisele sank the Wahine in April 1968. They were both examples of decaying tropical cyclones. So too was the great storm of February 1936, which has largely fallen from popular memory, but was arguably the most damaging storm to strike New Zealand this century.

This tropical cyclone formed south of the Solomon Islands on January 28, 1936, then moved southeast to pass between New Caledonia and Vanuatu. It met up with a cold front north of New Zealand on January 31, and intensified and crossed the North Island on February 2. It was not assigned a name as the practice of routinely naming tropical cyclones did not begin until 1963.

Heavy rain fell over the entire North Island, bringing most of the major rivers into flood. The Mangakahia River in Northland rose 19 metres at Titoki. Kaitaia's main street was flooded a metre deep and one man was drowned when a house washed away. Another man was killed in the Coromandel near Thames when his hut was carried into a flooded stream by a slip.

**DAMAGE** *Photo: New Zealand Free Lance Collection, Alexander Turnbull Library, Wellington, NZ.*
Coastal steamer John, driven ashore by the Hutt Road, Wellington, February 1936

In Whangarei almost 300 mm of rain fell in 24 hours and flood waters ran through the business district, tearing up footpaths and entering buildings. At Waitangi the water rose two and a half metres in twenty minutes, forcing eight men sleeping on the floor of the Tung Oil Company cookhouse to take refuge on the roof. When the structure began to move they clambered into a tree overhanging the cookhouse, which was later carried away by the flood.

A train was marooned by washouts near Kaikohe and a railway bridge north of Whangarei was destroyed, stopping rail traffic for days. Torrential rain fell on the slopes of Mount Pirongia between Kawhia and Te Awamutu, causing flash floods in the streams and gullies running down its flanks. A huge landslide fell across the valley floor of the Ngutunui stream, holding the floodwater up like a dam. When the increased pressure carried away the obstacle, an enormous body of water swept down the river bed with irresistible force, carrying away a large bridge and damaging four kilometres of road. Both banks of the river were swept clean of soil and vegetation.

One observer saw rimu and kahikatea trees borne along by the torrent rear up when their roots or branches caught against some obstacle, and topple end over end, with a crash that could be heard a long way off. When the water subsided, he picked up 40 dead trout and counted hundreds of dead eels killed by the rushing timber and large boulders carried along by the flood.
Drowned sheep, cattle, pigs, and chickens, mingled with trees, were a common sight in rivers all over the North Island.

In Hawkes Bay, the Tukituki river flooded the settlement of Clive, cutting the road and rail link between Napier and Hastings, and drowning 1500 sheep in stockyards. The Tukituki also broke its banks at Waipukurau, forcing the evacuation of 70 houses and drowning thousands of cattle and sheep. The Esk River flooded to over a kilometre wide, and began to flow down an old channel, threatening the township there, until the river mouth, which had been closed by the high sea, was reopened.

Roads and railways were inundated by floods and undermined by washouts, bridges were destroyed, and slips came down in their thousands all over the North Island. Near Stratford the main trunk railway line was blocked by more than a dozen slips, the biggest of which was 500 metres long. Another slip diverted a stream so that it flowed a metre deep through a tunnel, leaving it strewn with driftwood.

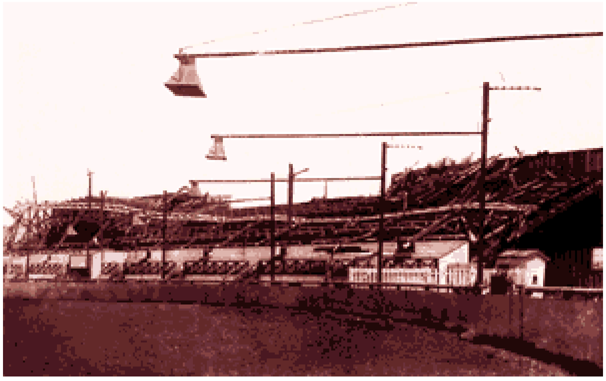
The Whanganui river flooded thousands of acres of farmland, entered a number of houses, and carried away two spans of the Shell Oil Company wharf. The Okehu water pipeline was cut, leaving the city with only one day's supply. The Whangaehu river rose almost two metres in half an hour, drowning hundreds of sheep and flowing through the Whangaehu hotel.

In the Wairarapa, the Ruamahanga river flooded farmland, cutting off Martinborough, and the Waipoua flooded several streets in Masterton. The Waiohine river flowed over the main highway for a time, and the Rimutuka road was blocked by a large slip.

Storm surge occurred along the east coast of the North Island, causing extreme high tides topped by large waves. At Te Kaha in the Bay of Plenty a sea higher than any in living memory washed a house into the ocean and swept away eight fishing boats. The road was washed away in some places, and in others covered by heavy logs and piles of driftwood.

Near East Cape, huge seas entered the estuary of the Awatere river and smashed a portion of a factory at Te Araroa. At Castlepoint on the Wairarapa coast the sea washed away the sand hills and invaded houses a hundred metres inland.

The wind blew in windows from Kaitaia to Picton, and brought down hundreds of thousands of trees, cutting power, telephone, and telegraph lines all over the North Island.



**STORM DAMAGE** *Photo: New Zealand Free Lance Collection, Alexander Turnbull Library, Wellington, NZ.* Remains of the members' stand at the Show Ground, Palmerston North, February 1936.

Palmerston North was hardest hit. Houses lost roofs, chimneys were blown over, and the grandstands of the A&P Association, the Awapuni Racecourse, and the Sports ground were demolished. A man was killed when he was blown off his roof as he was trying to repair it. Hoardings, fences, and brick walls were blown over. Twenty-eight trees came down over the main power lines in a 120 metre stretch of road. The Manawatu river rose five metres and flooded the Taonui Basin, turning it into an inland sea.

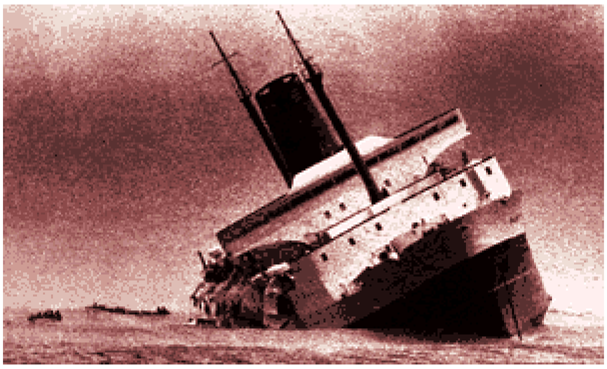
A train was derailed near Makerua, just south of Palmerston North. The last two carriages and the guards van were caught by a gust of wind and thrown down a bank into the Makerua swamp. Empty railway wagons on sidings at Levin and Linton were blown over and the small railway station at Karere was destroyed. Fallen trees blocked the line between Levin and Otaki, and passengers had to cut through them with axes before trains could pass.

At Longburn, the Anglican church was demolished and scattered over the road and railway line. A hall lost its roof, as did a nearby house where the chimney also fell in. A horse on a nearby farm was cut in half by a flying sheet of corrugated iron. The Feilding Aero club hanger was blown away and the two planes inside it destroyed.

Buildings were also destroyed in Taranaki. In Inglewood the badminton hall blew down and the Anglican church lost its roof. In New Plymouth the Frankleigh Park hall was destroyed, while in Waitara a number of large buildings disintegrated, and a 25 metre steel and brick chimney was blown over, as was the Harbour Board beacon tower.

The wind wrought havoc in orchards all over the North Island, destroying large portions of crops. Fields of maize, wheat, and oats were flattened from Northland to Marlborough, haystacks blew away, and in Pukekohe potato plants were sheared off at ground level.
A hunter and a tramper died of exposure in the Tararua Ranges, north of Wellington. At the height of the storm, trees were being uprooted from the ridges and thrown into the valleys, and the Waiopehu hut was blown into a gully. Trampers described whirlwinds in the gale twisting the crowns of trees around until the branches splintered off. The trunks of some of these trees are still standing today, more than 60 years after they died.

In Auckland 40 boats were sunk or driven ashore in the Waitemata Harbour and several more in the Manukau Harbour. In Cornwall Park hundreds of trees were snapped off or uprooted, accompanied by sounds likened to cannon fire. Falling trees brought down power lines in all suburbs and also delayed the trams. The Auckland Gliding Club hangar disintegrated and all the gliders were destroyed: iron and wood were strewn over hundreds of metres and one wing was blown a kilometre away.



**MARITIME DISASTER** *Photo: The Evening*
Fifty-one lives were lost when the Wahine sank at the entrance to Wellington harbour on April 10, 1968.

A fishing launch from New Plymouth was lost at sea and the crew presumed drowned. Numerous small boats were wrecked in Wellington Harbour and a coastal steamer was driven ashore near the city, at Kaiwharawhara.

Disaster was only narrowly averted when the inter-island ferry Rangatira steamed into rocks near the mouth of Wellington Harbour. After twenty minutes stuck fast she was able to reverse off the rocks then turn, and back slowly up the harbour. Taking water in through gaping holes in her bow, her propellers were half out of the water by the time she grounded next to Clyde Quay wharf, and her forward passenger decks were awash. Fortunately none of the 800 passengers and crew suffered serious injury, although many were plainly terrified by their experience.

Just as Drena followed Fergus last summer, the great storm of February 1936 was followed by another in March 1936, which affected a smaller area of the North Island, but caused more damage in some places.

Thirty-two years later, the fate the Rangatira escaped befell the inter-island ferry Wahine, when the remains of another tropical cyclone reached New Zealand. Although warned of the possibility of southerly winds in excess of 110 km/h occurring in Cook Strait as the low pressure zone passed over the North Island, the Wahine attempted to enter Wellington Harbour in deteriorating conditions. As she crossed Cook Strait, her barometer dropped 5.6 hPa in just over an hour and the gale force wind was rapidly intensifying. The waves were rising, causing difficulty in steering the ship even when it was still in deep water 45 minutes south of the harbour. As the Wahine moved into the shallow waters of the harbour mouth she was struck by several large waves. One broke over her stern and another rolled her partly on her side and swung her sharply off course. About this time, for reasons unknown, she lost the use of her radar. She became disorientated in poor visibility and manoeuvred in the harbour mouth for almost half an hour before striking Barretts Reef. Seven hours later she sank with the loss of 51 lives.
Although the worst of these storms from the tropics may only occur in New Zealand once or twice in a lifetime, their powers of destruction are so great, that they are remembered forever by the people who live through them.

# Heavy Rain and Snowstorms

## *Causes and Effects*

by Erick Brenstrum
Lead Forecaster, Meteorological Service of New Zealand, Ltd.

**THE BIG SNOW** *Photo: Christchurch Press.*
Christchurch City, under heavy snowfall, July 1992.

At New Zealand's latitude most raindrops begin their lives as snowflakes. More than 95 percent of precipitation over New Zealand is initiated by means of the 'ice crystal' mechanism, and whether it falls as rain or snow may depend, quite simply, on the temperature at the ground.

## How raindrops and snowflakes develop in clouds

The fascinating process which meteorologists call cloud physics produces heavy rain or snow. Though the two outcomes may be vastly different, both have similar beginnings in the clouds that foster them. Both cloud and precipitation development depend on ascending motion, whether that is associated with a depression, lifting over terrain, or within the updraft of thunderstorms.

When air, for example, ascends along the conveyor belt of a large depression, it cools by expansion and, as it cools, the relative humidity increases. When the relative humidity approaches saturation at 100 percent, tiny water droplets begin to form in dense concentrations, that we identify as the cloud base.

Nearly all of the rain or snow that falls to the ground is produced in the lower two-thirds of these clouds. Observations show that the cloud droplets do not all freeze at 0 C as they are carried aloft. Rather, because of impurities, the temperature at which they turn to ice is often much colder. Any liquid droplets that exist at temperatures colder than 0 C are said to be supercooled. Clouds with tops at temperatures between 0 and -4 C generally consist entirely of supercooled droplets. When cloud top temperatures drop to -10 C there is about a 50 percent probability of detecting embryo ice crystals, and for cloud top temperatures below -20 C there is better than 95 percent probability.

That region of a cloud that contains a mixture of water droplets and embryo ice crystals is of particular importance to the production of any rain or snow. Since the saturation vapour pressure over ice is slightly but significantly lower than that over water at temperatures colder than 0 C, vapour evaporates from the droplets and condenses on the developing ice crystals. Consequently, in mixed clouds ice crystals grow from the vapour phase much more rapidly than do the droplets, and at the expense of the droplets. This mechanism is often called the Bergeron effect, after Tor Bergeron, a Norwegian meteorologist who discovered it in 1928.

**PALMERSTON NORTH** *Photo: The Evening Standard.*
Flooding in the Amberly Avenue area, Palmerston North, July 1988.

Ice crystals growing by the Bergeron mechanism can assume a variety of shapes (or habits) and growth rates, according to the temperature at which they reside. Snow crystals are famous for their variety of six-pointed shapes and it is probably true that no two are alike. But only certain types of snow crystals are crucial to the production of heavy snowfall. At temperatures between -12 and -18 C, the shapes are most embellished and their growth is the fastest. This is the habitat of the familiar "Christmas-type" ice crystal of hexagonal dendritic shape (from the Greek, meaning 'branched like a tree') with fern like branches. Only between these temperatures do the small ice crystals quickly grow to the proper size and shape to collide with one another to build snow flakes, creating a proverbial blizzard inside the cloud.

Eventually, the snowflakes become heavy enough to fall from the cloud, and within 20 minutes they reach the earth. During most heavy snowfalls, this temperature band is just 4 km above the ground, and often at lower altitudes over mountains like the Southern Alps.

But the optimisation of this process also depends upon the temperature of the humid air entering the cloud at its base, and the altitude at which the process is operating. This is especially important during heavy rain events. For example, large amounts of warm, humid sub-tropical air must now be lifted higher, to near 7 km, in order to be transformed by the

Bergeron process into snow at that level, before falling to earth as heavy rain. This most likely happens during summer, and/or in northern New Zealand. For heavy snowfalls, on the other hand, the humid air might only need to be lifted to 4 km during the colder months, at southern districts, and/or near mountain tops.

**SOUTH CANTERBURY** *Photo: John Fridd, Central Otago News.*
A flock of merino wethers enjoy their first meal of hay in several days after being brought off the hillsabove Burkes Pass, South Canterbury, July 1992. Heavy snow falls caused severe stock losses and much distress to farmers around the region.

It is now evident that crucial amounts of supercooled water must be delivered to the critical temperature zone between -12 C to -18 C within the ascending airflow of the depression, creating the trillions of snowflakes needed for heavy snowfall or rainfall. The extent of such a zone is not always that large either. Most heavy snowfalls are only 100 km wide at any one time, but spread over the countryside like paint from a brush, so that by the end of the storm several districts may have been affected.

## Orographic effects and thunderstorms

While depressions are the principal way to lift air to the critical temperature regime, New Zealand is unique in another manner of forcing air upwards. Orographic effects, where mountains force air upwards as strong winds impact against the hills, provide an extra component of rising air which may add to the cyclonic effect.

Often, a ribbon of humid air rising over elevated terrain, like the windward side of the Southern Alps, the Tararua Ranges, or Mount Egmont, can be lifted sufficiently to allow clouds to form and the Bergeron process to become active. When prevailing winds are forced upwards by the mountains, a belt of heavy rainfall can be produced on the upper slopes of the windward side.

Thunderstorms, with their huge updrafts (vertical columns of rising air), can deliver copious amounts of supercooled cloud water to the -12 to -18 C region as well. The clouds and rain of a cyclonic depression can pass over New Zealand in few hours, but the persistence of heavy orographic rainfall can last many hours if the wind flow and necessary temperatures are unchanged.

**Snowstorm effects**

Snowflakes can often be observed at the ground at up to +5 C. More commonly, though, during the onset of heavy snowfall events, light rain first falls and gradually changes to moderate or heavy snow. This is because the snow falling from above begins to melt and form raindrops. However, in doing so, it takes heat from the air, cooling the air, and allowing the snow to then fall to lower elevations. During heavy snowfalls, this lowering of the melting level can take place over hundreds of metres, so that snowfall that begins at 700 m can lower to 200 m during the height of the storm. This is why weather forecasts may call for " snow at 700 m, lowering to 200 m through the day."

The density of snow can also vary from storm to storm. People often comment about the weight of the snow, or say that "it's a heavy snow". While the depth of snow is often reported, meteorologists and hydrologists are also interested to know the water content of the snow, or what depth of water in millimetres would result if the snow was entirely melted. Heavy snowfalls in New Zealand have been known to cause roofs to collapse because of the weight of water content of the snow, which, if it were water, would have drained away. The depth of snow compared to its equivalent depth of water is called the snow-melt water ratio, and ranges from 5:1 for heavy snows falling at temperatures near freezing, to as high as 20:1 for light fluffy powder snow sought after by skiers. An average value of 10:1 is used by weather forecasters as a first guess in estimating how much snow will fall.

Farming and transport would appear to be the two industries most impacted by heavy snowfalls. As little as 4 cm of fresh snow on the Desert Road can cause disruption to travel and road closures. But the largest threat to economic loss from heavy snowfall impacts on sheep farming, especially during lambing season. Heavy snowfall can stick to the fleece of ewes and newborn lambs. This increases the risk of hypothermia and hinders them from foraging for food that is snow-covered or distant.

**Heavy rain effects**

Heavy rain and flash floods are frequent events in New Zealand. Rainfalls of up to 500 mm in 24 hours occur in the Southern Alps above Hokitika at least once in every five years, as do events of 200 mm in three hours! In the upper reaches of the Tararuas, falls of 100 mm in just three hours can be expected once every three years. In central Otago a few years ago, 80 mm fell in just 45 minutes from a large slow moving thunderstorm, filling streams and rolling boulders the size of small cars downstream. But the record one hour rate belongs to Whenuapai with 107 mm falling in one hour on 16 February 1966, causing local flooding and road washouts.

Many of New Zealand's streams and rivers can show a runoff response to heavy rainfall about four hours after the event, so timely warnings are critical.

Under certain conditions, the intensity and duration of the rainfall can increase with elevation as the cloudy air is forced over the terrain. So when heavy rainfalls are being recorded at the feet of mountain ranges, it is often raining twice as much near the crests.

## The challenge for forecasters

The challenge, then, for weather forecasters is to determine if all the necessary ingredients will come together in the proper proportions, at the right time and place as clouds move across or develop over New Zealand. They must decide as a cyclonic system moves over the country whether precipitation will be produced by cyclonic and/or orographic lifting, and whether thunderstorms will form. Ultimately, wherever significant ascent occurs over New Zealand with the proper cloud physics, heavy precipitation is likely to occur. Temperatures must be considered, to discriminate between a rain or snow event.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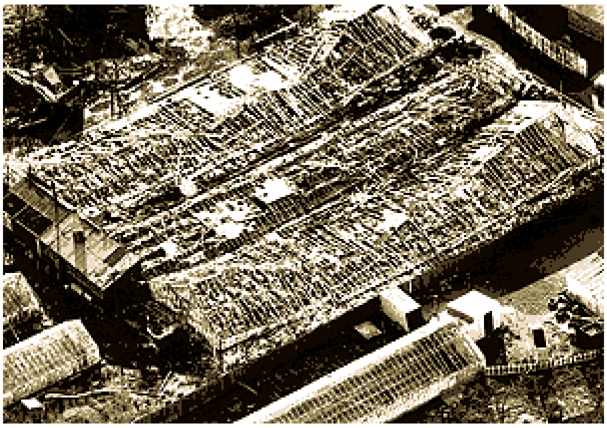
Downslope windstorms, squall lines, tornadoes, and tropical cyclones are weather phenomena that produce severe and damaging winds in New Zealand. In fact, the frequent strong winds experienced following the passage of mid-latitude depressions are responsible for New Zealand's reputation as a windy country. It may therefore be surprising to learn that the strongest winds in New Zealand, caused by downslope wind storms, have occurred at seemingly sheltered lee-slope locations in inland areas of the South Island. Thunderstorm related phenomena such as squall lines and downbursts are responsible for some of the records in the North Island, while others are due to strong cyclonic storms. Tornadoes and water spouts also produce hazardous winds, but their damage paths are very localised. Tropical cyclones occasionally affect New Zealand and they too are associated with extreme winds.

## DOWNSLOPE WIND STORMS

Wind hazards associated with orography are often caused by lee slope phenomena such as rotors, trapped lee waves, and downslope windstorms. Downslope windstorms are usually the most severe of these phenomena, as was amply demonstrated during the windstorm of August 1, 1975 which caused widespread damage to forests and structures east of the Southern Alps (Hill, 1979). The highest recorded wind speed was a gust of 195 km/h at Kaikoura. Strong winds in this storm were not confined to the immediate lee slopes but also affected more distant locations. The storm produced almost as many all-time records as the Wahine storm. Other kinds of wind hazards associated with topography, as any motorist towing a caravan through the Manawatu gorge or Waitaki valley will attest to, relate to the funnelling effect that accelerates air flows down gorges, creek beds and river valleys.

Other notable wind storms in the lee of ranges have also affected New Zealand. Te Aroha, in the North Island, was hit by two devastating windstorms, in 1936 and 1978, which were almost certainly caused by downslope windstorms. Te Aroha is situated near the base of a steep lee escarpment of the Kaimai Range. This geographical arrangement is ideal for Te Aroha to experience enhanced downslope winds during periods of strong easterlies. Lee-slope wind storms are quite localised on some occasions, as evidenced by the very strong winds in inland Canterbury on October 15, 1988, which blew down the power line supplying the Cook Strait cable.



**WIND DAMAGE** *Photo: Christchurch Press.*
Damaged glasshouses after a servere windstorm, Christchurch, July 1995.

No high wind speeds were measured at any recording station on this day. Instances of the highest wind speeds in storms occurring on the lee sides of mountain ranges are common throughout New Zealand. Further research on this type of storm is essential for an understanding of the New Zealand wind climate. An improved wind climatology would have benefits in the planning of forests and in the design of exposed structures such as power pylons.

Apart from the climatology, an understanding of the physical mechanisms responsible for wind storms is important for forecasters attempting their prediction. A simple qualitative understanding of these physical mechanisms can be gained by recognising the similarities between disturbances created when an object is towed through water and those created when air flows past a range of mountains. The nature of these "wake" or lee-side disturbances depends on the speed of the background flow, the degree of atmospheric stability and the nature of the underlying topography. For example, the steeper the lee-slope, the more severe the downslope winds. A parameter combining these three factors which indicates the type of expected flow disturbance is called the Froude number (see Fig. 1).

The different kind of flows that occur for different Froude numbers are shown in Figure 1. For low Froude number flows, i.e., Fr = 0.1 (perhaps due to the existence of very stable conditions) vertical motions and turbulence are strongly inhibited and the air is forced to flow around the mountains. No mountain wave activity is expected in this case, however channelling effects through passes and gorges may become pronounced.

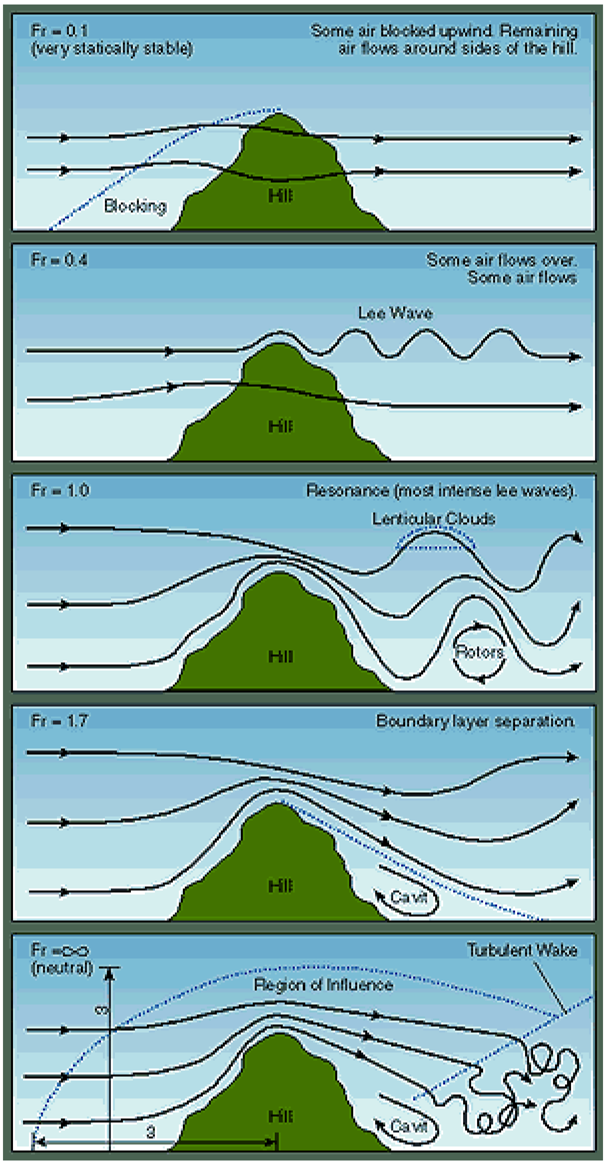



**FIGURE 1**
VARIOUS FLOWS THAT OCCUR OVER OROGRAPHY FOR
DIFFERENT VALUES OF THE FROUDE NUMBER
The Froude number (Fr) is often given by the expression:
Fr = PiV / NW
where V is the mean wind speed of the background flow, W is the width of the mountain barrier and N is the Brunt Vaisala frequency. The Froude number can be thought of as the ratio of the natural wavelength of the air to the natural wavelength of the terrain. The Brunt Vaisala frequency is a measure of atmospheric stability. Larger values of N indicate a greater degree of stability.
Source: Sturman and Tapper, 1996.

The Froude number can also be low when wind speeds are low and the mountain is large. In this case air is forced to flow around the mountain, because it has insufficient strength to rise over the summit. For slightly higher Froude numbers, i.e., Fr = 0.4, some air passes around the mountain, and some air is able to flow over the mountain generating a sequence of downstream gravity waves (lee waves). These waves are often evident by a series of arc shaped clouds spaced between 3 and 25 km apart occurring downstream of a mountain range. Clear air turbulence can be associated with these waves but this may only become a hazard as the intensity of the waves increase as the Froude number increases.
The most intense waves occur when the Froude number is close to 1. At this point resonance can occur as the frequency of the forcing (i.e. the
time it takes an air parcel to traverse the mountain) matches the natural frequency of the atmosphere (i.e. N). Downslope windstorms and rotors occur under this regime.
As the Froude number becomes much larger than 1, i.e., as the background wind speed increases or the atmosphere becomes less stable (or both), only one wave crest is evident, and the flow is characterised by a separation of the lee-side boundary layer from the fast moving atmosphere above with a turbulent wake further downstream.

Researchers from NIWA and the University of Auckland have conducted studies in the Mount Cook region (Revell et al, 1996) to learn more about the wind gusts and surface wind surges associated with large lee-side eddies (of around 1 km in scale) that occur in this latter regime. This research forms part of the NIWA-coordinated SALPEX mountain meteorology research campaign.

SALPEX participants aim to better understand processes leading to strong downslope winds and to test and improve computer models for predicting them. Their work will lead to better forecasts of strong winds, and better information on the associated risks to buildings and other structures.

Many structural similarities between hydraulic jumps in water tanks and downslope windstorms in the atmosphere have been observed. Such similarities lead us to deeper understanding of how downslope windstorms are produced when the Froude number is close to 1. Consider the following explanation which applies to Fig. 2. For flows where Fr > 1 (called supercritical flow), the flow will decelerate and deepen during ascent of the mountain, however it will accelerate and thin as it goes down the slope. For subcritical flow (Fr < 1), the opposite is true, acceleration and thinning of the fluid occurs as the crest is approached followed by a deceleration along the downslope. In some cases of subcritical flow, when Fr is only just less than 1, the fluid may be accelerated and thinned sufficiently during ascent to cause a transition to supercritical flow. In this case air traversing the mountain will be accelerated at all times, thus very high downslope wind speeds can be attained. In these situations hydraulic jumps will occur, marking the transition from the supercritical high speed downslope flow to the pre-existing slower downstream subcritical flow regime.

One difficulty with this "hydraulic analogue" explanation is that it requires the existence of a free surface, since a thinning and thickening of the flow is necessary to allow for the transition from subcritical to supercritical flow. The atmosphere, unlike a body of water, does not have a free surface so such a thinning and thickening of the fluid is not possible. However, sometimes levels with strong gradients in temperature and winds exist in the atmosphere and these levels can be thought of as dividing the atmosphere into distinct layers. These dividing levels may then act like a free surface. It is thought that the breaking of large amplitude mountain waves can create a level of flow reversal above the crests of mountains, which therefore produces the required free surface.

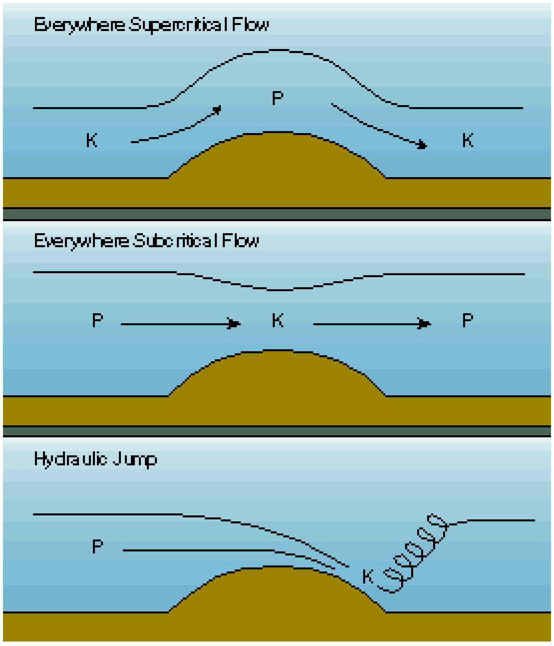



**FIGURE 2**
BEHAVIOUR OF A SHALLOW FLUID FLOWING OVER AN OBSTACLE
(Adapted from Durran, 1990)

Some scientists discount the hydraulic-analogue theory, and argue that it is the breaking of the large amplitude mountain waves alone that produce the downslope windstorms. This view has been supported by computer simulations which showed that surface gustiness within a windstorm resulted from the direct advection (transfer by flow of air) of turbulence from the wave-breaking region aloft.

Much of the motivation for the research which has led to advances in the understanding of lee wave phenomena comes from a desire to improve forecasts of turbulence and windstorms about mountain ranges such as the Southern Alps. In spite of these advances in our understanding, it is still very difficult for a forecaster to assess the potential for wave development, or predict in detail the strength, duration and location of mountain wave activity on the basis of antecedent environmental conditions. However, it has been encouraging to note that the inclusion of the drag (i.e. braking) effect of mountain waves on the winds in large-scale numerical weather prediction models has improved their accuracy. Such developments have given hope that high-resolution atmospheric models may allow for improvements in the operational forecasting of mountain wave activity. Researchers at NIWA are currently using the Regional Atmospheric Modelling System (RAMS) to investigate this issue.

**RESEARCH AIRCRAFT** *Photo: NIWA*
The Australian research aircraft used for making measurements during the SALPEX '96 wind and rainfall research campaign.

## WINDS FROM THUNDERSTORMS

As mentioned earlier, thunderstorm related phenomena, such as squall lines, downbursts, waterspouts, and tornadoes are another major cause of hazardous winds in New Zealand. Thunderstorm formation occurs in regions of convective instability, i.e. regions where there is potential for the development of strong updraughts (see Fig. 2 on convection). Such conditions commonly occur along frontal zones, within tropical cyclones, and on hot sticky summer days. Additionally, updraughts forced by the ascent of air over mountains may also trigger thunderstorms.

Cumulonimbus, or thunderstorm clouds often develop over the warm waters in the Tasman Sea and are carried onto western coasts of New Zealand. Their effects are shown by higher frequencies of thunderstorms in western and northern districts than in the east. Sometimes these thunderstorms become organised into squall lines, evidenced on satellite images by bands of cumulonimbus, which are accompanied by heavy rain and strong winds. Wind gusts associated with squall lines are responsible for some of the highest recorded winds in the north of New Zealand.

**WIND DAMAGE** *Photo: Waikato Times*
A Cooks Beach resident surveys wind damage to her property, August 1996.

For example, the highest wind speed at Auckland Airport was on September 6, 1981, where speeds in an intense squall reached 145 km/h. The passage of a squall was marked by the sudden onset of very high wind gusts followed by a gradual decrease in intensity over several minutes.

The high winds may result from strong thunderstorm downdraughts or they may result from the strong local pressure gradients that form along and behind the squall line. An area of low pressure, called the pre-squall mesolow, is often observed ahead of the squall line. As the squall line passes a large pressure jump accompanied by the onset of high winds is often observed. This region of high pressure is known as a mesohigh, and is formed by the accumulation of evaporative cooled air beneath the thunderstorms. Trailing the mesohigh is another area of low pressure called the wake-low. This region of low pressure is formed by the forced descent of warm dry air away from the thunderstorms. Squalls may also be experienced during the passage of tropical cyclones, and are also associated with southerly changes along the east side of New Zealand.

Another example of a squally occurrence was on April 24, 1991. This storm, which caused one fatality, was known as the 'Albany tornado' because it demolished a historic building in Albany. Whether there was an actual tornado associated with this storm is questioned by some scientists as strong winds associated with a long north-south band of cumulonimbus clouds (a squall line) were tracked passing through weather stationes between Whenuapai and Kaitaia around this time. While debate over the 'Albany tornado' exists, there is little doubt that many instances of wind damage in New Zealand have been mistakenly blamed on tornadoes. However, tornadoes do occur in New Zealand and they are capable of inflicting damage and destruction to property and lives. Fortunately for New Zealanders, the truly monster tornadoes, as depicted in the movie "Twister", occur mainly in the US Midwest. Tornadoes in New Zealand tend to rotate clockwise, the same way as tropical cyclones, and they too have low pressures at their centre. In fact the tornadoes' distinctive funnel cloud is formed because water vapour condenses more easily at low pressures. The reader should also note that it is the winds, not the low pressure, of a tornado that causes destruction to property. So if a tornado or waterspout is approaching your house, don't waste time opening windows, take cover immediately!

Scientists are still trying to figure out exactly what causes tornadoes. They know by conservation of angular momentum arguments, that if the radius of a slowly spinning column of air over a large area is decreased, perhaps by stretching of the vortex, then the spin rate will increase. Therefore, scientists have to determine what could cause the contraction of the spinning column, and what causes the column to spin in the first place. One possibility is that vertical wind shear (changes of wind speed with height) may cause air to rotate horizontally, and that strong updraughts may then tilt and stretch the columns into a vertically oriented position (see Fig. 3).

This sequence of events is often used to explain how the parent thunderstorm (mesocyclone) of the tornado gets its rotation, but how the tornado gets spawned from the mesocyclone is still not completely understood. Complicating matters is that not all tornadoes are spawned from mesocyclones and not all mesocyclones spawn tornadoes. Another poorly understood feature of tornadoes are the multiple suction vortices that often dance around the main vortex and which contain the most damaging winds within a tornado.

Water spouts resemble tornadoes in many respects and are often mistaken for them. However, they are much smaller and weaker and different physical mechanisms may be responsible for their existence. Intense updrafts and thunderstorms do not seem to be a requirement for their formation, although convection almost certainly is.

Downbursts are another way in which thunderstorms can produce damaging winds. Downbursts are plummeting downdraughts of cold, heavy air that collide with the earth. The damage pattern from a downburst often resembles that from an aerial bomb blast, e.g., trees at ground zero may remain standing, while those further away will be blown over in direction pointing away from the centre. Downbursts are an aviation hazard and caused a 1985 crash of a commercial airliner in Dallas, Texas. The problem for pilots is that as an aircraft enters a downburst, it suddenly loses lift. Pilots compensate for this by pulling the nose of the aircraft up. However, when the aircraft suddenly comes out of the downburst the compensating manoeuvre has left it vulnerable to stalling.

## TROPICAL CYCLONES

Tropical cyclones are synoptic-scale storms with tropical origins that have belts of sustained winds exceeding 63 km/h wrapped around a central area of low pressure. Intense tropical cyclones are often characterised by the existence of an area of relatively light winds, called the eye, at the centre of the storm. Immediately surrounding the eye is the eye wall, where there is an abrupt transition to the most severe conditions experienced in the storm. Here the winds are strongest and the rain is heaviest.

Similar, but less intense, conditions are also experienced in the spiral rain (or feeder) bands that are often readily identifiable in radar and satellite images of the storms. Away from the feeder bands and eye wall, broad regions of strong sustained winds are experienced. Within the feeder bands and eye wall region, tornadoes and other embedded vortex-like features are often spawned, and these are responsible for some of the most severe damage in cyclones.

In the southern hemisphere, the left front (relative to the cyclone and its motion) part of the storm is where the greatest wind damage is to be expected upon landfall of the cyclone, it is also the region in which the flooding from a storm surge can be expected. What causes the left front-sector to be favoured for tornado formation? It is known that the strong onshore winds in the left-front sector encounter greater frictional drag as they cross from ocean to land. This increased drag causes the wind to twist clockwise (i.e. cyclonically). Atmospheric scientists hypothesise that this cyclonic twisting creates an environment favourable for the development of tornadoes.

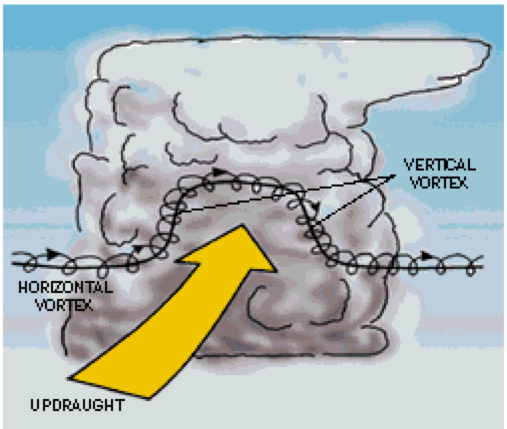



**FIGURE 3**
EFFECT OF STRONG UPDRAUGHTS IN TILTING HORIZONTAL VORTEX INTO THE VERTICAL (Adapted from Sturman and Tapper, 1996)
Convection: When rising parcels of warm moist air encounter cooler drier surroundings, they will continue to rise at an accelerated rate upwards. This is called convection. If these accelerations continue, the rapidly rising columns of air (called convective updraughts) will eventually form cumulonimbus clouds which may ultimately evolve into thunderstorms. Vertical speeds in some thunderstorm updraughts have been observed to exceed 180 km/h, but this was in the United States where thunderstorms and their updraughts are generally much more intense than in New Zealand. The reason being that over the US much sharper contrasts exist between the warm moist masses originating from the gulf of Mexico and the cool dry air masses of Canadian origin.

Tropical cyclones sometimes affect New Zealand in the season between December and May. They approach from the north and generally produce more severe effects in the North Island than the South Island. Many of New Zealand's best remembered storms originated in the tropics, sometimes (like Bola in 1988) evolving from small tropical storms into large mid-latitude storms near New Zealand. Others (like Ida in 1959) affected only the very northern parts of New Zealand, and some others (like Hal in 1978 and Gisele in 1968) more southern parts of the North Island. The latter became known in New Zealand as the Wahine storm. It was not a notable storm in the tropics but was quite intense in the vicinity of New Zealand.

Cyclone Gisele, during the evening of April 9 and the morning of April 10, 1968, travelled quickly southwards off the east coast of Northland, across Tauranga then moved towards Castlepoint. At 9 am, when wind speeds were close to their highest values at Wellington, it lay east of Cape Palliser.

In spite of Wellington's reputation for wind, no other recorded event has approached the speeds which were experienced in this storm, during which the interisland ferry Wahine sank in the entrance to Wellington Harbour. Winds in Auckland reached over 110 km/h. They were a little higher than speeds in Tauranga which was directly in the path of the storm. Fig. 4 shows the pressure at Tauranga over the 40 hour period during the passage of the Wahine storm. Pressures were high over New Zealand before the storm was close, but as it moved towards the country there was a gradual drop which became rapid as the storm centre approached. The centre passed over Tauranga about 4 am on April 10, 1968. There was a period of about an hour in which the pressure was almost constant. The wind speed fell away for a similar period and was calm for a period about fifteen minutes.

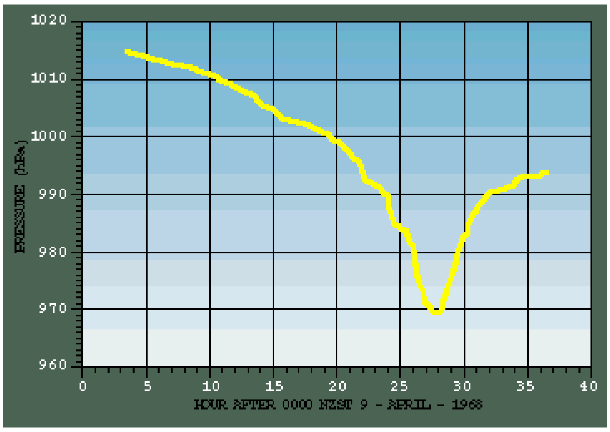



**FIGURE 4**
Time series of surface pressure at Tauranga on 9 10 April 1968. The series have been obtained from a scan of the barogram using a digitiser.

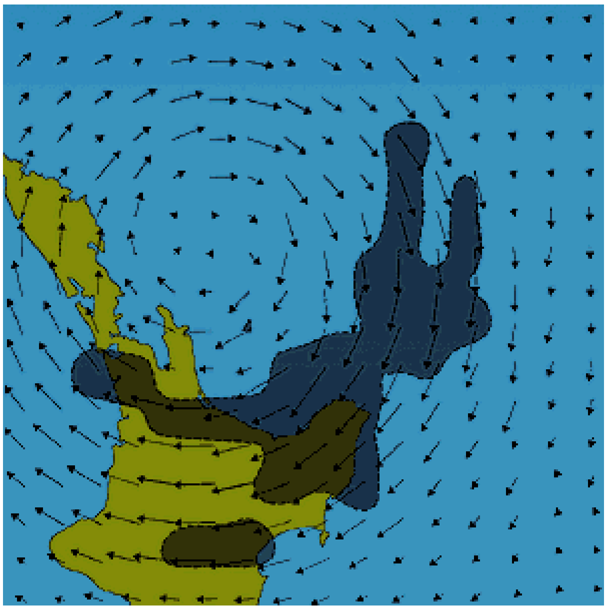


**FIGURE 5**
Grid point winds above the boundary layer calculated for 3 am on April 10, 1968 at 50 km spacings when the centre of the Wahine storm was just north of Tauranga. The wind direction is given by the arrow direction and the speed is proportional to the arrow length. The shaded region shows speeds over 110 km/h.

The sharp symmetrical trough as the cyclone centre passes Tauranga is strong evidence that the Wahine storm was a roughly circular system with a core of low wind speeds. The central pressure was typical of a moderate tropical cyclone; severe tropical cyclones can have central pressures as low as 920 hPa. The pressure distribution recorded as the centre moved south can, given the speed of translation, be used to derive the pressure gradient and hence the wind speed distribution. This has been carried out and the result is shown in Fig. 5 for a time at which the cyclone centre was over the Bay of Plenty. Winds are strongest in the eastern and southern sectors of the cyclone, with speeds aloft reaching between 110 and 145 km/h. Speeds at the surface would be less but are reduced by different amounts depending on the nature of the surface. The time sequence of predicted speeds at the position of the Tauranga anemometer has been checked against the observations and has been found to be quite similar.

As modelling capabilities improve it may be possible to determine what wind speeds could occur when storms similar to the Wahine storm affect different places in the future. It is unlikely that future storms will move along the same path, indeed, cyclone Bernie in 1982, which had a similar central pressure to the Wahine storm, moved along a south-easterly path well clear of New Zealand. Cyclone track charts show Auckland to be in an area with tropical cyclone frequencies intermediate between those in the areas around Brisbane (about 10 tropical cyclones cross the square covering 5 degrees of latitude by 5 degrees of longitude in 10 years there) and Sydney (two per 10 years). An increase in the frequency of tropical cyclones, as might occur with climatic warming, could become a constraint on Auckland's development.

**WIND DAMAGE** *Photo: Hawkes Bay Herald Tribune*
Uprooted macrocarpa tree after strong winds, Hawkes Bay, November 1996.

## WIND DATA AND DETERMINATION OR RISKS DUE TO EXTREME WINDS

In order to assess the susceptibility of different parts of New Zealand to severe winds, two main approaches are available.

First, studying meteorological databases, and other records, to determine the frequency at which high winds occur at different locations. The use of these databases is not straightforward, because the instrumental records suffer discontinuities in siting (different sites do not have the same exposure to the wind) and instrument type (different instruments respond in different ways to high winds). Qualitative wind records are not suitable for measuring intensity, but can be useful to determine spatial extent of high winds. Records of damage can provide valuable information, if it is known the wind speed that structures were capable of withstanding at the time of the storm.

Second, studying specific historical cases of weather systems known to have produced high wind speeds. These can help quantify the risks from extremely unusual events. For example, the Wahine storm produced the highest recorded wind speeds at most monitoring stations in the east and south of the North Island. By knowing the recurrence time of depressions of similar intensity and knowing the probability of different cyclone tracks, a calculation can be carried out to give expected wind speed frequencies over a period that is much longer than the instrumental data record.

When wind speeds are obtained from the same site over a long period, the measured wind speeds and their frequency above certain thresholds are directly useful for climatological purposes. A wind speed which is reached and exceeded, for example five times in one hundred years, is likely to continue recurring at this frequency and is called a 20 year return period speed. This can be used as a criterion, for example for building sway, because one occurrence of perceptible sway in 20 years might be acceptable where occurrences at monthly intervals would not.

The concept of a 20 year return period assumes that the climate is not changing; but any small shift in climate can potentially alter the return period of a particular speed by a large amount. However, in practice it is not usually possible to detect changes of frequency because of the difficulties outlined above. There are no records as far back as one hundred years in New Zealand because there were no instruments before 1912. Several records start about 1940, but are broken by instrumental and site changes. Lack of reliable data is always a difficulty in assessing the occurrence of extremes, and indeed any meteorological phenomenon. Moreover, the present day climate has such a wide range of irregularities of storm occurrence that it is a major task to represent it.

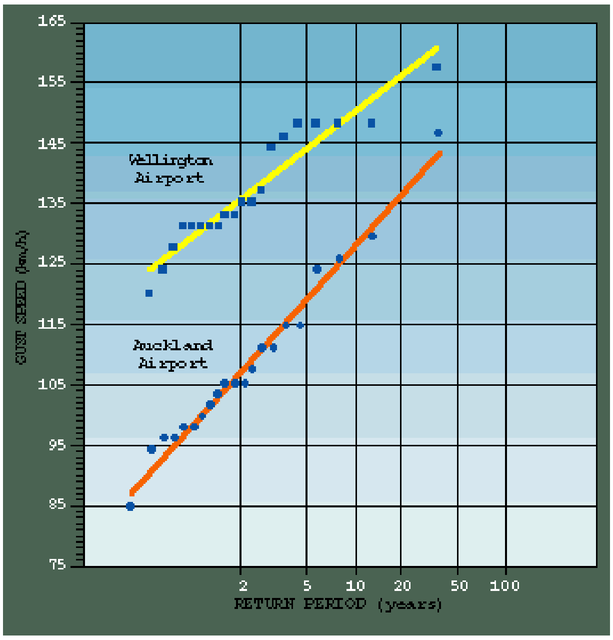



**FIGURE 6**
Extreme value plots of annual maximum wind gust speeds in the years 1972 to 1992 at Wellington and Auckland airports. Best fit lines have been drawn through the data points.

Meteorological practice is also important for determining what data are available for study of extremes. Most wind data is obtained for real-time monitoring associated with aircraft and marine operations, and applications to the study of extremes have not had a strong influence on the type of data collected. As a result, most digitised wind data consist of ten minute average speeds and directions obtained over just one ten minute period in each hour. Wind fluctuations over the remaining fifty minutes are unmonitored. This means that strong winds from short lived extreme events such as squall lines are often not observed. Winds in large-scale storms such as extratropical and tropical cyclones are well observed.

Meteorological practice from the 1940s to the early 1990s was to supplement the hourly reports with continuous charts or anemograms so all phenomena were recorded. Daily extreme wind gust speeds and directions at their time of occurrence were analysed from the anemograms and recorded. In the 1990s, these anemograph stations have been replaced and supplemented with Automatic Weather Stations (AWS) which do not produce anemograms so there is no longer backup information. However, many of the AWS stations are continuing to supply daily maximum gust data, but because of the different method of obtaining the maximum gust within the AWS, this data may not be compatible with the data obtained from the anemograms. At present, data series are too short to verify this.

New Zealand maximum gust data from 1972 to 1992 have been used in the analyses below. This period provides the most complete set of gust data available, and ends before the removal of the anemograph stations. Fig. 6 gives analyses of gust speeds from two reasonably long wind records from sites at airports. Although both sites have been moved small distances, the open airfield locations mean that there is likely to have been fairly constant exposure.

Fig. 6 suggests that at long return periods, wind speeds at Auckland and Wellington should approach each other, although at short return periods Wellington is very much windier than Auckland. An extrapolation which leads to the conclusion that Auckland is windier than Wellington at long return periods is not verifiable because it is possible that the relationships become curved outside the range of the data.

Wind speed extremes at certain return periods are used for design purposes, so that structures, built using them, can be expected to withstand wind loads during their lifetimes. The methodology for calculating values of the winds over all directions and at moderate return periods is well established and uses graphs such as that in Fig. 6. Loading code developments have made use of wind data from different direction sectors and at long return periods. Also, much work has been put into the accuracy of the wind speed determinations, which are important for calculating probabilities of failure. It has been found in Australia that uncertainties in return period winds are such that apparent differences between stations are often unreal, and the extreme wind climate of a country the size of the USA can be described using only five zones.

Two 30 year samples from the same parent distribution are each likely to give a 50 year return period value differing by 10 percent from the true value. For this reason, as New Zealand practice is closely linked to Australia, apparent differences between stations are smoothed out and regional wind speeds are developed from the data. Factors allowing for site differences are included so effects of gaps between hills, hill slope, lee winds and elevation can be incorporated in design.

# How Does MetService Forecast and Communicate Weather Information?

*by Rod Stainer Manager, National Forecast Centre,*
*and August H. Auer, Jnr., Chief Meteorologist*

## Background

The earliest form of weather forecasting, by signs and portents, which has come down to us in proverbial form as 'weather lore', is inextricably linked to human activities. Climatology came much later, beginning with monkish records and country diaries; and it was some time before it was realised that the variations of weather and climate are far more complex than the motions of the stars that so dominated medieval thought. Today we are living in the period of most rapid advance yet achieved in the science of the atmosphere. Since about the middle of this century the forecasting of weather over short periods has become increasingly precise and accurate, as practising forecasters will steadfastly argue, thanks to a better understanding of theoretical meteorology, improved numerical models with better physics and parameterisations, better data assimilation, improved computer processing, introduction of weather satellites and advances in remote scanning devices such as weather radar and automatic weather stations. Even long-range weather forecasting (or more accurately, the prediction of climatic anomalies for periods up to a month ahead) has made sufficient progress to justify publication on a routine basis.

Here in New Zealand, we are seeing, in our opinion, an explosion in the interest and literacy in meteorology led by our zest for outdoor recreational sport and travel, but bolstered by increasing awareness of decision making using weather information in the agricultural and commercial sectors. It is the successful awareness in these areas that has increased our appeal to more consummate, discriminating customers who are demanding a higher degree of quantification and timing in their forecasts. The infotainment of the evening's television weathercast is no longer adequate for a larger segment of commercial interests. Users of weather information are now appreciating more and more the potential value of weather forecasts as a management tool in the mitigation of weather impacts on their businesses.

# The Science of Weather Forecasting

The term 'weather forecast' was first applied in meteorology by Admiral Fitzroy around 1862. Today, it is meant to be a statement of anticipated meteorological conditions for a specified place (or area, route, etc.) and a period of time. Thus, weather forecasting basically entails predicting how the present state of the atmosphere will change. At the METSERVICE, weather forecasts are prepared using a select, logical process incorporating four necessary steps:

- Observation (Verification)
- Diagnosis
- Prediction
- Dissemination

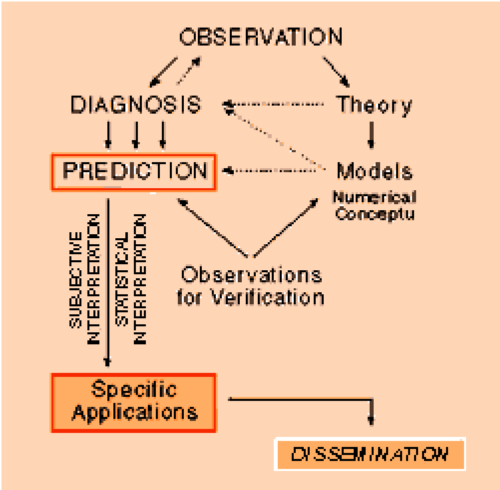



**FIGURE 1**

Illustration of the interaction between these processes and the role of each in producing a weather forecast.

# OBSERVATION

Weather reports describing the current state of the atmosphere are the first requirement to issuing a forecast. Additional information, especially upper air data, is supplied by balloon-borne radiosondes, aircraft, and satellites. New Zealand, with its network of observing stations, is a member of the World Meteorological Organization. This is a United Nations agency which oversees the international exchange of weather data and certifies that the observational procedures do not vary among nations, since the observations must be comparable.

**MetSeRVICE WELLINGTON** *Photo: Rod Stainer, MetService, Wellington, NZ.*
MetService staff Erick Brenstrum (lead forecaster), and Mark Pascoe (severe weather forecaster) discuss a guidance forecast which they are drafting. Wellington, April 1997.

# DIAGNOSIS

Following the collection of weather reports, these data are compiled and plotted onto weather maps to be used in the second and very critical step of forecast preparation: analysis and diagnosis, or understanding what's going on in the atmosphere. Today's weather may be governed by weather patterns over New Zealand, but tomorrow's may be rooted in jet streams and depressions forming over Australia or elsewhere. Thus, the diagnosis follows a funnel approach whereby the larger planetary and hemispheric patterns are first analysed, followed by weather systems on successively smaller scales until events on the order of a few hundred kilometres are diagnosed to understand the weather affecting specific districts of New Zealand.

# PREDICTION

Only when arriving at this point, following the acquisition of weather observations and synthesising them into a viable diagnosis, can the meteorologist predict the future state of the atmosphere the weather forecast through a careful mix of numerical guidance from computers and their own training and experience. With today's computer technology, numerical weather prediction has become a mainstay in all forecasting operations. Because the many weather variables are constantly changing, meteorologists have devised atmospheric models that describe the present state of the atmosphere. These are not physical models, but rather are mathematical models consisting of numerous mathematical equations that describe how atmospheric temperature, pressure, and humidity will change with time. These formulations attempt to retain the most important aspects of the atmosphere's behaviour. The forecaster for their sake might employ the analogue method relying on the fact that existing features on today's weather chart, or series of charts, may strongly resemble features that produced certain weather conditions sometime in the past. Prior weather events can then be used as a guide to the future. The problem here is that, even though weather situations may appear similar, they are never exactly the same, so predicting the weather by pattern recognition employs techniques where weather patterns are categorised into similar groups or 'types' using such criteria as the position of highs, upper-level lows, and the prevailing storm track.

Although it does seem sensible to set a target accuracy for different weather forecasts, it should be recognised that the quality of a weather forecast is dependent upon what the client, be it a commercial organisation or member of the general public, wants or perceives to be important.

Weather forecast accuracy, like beauty, is often in the eye of the beholder. One of the major problems is establishing when a forecast is correct. It must be kept in mind that all forecasts include both time and distance scales. For example, if a forecast predicts a minimum temperature of 10 C and the temperature falls to 9 C, is that forecast incorrect? When a heavy rain warning calls for 75 mm between noon and 6 pm over Waikato, and only the northern two-thirds of Waikato receive 80 mm, is that forecast incorrect, or is it two-thirds correct? What if the rainfall fell between 2 pm and 7 pm? Is the forecast inaccurate? Did the missed timing have any change in the impact of the forecast for the client? The problems of assessing forecast accuracy are many, as can be seen from these examples.

The partial solution to this dilemma may be to evaluate the forecast in term of its impact and/or economic utility. Worldwide insurance statistics suggest that 80 percent of economic losses from weather events are caused by only 20 percent of the storms. In other words, to mitigate storm losses through early warning; diligent monitoring, diagnosis and prediction have to be made for that small, but highly significant, proportion of responsible weather events.

## COMMUNICATING INFORMATION ABOUT STORMS

Communicating information about the likely severe weather conditions accompanying a storm is the final and arguably the most critical phase of the 'Forecast Process'. Failure at this point renders useless all the intensive work carried out previously to diagnose and predict the storm. METSERVICE pays meticulous attention to the ways storm and severe weather information is disseminated to ensure that in extreme conditions the effects on life and property are minimised.

For example, the early warning given to Civil Defence officials regarding the timing and scale of Cyclone Fergus during the Christmas holiday season is credited for allowing holiday makers to make right and proper decisions to evacuate from

**SPECIAL WEATHER BULLETIN**
ISSUED BY MetService AT 1:45 pm 10-Jan-1997
SITUATION AT 12 pm
Cyclone Drena was centred about 250 km west northwest of Cape Reinga and is moving southwards. It is expected to pass about 350 km west of Auckland this evening and lie near Farewell Spit about midday on Saturday. The low is preceded by a very moist, strengthening northeast flow.
On Saturday afternoon the low will probably start weakening but a new centre is likely to form off the Kaikoura Coast and deepen as it moves away to the southeast.

**HEAVY RAIN WARNING**
AREA/S AFFECTED:
HILLS NORTH OF AUCKLAND CITY, COROMANDEL PENINSULA, BAY OF PLENTY/ROTORUA, GISBORNE NORTH OF RUATORIA, NORTHERN SLOPES OF MT EGMONT/TARANAKI ALSO THE KAIKOURA RANGES
FORECAST:
HILLS NORTH OF AUCKLAND CITY
In the 7 hours from 2 pm today expect up to 70 mm of rain.
COROMANDEL PENINSULA AND KAIMAI RANGES

the storm's path, thereby preventing the loss of a single life on land or at sea.

Whenever severe weather is likely to affect any part of New Zealand, METSERVICE forecasters will issue warnings. There are three types of warnings which are issued:

1. Heavy Rainfall Warnings are issued whenever more than 50 mm of rain is expected to fall in 6 hours or less, or greater than 100 mm within 24 hour over an area of at least 1000 km2.

2. Heavy Snow Warnings are issued whenever widespread snowfall (over an area greater than 1000 km2) occurs below 1000 metres on the North Island and below 500 metres on the South Island, with a snow depth to at least 10 cm with 6 hours, or 25 cm within 24 hours.

3. High Wind Warnings are issued whenever either the sustained wind speed is expected to exceed 90 km/h or frequent gusts greater than 110 km/h are likely to be experienced over a land area of 1000 km2 or more.

These criteria for issuing warnings are specified in a contract for weather forecasts and warnings between METSERVICE, (a State Owned Enterprise) and the Funder, (the Minister of Transport).

The weather forecasts issued during times of severe weather follow the same simple but proven steps of success for predictions made every day.

Rain is expected to set in this afternoon. In the 9 to 12 hours from 3 pm today expect 150 200 mm of rain in the ranges (and 50 75 mm at low levels).
FOR THE REMAINDER OF THE BAY OF PLENTY INCLUDING RAUKUMARA RANGE ALSO GISBORNE NORTH OF RUATORIA
In the 15 to 18 hours from 3 pm Friday, expect 100 150 mm in the ranges (and 50 75 mm at low levels).
NORTHERN SLOPES OF MT EGMONT/TARANAKI
Rain is expected to become heavy tonight. In the 6 to 9 hours from about 1 am Saturday,
100 mm is likely.
KAIKOURA RANGES
Rain is expected to become heavy in the early morning. In the 12 hours from 9 pm Friday, 100 mm of rain is possible.
FREEZING LEVEL/SNOW CONDITIONS:
FREEZING LEVEL 3000 TO 4000 METRES LOWERING TO 2600 METRES IN THE KAIKOURA RANGES ON SATURDAY

**STRONG WIND WARNING**
AREA/S AFFECTED:
NORTHLAND, AUCKLAND, COROMANDEL PENINSULA AND WESTERN SLOPES OF KAIMAI RANGES
FORECASTS:
NORTHLAND
North easterlies are averaging 120 km/h at Cape Reinga. Winds are expected to reach 90 km/h with gusts 120 km/h in exposed places this afternoon but from about 6 pm should turn northerly and start to ease.
AUCKLAND
North easterlies are expected to reach 80 km/h at times with gusts around 110 km/h, especially from Whangaparoa northwards. From about 9 pm today, winds are expected to turn north northwest and start to ease.
COROMANDEL PENINSULA AND WESTERN SLOPES OF KAIMAI RANGES From about 5 pm today, northeast winds may reach 90 km/h at times with gusts up to 120 km/h. Winds should turn north northwest and start to ease overnight.
NEXT SPECIAL WEATHER BULLETIN WILL BE ISSUED AT OR BEFORE 9.00 PM FRIDAY 10 JANUARY
Forecast prepared by: IAN MILLER
A service provided through a contract with the Meteorological Service of New Zealand Limited, Crown Copyright1997

**FIGURE 2**

When a warning is prepared, the forecaster describes the current weather situation and developments which are responsible for the severe weather, the type of warnings (rain, snow or wind), areas and regions that are affected, and details of specific weather elements, such as total accumulations of rain or snow, average and maximum rainfall rates, expected average wind speeds and gusts. This complete message is called a Special Weather Bulletin (SWB) see Fig. 2 and is sent by telefax to affected local authorities, Ministry of Civil Defence, Police and to the media for dissemination to the public. The METSERVICE warnings contain only information about the weather and do not attempt to specify the impacts on the community. Council hydrologists assess river levels and the likelihood of flooding, and local civil defence may provide advice on what actions people should take to combat the worst effects of the weather.

Immediately after the SWB is sent, the forecaster follows up with telephone calls to confirm receipt by the Ministry of Civil Defence, Police and regional councils. In the case of regional councils, this call is an opportunity for a mutual exchange of information between the meteorologist and the council's hydrologists. The hydrologist will often seek further clarification of details in the SWB, and the forecaster may request rainfall data from council operated rain gauges to assist with monitoring and verifying forecasts.

**SPECIAL WEATHER ADVISORY**

Issued by MetService at Monday 21-Oct-1996 12:22

FOR HILL COUNTRY FARMERS ESPECIALLY:

A BRIEF WINTRY OUTBREAK FOR THE SOUTH AND EAST OF THE SOUTH ISLAND.

Situation:

A low in mid Tasman Sea is drifting east and should move onto the North Island or central New Zealand on Tuesday night.

A cold front south of Tasmania is racing eastwards and is expected to reach Southland early tomorrow morning and sweep up the east coast reaching Cook Strait on Tuesday afternoon.

The front is likely to bring cold rain and some snow in the ranges but this will probably be short lived.

Forecast:

SOUTHLAND AND OTAGO

On Tuesday morning we expect a cold southerly change with showers. This will probably bring some snow as low as 500 metres and windchill temperatures of zero to minus 5 Celsius on the hills. It may be of concern to farmers with newborn lambs but the good news is that in the afternoon showers should clear inland and the sun break through.

CANTERBURY AND MARLBOROUGH

A cold southerly outbreak is expected to bring rain and snow down to 800 metres in Canterbury and 1000 metres in Marlborough tomorrow. 6 to 9 hours of cold rain are possible with windchill temperatures down to minus 3 Celsius in the hills and ranges starting between 6 am and 10 am in Canterbury and about midday in Marlborough. This is likely to be of concern to farmers with newborn lambs in the hill country.

**FIGURE 3**

The criteria for issuing a SWB, which were explained earlier, are somewhat arbitrary and METSERVICE will agree to lower these thresholds for limited periods at the request of regional councils. Such was the case following the floods in South Canterbury on March 19, 1994 when the Canterbury Regional Council asked METSERVICE to warn them of 30 mm or more of rain within a 24 hour period.

There are occasions of course, when weather which does not meet the criteria for the issue of SWBs will nevertheless cause inconvenience to some sectors of the community. This is often the case with snow. For example, a few centimetres of snow on the Desert Road overnight is often enough to close it until the snow has either been cleared or has melted.

Similarly, widespread snow in Canterbury with accumulations between 10 and 20 mm over 24 hours is generally enough to disrupt transport and cause farmers to seek shelter for their stock. In these types of cases a full warning may not be warranted in terms of the stated criteria but the public may still be inconvenienced, in some cases seriously so.

METSERVICE recognises it has a clear responsibility to advise the public and user groups of such weather and not merely through the production of routine forecasts, but more proactively through the issuing of Special

Weather Advisories and press releases.

A Special Weather Advisory (SWA), Fig. 3, is issued for a weather event which is considered likely to impact significantly on certain sectors of the community, such as farmers. Again the intention is to bring possible adverse weather conditions to the attention of those who may need to make crucial decisions to maintain their livelihood. SWAs have primarily been used to alert farmers of unseasonably cold conditions. The example given describes an unseasonable cold snap in southern New Zealand which did not merit a full warning but was clearly a situation that farmers would want to know about. SWAs have also been the vehicle to pass forecast information about very localised heavy rain and damaging hail. Essentially a SWA is a mechanism whereby METSERVICE rapidly communicates possibly critical weather information directly to specific user groups.

METSERVICE issues a press release whenever it considers that the weather is likely to cause significant disruption to the normal course of events in people's lives or business. They may be issued for a comparatively minor event, such as a local 'opera in the park' or for the imminent arrival of a major cyclonic storm from the tropics. Certainly with the cyclones of tropical origin of late 1996 and early 1997, METSERVICE made extensive use of press releases to communicate with the public at large. Fortunately these were such significant events that the newspapers and radio eagerly ran the stories prominently. In fact, in these situations the media has an understandably insatiable appetite for information, such that METSERVICE was inundated with requests from the media for situation and forecast updates, and interviews.

During Cyclones Fergus and Drena, TVNZ had a live feed into the National Forecast Centre for the 6 pm news, and crossed to Chief Meteorologist Augie Auer for updates on the cyclones' progress and expected weather conditions.

Anticipating intense interest from the media with the approach of Cyclone Fergus toward northern New Zealand at the height of the Christmas New Year holiday period when large numbers of people were camping and therefore exposed to the elements, METSERVICE made a decision to hold its first ever press conference. Following this success, current METSERVICE policy is to conduct regularly scheduled press conferences during episodic weather to present with continuity a simple unified message of storm status and updated warnings to the media. This strategy also prevents misinterpretation of critical elements or timing within the warning text and minimises the need for repetitive time-consuming interviews.

## SUMMARY

The use and impact of any weather forecast must be strongly entrenched in the operational philosophy of observation-diagnosis-prediction-dissemination. Inadequacies, deficiencies, or neglect of any of these functions results in a basically flawed forecast. Weather forecasters, as well as user groups, should be encouraged to continue dialogue aimed at developing useful and meaningful terminology to communicate weather information.

Special Weather Advisory

**METSERVICE NEWS RELEASE**

ATTENTION NEWS STAFF

Issued at 05:04 pm 09-Jan-1997

For Immediate Release

CYCLONE DRENA ON TRACK TO AFFECT NORTH ISLAND ON FRIDAY

Cyclone DRENA has been battering Norfolk Island all day Thursday with wind and driving rain. The cyclone is still on track to take a path along the west coast of the North Island during Friday.

MetService has issued severe wind warnings, at this stage, for Northland, Auckland, Coromandel Peninsula, and Waikato just west of the Kaimais and heavy rain warnings for Northland, Auckland, the Coromandel, Kaimai and Gisborne ranges, and the lowlands of the Bay of Plenty.

"Another feature of this storm worth mentioning", commented MetService Weather Ambassador, Bob McDavitt, "is the expected sea conditions. On Friday, along the East Coast north of Cape Brett, the combined effect of vigorous onshore winds and low barometric pressure may produce a damaging surf of four to six metres sweeping well on to the beaches. We are approaching the time of the month for spring tides and high water on Friday evening around the Hauraki Gulf may be around half a metre higher than that expected by the tide tables."

"The cyclone may, of course, change track at any time. Those concerned about developments should always seek the latest information," concluded Mr. McDavitt.

MetService plan to conduct another news conference at 11 am, Friday 10th January at

30 Salamanca Road,
Kelburn
Wellington

**FIGURE 4**
News Release

# forecasting

## CURRENT PRACTICE

Weather forecasts for New Zealand currently rely to a large extent on global forecasting systems in operation on the other side of the world. The European Centre for Medium-Range Weather Forecasts (ECMWF) and the UK Meteorological Office (UKMO) both located in the United Kingdom; and the National Center for Environmental Prediction (NCEP) in the United States, rely on complex data-handling systems to process and combine observations from around the globe into an analysis of the state of the atmosphere at a particular time. The analyses are then used to initialise sophisticated computer models of the atmosphere to produce forecasts for all parts of the world. For example, a 10 day global forecast cycle from the ECMWF is run once each day, and the resulting estimates of pressure, wind, temperature, etc. are then broadcast for use in national weather offices in every country. In a similar fashion, the UKMO disseminate 5 day forecasts twice daily. The major user of this information in New Zealand is the METSERVICE, which adds value to this raw material in constructing its forecasts and guidance for the public and other clients.

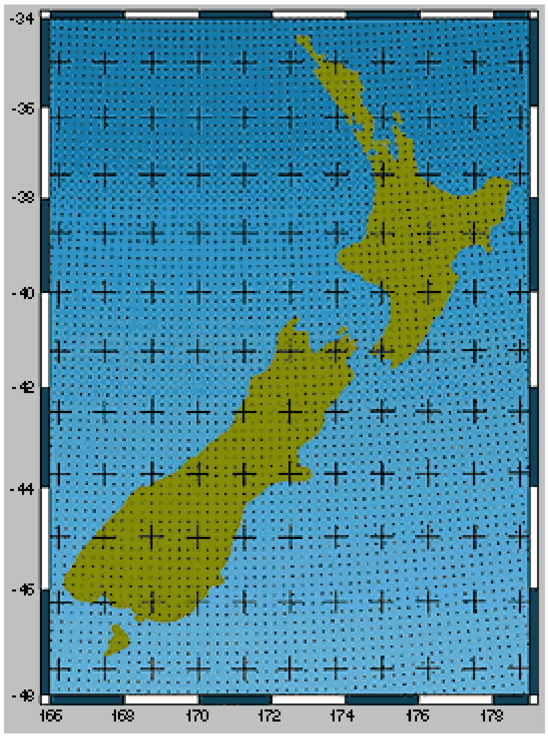



**FIGURE 1**
Schematic showing resolution of various atmospheric models. The large crosses show points at which MetService receive forecast data from UKMO - these crosses are 1.25 degrees apart. The dots show the grid for an experimental 20 km resolution mesoscale forecast currently under evaluation at NIWA. The extra resolution in the RAMS (Regional Atmospheric Modelling System) runs offers a much better chance of capturing the small-scale detail of weather systems as they interact with New Zealand's orography.

Although the forecast data cover this part of the world, a current limitation is their resolution in time and space. ECMWF forecast data received by the METSERVICE are at a horizontal resolution of 2.5 by 2.5 degrees and at 12 hour intervals, while those from the UKMO are at 1.25 by 1.25 degrees at 6 hour intervals. Although the original calculations are done at higher resolution, bandwidth limitations on data transfer mean that New Zealand METSERVICE forecasters have to make do with the relatively coarse forecast data. Fig. 1 shows how UKMO data cannot represent small-scale features of flow around our dramatic topography, particularly those features generated by the Southern Alps, which rise to a maximum height of 3000 m with in 50 km of the coast, and by Cook Strait, which is 25 km across its narrowest point.

Local details are filled in using statistical methods and the experience of skilled forecasters, but a large portion of forecast error is still a result of erroneous global model guidance. Better computer guidance may improve overall forecast skill. Consequently, one major trend overseas at the moment to supplement forecaster skill is to take advantage of output from higher resolution, "mesoscale" forecasting systems. These are basically miniature versions of the global systems with calculations done on a much finer grid to give the detail required, but over a much-reduced area and for much shorter periods than the global forecasts, for example, out to 48 hours only. The total computational burden is therefore much smaller than that of a global system and well within the capabilities of organisations with moderate resources, such as universities and small countries in the south Pacific.

A segment of the grid for an experimental mesoscale forecast system at 20 km resolution currently under trial at NIWA is also shown in Fig. 1. The extra resolution gives a much better chance of capturing the often intense small-scale features around the country. The whole project is a collaborative effort involving scientists from NIWA, forecasters from the METSERVICE and students from Victoria University of Wellington, to make the most of new data products and improvements in modern computing methods. This article discusses the main components of our mesoscale forecasting system and some of the planned developments which will surely give rise to improved weather forecasts for New Zealand in the next few years.

## MESOSCALE FORCAST MODELLING

The heart of the system is a sophisticated numerical model of the atmosphere, which solves numerous mathematical equations describing air motion, clouds and precipitation, passage of sunlight through the atmosphere, interactions with land and sea surfaces, and other physical processes. It requires initial data on atmospheric conditions of winds, temperature, pressure, and humidity within its domain. These data are obtained from observations. The state of the atmosphere along the boundaries of the model domain must also be specified during the forecast period. These are usually obtained from global model output. Errors in the timing or location of weather systems in the global model will be passed to the mesoscale model through the boundary conditions and will lead to errors in the forecast.

Output from a mesoscale forecast model can be used in traditional fashion to produce spatial maps or time series at locations of interest of weather conditions. Derived forecast products, such as potential areas of aircraft icing or visibility, can also be obtained from the mesoscale model output. An expanding area of research is coupling mesoscale model output with other models such as river models (for flow and flood forecasts), dispersion models (for air quality and volcanic ash plume transport forecasts), and ocean models (for wave and storm surge forecasts). It is the fine spatial and temporal scale of the mesoscale forecast model, along with detailed representation of physical processes, that provide for useful forecast products.

## IN THE NEXT COUPLE OF YEARS

Mesoscale models have been used in New Zealand over the past few years at different resolutions for scientific studies on a variety of weather systems. What follows are several examples of what could become operational practice within the next couple of years.

## TROPICAL CYCLONE GAVIN

An experimental mesoscale forecast model was operational at NIWA during the passage of tropical cyclone Gavin in March 1997. At the time the model was producing 72 hour forecasts at a resolution of 40 km over New Zealand. Model forecasts of this type are currently possible using seven hours of computer time on NIWA's most powerful workstation.

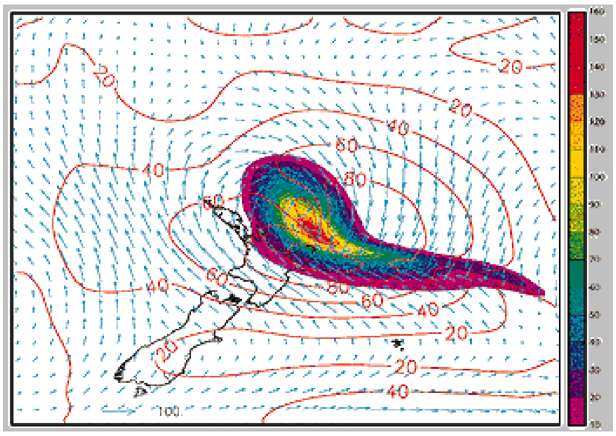


**FIGURE 2**
Forecast of tropical cyclone Gavin for 6 am March 12, 1997. The colour filled contours show 12 hour accumulated rainfall in millimetres, contour lines show wind speed in kilometres per hour, and arrows show wind direction.

Forecast wind speeds for March 12, 1997 at 6 am local time (Fig. 2) correspond well to reports from the Bay of Plenty of winds in excess of 100 km/h. The wind arrows show the clockwise rotation of the winds about the eye of the tropical cyclone which is passing just to the north of East Cape.

Accumulated rainfall for 12 hours prior to 6 am on March 12 is also shown. While the heaviest rainfall occurred offshore near the centre of the storm, we can see that substantial amounts are falling north of Gisborne, up to 80 mm for the 12 hour period

An example of a time series from the forecast model for Gisborne (Fig. 3) shows that the strongest winds and heaviest rainfall were predicted to occur between midnight and 6 am on March 12. The forecast suggests a cooling trend due to weakening south-westerly winds after the passage of Gavin.

While additional work needs to be done to validate the forecast model for the whole variety of weather systems New Zealand is subject to, it is highly encouraging to see results like this.

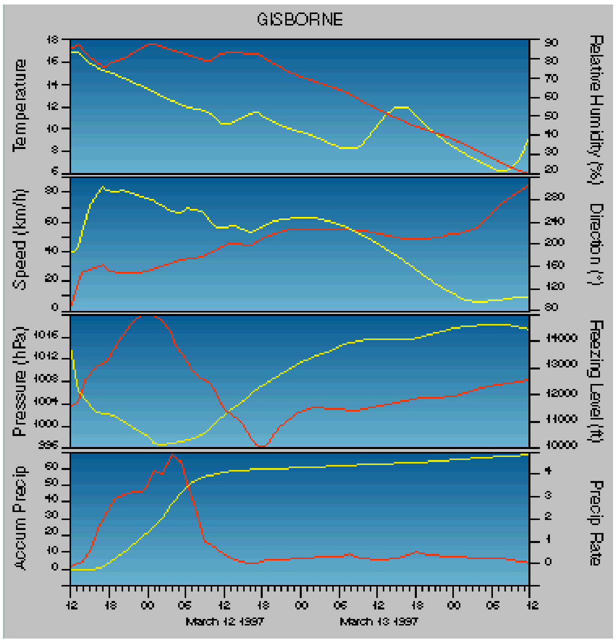



**FIGURE 3**
Meteogram time series at Gisborne of tropical cyclones Gavin's passage.
*Left scales apply to yellow curves, right scales to orange curves.*

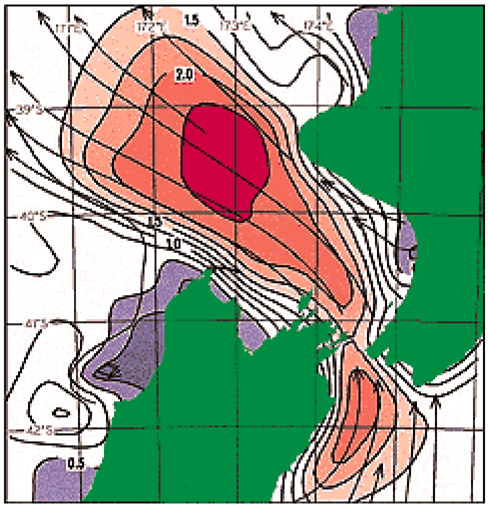



**FIGURE 4**
The "river of wind" through Cook Strait resulting from a stable South-easterly flow. The contours show the speed-up factor, so a 35 km/h SE flow attains a maximum of 90 km/h in the red region south-west of Taranaki. Figure kindly donated by Andrew Laing and Mike Revell of NIWA

# RIVERS OF WIND

Running the model at the resolution shown in Fig. 1 brings some immediate benefits. One that has come to light in the past few years results from the work of Andrew Laing and Mike Revell at NIWA and Erick Brenstrum at METSERVICE. Realistic modelling has been carried out of the "rivers of wind" that occur over the ocean within 50 100 km of New Zealand's coastline, when stable airflows are forced to flow around our mountainous country rather than over the top of it. A dramatic example of this is given in Fig. 4, which shows the increase in surface wind as a prevailing south-easterly is squeezed through Cook Strait: a 35 km/h flow reaches a maximum of 90 km/h in a region south-west of Taranaki and north of Farewell Spit. Knowledge of conditions of this sort is no doubt of use to workers on the Maui gas platforms, but there is no way that this sort of detail is possible in models run on the coarse 1.25 degree grid shown in Fig. 1. Note also however the light weakening of the apparent flow in the narrowest part of the Strait this probably shows the limitations of the 20 km calculations. More accurate predictions would require 5 km or finer resolutions to capture these very small-scale features adequately. Calculations such as these are possible, but are very computer intensive and cannot at present be performed in real time.

# SOUTH ISLAND RAINFALL

Fig. 5 shows the accumulated rainfall, as simulated by the mesoscale model at 10 km resolution, over the South Island for November 5 1994, during what has become known as the Guy Fawkes storm. Scientists from NIWA and collaborating organisations collected data during this storm as part of the 1994 SALPEX mountain meteorology field campaign. This was an extreme frontal storm which produced severe winds and heavy rainfall from November 4 10 1994. The simulated rainfall from the mesoscale model was generally 90 percent of the observed rainfall, while rainfall from global models is typically only 20 35 percent of that observed.

With increases in computer speed it may be possible to run the mesoscale model operationally at this kind of resolution for forecast purposes within a couple of years. A potential application of a mesoscale forecast model which can produce accurate high resolution rainfall totals is coupling the forecast rainfall to flood prediction systems. Having access to such information could possibly avert, or at least better forewarn stock losses, road closures and property damage.

## THE NEXT FIVE YEARS

We have seen that running a high-resolution model brings some benefits almost automatically: forecasts of features fixed to the topography of New Zealand mentioned above would undoubtedly improve with higher resolution. But improved forecasts of fast-moving small-scale features such as bands of intense rain and hail will be much harder to achieve. For this we essentially have to correctly specify the initial positions of these features and then rely on the model to accurately predict their movement. There is a concerted, long-term effort at NIWA to address this problem, funded by the Public Good Science Fund.

## MESOSCALE DATA ASSIMILATION

The traditional approach to incorporate more detail into the forecast process is through the use of additional surface observations and upper-air data from balloons and radiosondes, but in New Zealand the number of these types of observations has been reduced in recent years. At present only three radiosonde flights are operated on a regular basis in New Zealand: at Kaitaia, Paraparaumu and Invercargill. The data collected from these flights is far too widely-spaced to be of much use in capturing the small scale features we are interested in.

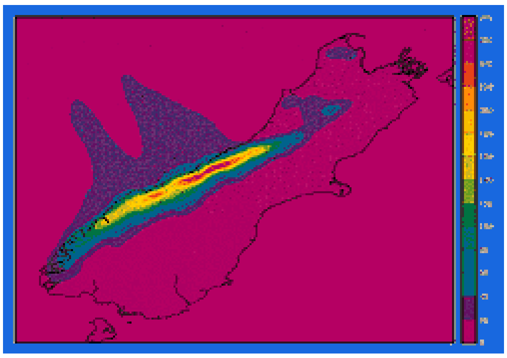


**FIGURE 5**
Simulated total accumulated rainfall, in millimetres, for November 5, 1994 during the Guy Fawkes storm.

A better option is to use satellite imagery in the forecast process. For example, the hourly infrared and visible images from the

Japanese Geostationary Meteorological Satellite (GMS), with which readers of the weather reports in the major daily papers are no doubt familiar, are indispensable in providing qualitative interpretations of recent events, and information on weather systems approaching from the west over the Tasman Sea. These relatively coarse data are supplemented by very high resolution imagery from two polar-orbiting satellites run by the National Ocean and Atmosphere Administration (NOAA) in the United States, offering the potential for adding small-scale details to our computerised forecast process.

Eight sets of infrared and visible images from these satellites are received daily in New Zealand at a resolution of between 1 and 2 km, and current work by Michael Uddstrom and Warren Gray at NIWA demonstrate that with some typical Kiwi ingenuity, these images can be turned into a very useful product of precisely the sort required to improve detailed rainfall forecasts over New Zealand. Using a large database of co-located radar and satellite imagery, they have trained a sophisticated pattern-matching algorithm to recognise areas of rain and determine rain-rates in the images over the whole New Zealand region not just over the small areas around Wellington, Christchurch and Auckland for which radar have previously been used. Fig. 6 shows a sample rainfall rate from the new scheme. Heavy rainfall along the main divide of the South Island has been identified, along with pockets of heavy rain off the west coast.

Although currently still being evaluated and optimised, this sort of product offers the possibility of improved rain forecasts because it can be generated in real time and used in the forecast process. In fact, research overseas indicates that information even as simple as knowing where it has been and where it is currently raining (rather than knowing the rainfall rate as shown here) can be used with great effect to improve short-term forecasts of rainfall. Fig. 7 gives a schematic of a possible forecast process to take advantage of this sort of information.

Coarse resolution analyses and forecasts from overseas, recent satellite imagery, and the results of previous mesoscale forecasts are combined to produce an estimate of the state of the atmosphere around New Zealand for a particular period (12 hours in Fig. 7) leading up to the current time. This is then used to initialise and nudge the model towards the known behaviour of the atmosphere during the "spin-up" phase of the model. The model then moves into forecast mode, the only constraint being provided from boundary conditions from coarse-resolution forecast data. Because the model works at faster than real-time, it is possible to make up for the time lost in transmission of data and produce useful mesoscale forecasts. Work on the construction and testing of such a scheme has started as a joint effort between NIWA and Victoria University of Wellington, and results should begin to appear sometime in 1998.

NIWA is coordinating a major collaborative research campaign on the effects of mountains on rainfall and strong winds. Researchers from several countries used aircraft, radars and atmospheric sounding systems during October and November of 1996 to make detailed measurements over and upwind of the Southern Alps. Detailed satellite observations were collected of atmospheric and cloud properties over the Tasman Sea, and rainfalls and river flows were measured. Field campaigns were also mounted in 1994 and 1995. SALPEX provides the testbed for much of the New Zealand research on mesoscale forecast models and data assimilation. The SALPEX data sets are being used to test and improve systems for forecasting rainfall, snowfall and river flows. (Wratt and Sinclair, 1996).

## FURTHER AHEAD

Future improvements to the forecasting process will be of three basic kinds.
The first will occur slowly (as they always have done) as subtle improvements in understanding lead to better physical models of the processes occurring in the atmosphere, and hence better forecasts as these models are embedded in the forecast system. NIWA is actively involved in several projects of this sort, including one led by Michael Revell and Mark Sinclair to study the processes such as the fluxes of heat from the ocean surface, which lead to the rapid intensification of storms originating on the east coast of Australia. These cross the Tasman Sea very quickly and are very difficult to predict, especially in winter. A related sort of forecast improvement will come by furthering collaboration between meteorologists, oceanographers and hydrologists. We foresee distinct opportunities in using high-resolution wind and precipitation data (such as forecast from our operational mesoscale system) to drive storm-surge and flood models to provide warnings for Civil Defence and affected regional councils.

The second kind of improvement hinges on the availability of new types of data of a resolution much higher than used up until now. For example, new types of instruments aboard latest versions of the polar-orbiting NOAA satellites are currently under evaluation which will give fine-resolution, three-dimensional information on the moisture and cloud in the atmosphere. These data should make improvements to rain and cloud-related forecasts, over and above the advances expected from the use of two-dimensional satellite imagery described in a previous section. Another source of new data are satellites managed by the Japanese. These will offer very high resolution sea-surface temperatures and surface wind observations. The former are crucial in forecasting the track of tropical cyclones (which tend to decay when passing over cooler seas), while the latter will improve forecasts of conditions at sea (especially when coupled to wave models).

The third kind of improvement arises from developments in computer technology, both hardware and software. A general rule in the computer industry is that processor power per dollar doubles every 18 months; and a similarly dramatic rule holds for the amount of disk and memory available for applications. What can we do to improve forecasts by taking advantage of developments of this sort?

There are several options. The first is to absorb available processor power, memory and disk space by conducting forecasts at ever finer resolution, e.g. operational 20 km resolution runs are possible now, so by the year 2000 we may be able to run at 10 or 5 km. In theory this permits the forecast of ever finer features in the flow field.

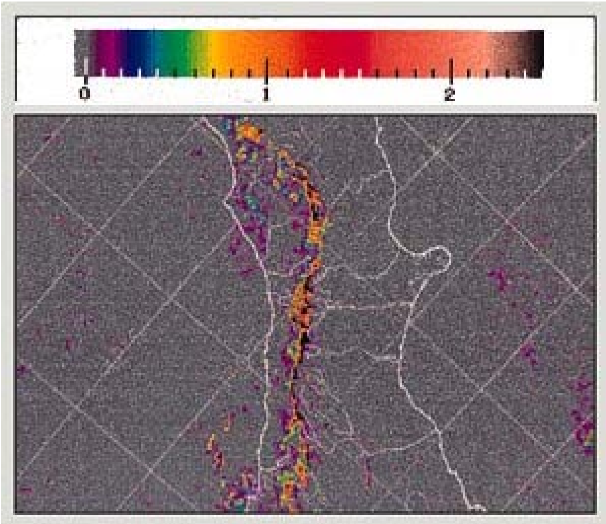


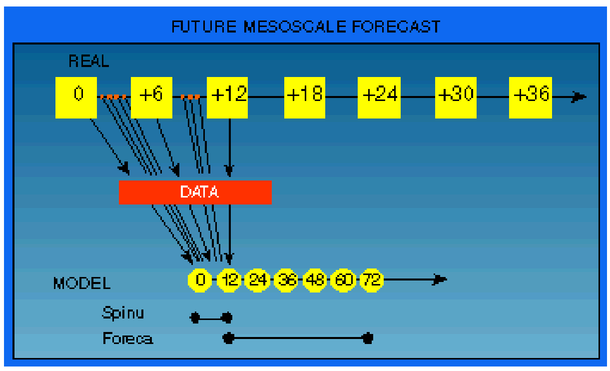

**FIGURE 6**
Rainfall rates (mm per hour) derived from infrared satellite images. See text for more details. Figure kindly donated by Michael Uddstrom and Warren Gray of NIWA.

For example, downslope wind-storms and turbulence in the lee of large mountain ranges (such as on the Canterbury plains) are the result of the "breaking" of waves in the atmosphere: energy and momentum are converted to turbulent motion which is dissipated at small scales (in much the same way that ocean waves break and are dissipated when they meet a beach). A current study at NIWA led by Don Purnell indicates that successful modelling of this process requires a much finer resolution than is possible in an operational mode at present, e.g. approximately 2 km in the horizontal, but it is not out of the question in five years time.

Going to finer resolution as available computer power increases has been the approach taken by every operational global forecasting centre over the past decade, but suffers from the "all your eggs in one basket" syndrome.

The data on which the forecasts are based are uncertain, and research overseas has shown that in some conditions small differences in these data can lead to surprisingly different forecasts of the weather at a particular location a week or so later. (This work, originated by Ed Lorenz at MIT in the 1960s, has led to the notion of the "butterfly effect" a butterfly flaps its wings in New York and there is a typhoon in Fiji one week later.) A consequence of this is the adoption of "ensemble" forecasting at these global centres in the past year or so: excess computer capacity is mopped up by running multiple cheaper forecasts (all from slightly different initial conditions) rather than one very expensive one. The collective behaviour of the runs in the ensemble then gives a better idea of what the forecast should be. If the runs all look the same then one may make a sensible forecast with some certainty; but if they all look different it is probably best to say that the weather is currently unpredictable.

Although these techniques have been developed for use with large, global forecasting systems, the same arguments apply to some extent to the mesoscale forecasting systems discussed in this article.
A particular example of how such techniques may be of use in New Zealand is provided by the case of errant tropical cyclones, which may cause damage on New Zealand soil if they approach too closely. Predicting the tracks of these cyclones is difficult at present, so the ensemble approach in which initial conditions and model parameters are subtly varied across a number of cheap forecast runs may offer a



way of "putting an envelope" around the possible behaviours of the storm.

Finally, continuous innovations in the software industry offer unprecedented scope for the dissemination of forecast products and for tailoring them to the requirements of specific customers.

**FIGURE 7**
A schematic of a typical run of a mesoscale forecast system currently being investigated at NIWA. The top line shows recently arrived data: the boxes denote times (hours from analysis) of the most recent coarse-resolution forecasts from the UKMO, which in general arrive 12 or so hours late in New Zealand. The crosses denote recently received satellite observations. The bottom line shows the progression of the mesoscale forecast, the circles showing times relative to those in the top line. See text for more details.

The internet provides the backbone of this service: on completion forecast products can be moved from internally secure systems to ones to which external clients have access at the click of a mouse-button. NIWA is already experimenting with this sort of service for tuna fishers, who have found maps of latest sea-surface temperature produced by Michael Uddstrom and co-workers at NIWA to be most useful in chasing their prey. The latest maps can be accessed via PC and cell-phone while at sea! In addition, experimental forecasts from our RAMS (Regional Atmospheric Modelling System) are currently accessible only internally within NIWA, but once they have been validated we hope to make the products more widely available, possibly in conjunction with the METSERVICE.

Combine the internet technology with tools to dynamically configure the forecast systems for special events (such as a wider area for the approach of a big storm, or as a very fine resolution forecast for a sports event) and we see fantastic flexibility to align technology with opportunities to do business and contribute to the public good. We're looking forward to it.

# Further Reading


## General Overview

Ahrens, C.D, 1985: Meteorology today An introduction to weather, climate and the environment (2nd Edition). West Publishing Co., 524 pp.
Ryan, A.P., 1984: Flying Weather Manual of New Zealand aviation climatology. New Zealand Meteorological Service, 120 pp.
Sturman, A., and N. Tapper, 1996: The weather and climate of Australia and New Zealand. Oxford University Press, 476 pp.

## Tropical cyclones

Elsberry, R.L. (Ed.), 1987: A global view of tropical cyclones. (Available from Department of Meteorology, Naval Postgraduate School, Monterey CA 94943, USA).
Holland, G.J., 1983: Tropical cyclones in the Australian southwest Pacific region. Dept. of Atmospheric Science Paper No. 363, 264 pp. (Available from Colorado State University, Ft. Collins CO.) ISSN 0067-0340.
Radford, D., R. Blong, A. d'Aubert, I. Kuhnel, and P. Nunn, 1996: Occurrence of tropical cyclones in the southwest Pacific 1920 1994. Greenpeace Report (Available from Greenpeace International, Keizersgracht 176, 1016 DW Amsterdam, The Netherlands.)
ISBN 90-73361-30-3.
Revell, C.G., 1981: Tropical cyclones in the southwest Pacific. Misc. Pub. 170, New Zealand Meteorological Service, Wellington, New Zealand, 53 pp.
ISSN 0110-6937.

## Extratropical cyclones

Carlson, T.N. 1991: Mid-latitude weather systems.
Harper Collins Academic, 507 pp.
Newton, C.W., and E.O. Holopainen (Eds.), 1990: Extratropical cyclones. The Erik Palmén Memorial Volume. American Meteorological Society, 262 pp.
Sinclair, M.R., 1995: An extended climatology of extratropical cyclones over the Southern Hemisphere. Weather and Climate, 15, 21 32.

## Tropical cyclones affecting New Zealand

Hill, H.W., 1970: The precipitation in New Zealand associated with the cyclone of early April 1968.
New Zealand Journal of Science, 14, 641 662.
Sinclair, M.R., 1993: Synoptic-scale diagnosis of the extratropical transition of a southwest Pacific tropical cyclone. Monthly Weather Review, 121, 941 960.
Sinclair, M.R., 1993: A diagnostic study of the extratropical precipitation resulting from Tropical Cyclone Bola. Monthly Weather Review, 121, 2690 2707.
Tomlinson, A.I., 1975: Cyclone Alison. Technical Information Circular No. 148, New Zealand Meteorological Service, 20 pp.

## Storm Surge

Bell, R.G., and D.G. Goring, 1996: Techniques for analysing sea level records around New Zealand.
Marine Geodesy, 19, 77 98.
Goring, D.G., 1995: Short-term variations in sea level (2 15 days) in the New Zealand region. New Zealand Journal of Marine and Freshwater Research, 29, 69 82.
Hamon, B., 1966: Continental shelf waves and the effects of atmospheric pressure and wind stress.
Journal of Geophysical Research, 71, 2883 2893.
Heath, R.A., 1979: Significance of storm surges on the New Zealand coast. New Zealand Journal of Geology and Geophysics, 22, 259 266.
de Lange, W., 1996: Storm surge. Tephra, 15, 24 31

## Precipitation in New Zealand

Henderson, R.D., 1993: Extreme storm rainfalls in the Southern Alps, New Zealand. In: Extreme Hydrological Events: Precipitation, Floods and Droughts. International Association of Hydrological Science, Publication No. 213, 113 120 (also available from NIWA).
McKerchar, A.I, and C.P. Pearson, 1989: Flood frequency in New Zealand. Publication No. 20. Hydrology Centre, Christchurch (available from NIWA, PO Box 8602, Christ church)
Tomlinson, A.I., 1980: Frequency of high intensity rainfalls in New Zealand. Water and Soil Technical Publication No. 19, 36 pp, plus maps (available from NIWA)
Sinclair, M.R., 1994: A diagnostic model for estimating orographic precipitation. Journal of Applied Meteorology, 33, 1163 1175.
Wratt, D.S., R.N. Ridley, M.R. Sinclair, H.R. Larsen, S.M. Thompson, R. Henderson, G.L. Austin, S.G. Bradley, A. Auer, A.P. Sturman, I. Owens, B. Fitzharris, B.F. Ryan, and J.F.Gayet, 1996: The New Zealand Southern Alps Experiment. Bulletin American Meteorological Society, 77, 683 692. (See also SALPEX under NIWA's home page http://www.niwa.cri.nz)

## Windstorms

Baines, P., 1995: Topographic effects in stratified flows. Cambridge University Press, 482pp.
Bluestein, H.,1993: Synoptic dynamic meteorology: Volume II, Observations and theory of weather systems. Oxford University Press, 594pp.
Davidson, K., 1996: Twister: The science of tornadoes and the making of an adventure movie. Pocket Books, 202 pp.
Durran, D. R., 1990: Mountain waves and downslope winds. Atmospheric Processes Over Complex Terrain.
W. Blumen, Ed. Meteorological Monographs, No 45.
Amer. Meteor. Soc., 59 81.
Gill, A. E., 1982: Atmosphere-Ocean Dynamics. Academic Press, 662 pp.
Hill, H. W., 1979: Severe damage to forests in Canterbury, New Zealand resulting from orographically reinforced winds. New Zealand Meteorological Service Technical Information Circular No. 169.
Littlejohn, R.N., 1984: Extreme winds and forest devastation resulting from Cyclone Bernie. Weather and Climate, 4, 47 52.

Revell, M. J., D. Purnell, and M. K. Lauren, 1996: Requirements for large eddy simulations of surface wind gusts in a mountain valley. Boundary-Layer Meteorology, 80, 333 353.
Smith, R. K., R. N. Ridley, M. A. Page, J. T. Steiner, and
A. P. Sturman, 1991: Southerly changes on the East coast of New Zealand. Mon. Wea. Rev., 119, 1259 1282.
Sturman, A., and N. Tapper, 1996: The weather and climate of Australia and New Zealand. Oxford University Press, 476 pp.
Wratt, D.S. and Sinclair, M., 1996: SALPEX The Southern Alps Experiment. Water and Atmosphere 4, 26 28.