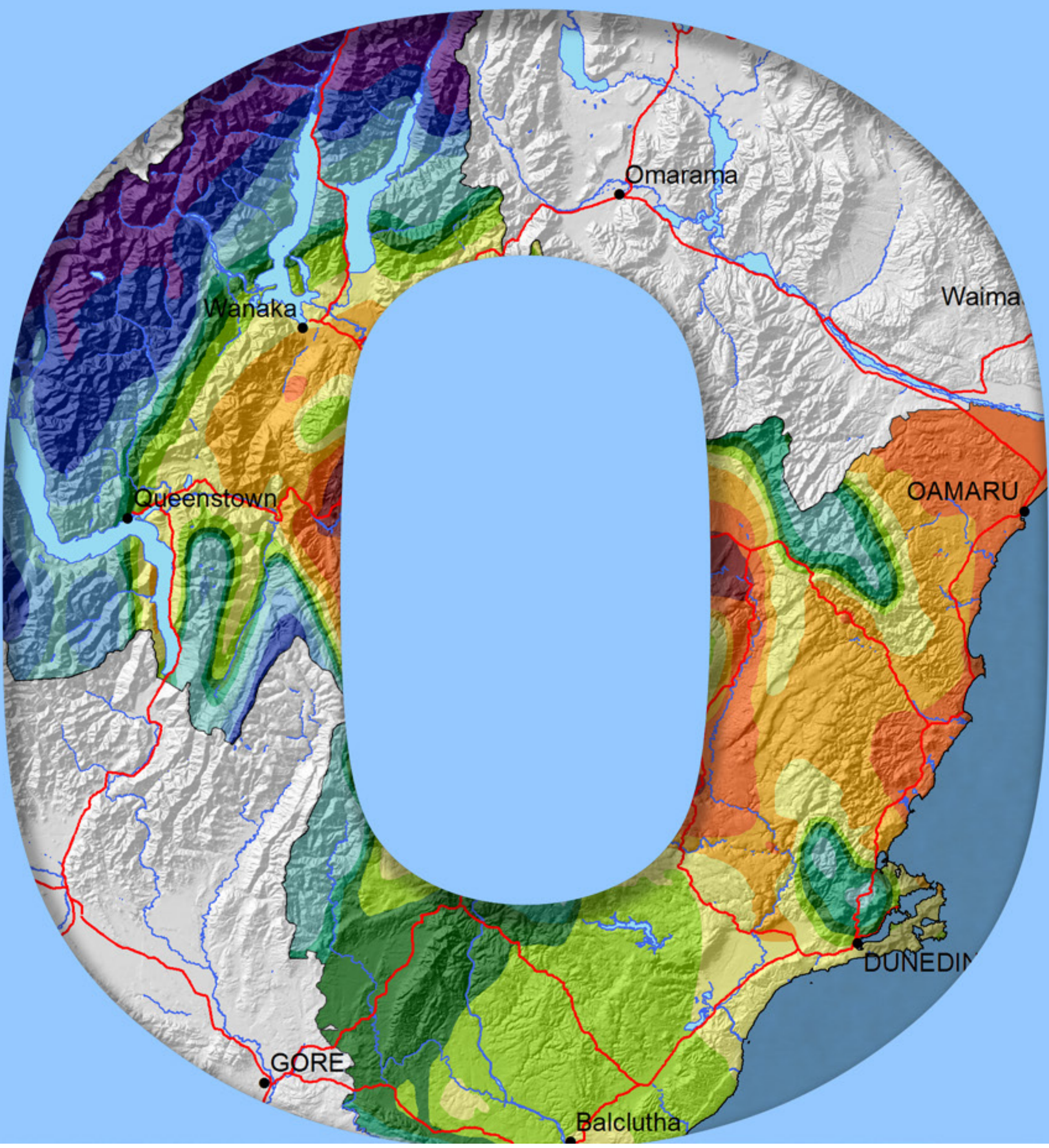
NIWA
Taihoro Nukurangi

THE CLIMATE AND WEATHER OF
O T A G O

2nd edition

G. R. Macara



NIWA SCIENCE AND TECHNOLOGY SERIES
NUMBER 67

ISSN 1173-0382

Note to Second Edition

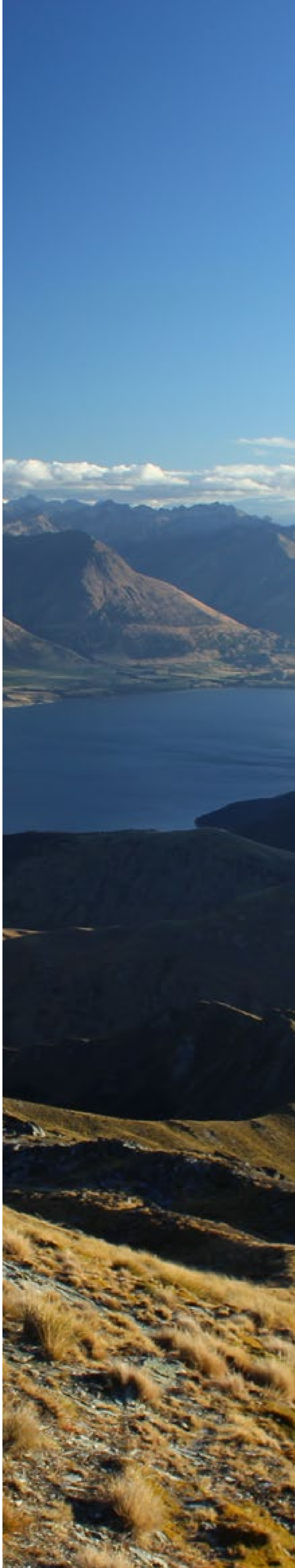
This publication replaces the first edition of New Zealand Meteorological Service Miscellaneous Publication 115 (4), written in 1968 by J. F. de Lisle and M. L. Browne. It was considered necessary to update the first edition, incorporating more recent data and updated methods of climatological variable calculation.

THE CLIMATE AND WEATHER OF OTAGO

2nd edition

G. R. Macara

CONTENTS



SUMMARY

The climate of Otago is perhaps the most diverse of any region in New Zealand. The region is in the latitudes of prevailing westerlies, and exposed coastal locations often experience strong winds, but the winds are lighter inland. Winter is typically the least windy time of year, as well as for many but not all areas, the driest. Annual precipitation in Otago typically decreases with increasing distance from the western ranges and the east coast. Indeed Central Otago is the driest region of New Zealand, receiving less than 400 mm of rainfall annually. Dry spells of more than two weeks occur relatively frequently in Central Otago, but less so elsewhere. Temperatures are on average lower than over the rest of the country with frosts and snowfalls occurring relatively frequently each year. However daily maximum temperatures in summer can exceed 30°C, especially about inland areas of Otago. On average, coastal Otago receives less sunshine than many other parts of New Zealand.

INTRODUCTION

New Zealand spans latitudes 34 to 47 degrees south, and so lies within the Southern Hemisphere temperate zone. In this zone, westerly winds at all levels of the atmosphere move weather systems, which may also be either decaying or developing, eastwards over New Zealand giving great variability to its weather. These prevailing westerlies sometimes abate, and air from either tropical or polar regions may reach New Zealand with heavy rainfalls or cold showery conditions respectively. The main divide of the Southern Alps acts as a barrier to the prevailing westerlies and has a profound effect on the climate of Otago, separating the New Zealand's wettest region (the West Coast) from New Zealand's driest region Central Otago. No area of New Zealand has a climate where the hot dry summers and cold dry winters more closely approximate a semi-arid 'continental' climate than does Central Otago. In coastal areas of eastern Otago, conditions are tempered by relatively cool sea surface temperatures nearby and by the absence of shelter from airflows moving over the area from the south and south-west. Otago is topographically diverse east of the main divide, consisting of large mountain blocks and relatively low elevation basins. The climate of these inland basins lends itself to a burgeoning viticulture industry, whilst horticulture has been the mainstay of the area for some time.

Note that all numbers given in the following tables are calculated from the 1981-2010 normal period (a normal is an average or estimated average over a standard 30-year period), unless otherwise stated.

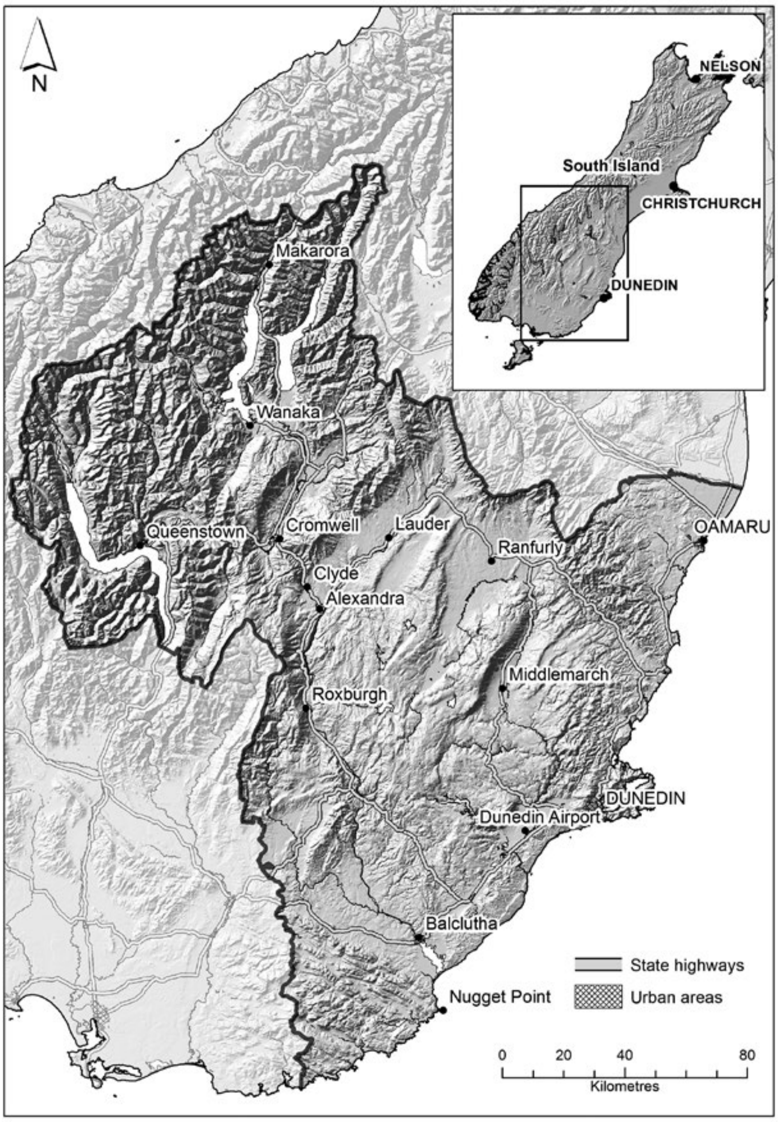


Figure 1. Map of the Otago region, showing the places mentioned in this publication.

TYPICAL WEATHER SITUATIONS IN OTAGO

The weather in Otago is dominated by the west-to-east passage of anticyclones and intervening troughs of low pressure across the New Zealand region. The weather conditions associated with a particular type of meteorological situation can vary widely from one part of Otago to another. This is largely due to the extensive geographic spread of the region, which encompasses both the Southern Alps to the west and coastal areas to the east. The irregular topography of Otago, with its many mountain ranges, has a considerable influence on the weather experienced across the region.

Anticyclones and ridges of high pressure typically result in fine and calm weather across Otago. More often, however, anticyclones are located to the north of the region, which results in a disturbed westerly air stream over Otago. Cold fronts or depressions in the troughs between anticyclones will thus traverse Otago fairly frequently. Northerly or westerly winds associated with an approaching front bring rain (which may be heavy and persistent) to western areas. However, little-to-no rainfall occurs over central and eastern parts of the region due to the rain-shadow effect of the western ranges. Additionally, foehn winds occur to the lee of the western ranges, bringing mild temperatures in winter, and warm or hot temperatures in summer.

As a cold front moves across Otago, rainfall may become widespread for a period of time, before easing to increasingly isolated showers as a new anticyclone approaches from the west. The passage of a cold front is associated with a considerable drop in temperature, and often results in snow falling to relatively low levels, especially during May to October. When a cold front passes from the south, rain and showers chiefly affect areas east of the western ranges. Similarly, rain-bearing easterly winds may result in heavy rain about the eastern parts, but dry conditions farther west. Indeed, western-most parts of Otago often have their sunniest weather when winds over the Otago region are from an easterly direction. Central Otago is shielded from rain on many occasions due to its inland location, with substantial rainfalls only occurring there when depressions and fronts are unusually vigorous.

Although many different weather situations are possible in Otago, they tend to fall into only a few characteristic categories: (a) fine weather spells, (b) heavy rain, and (c) showery weather.

Fine weather spells

Prolonged spells of fine weather of six days or more are usually associated with an anticyclone moving slowly eastwards over the South Island, or the area just south of it. If a depression develops to the north or north-east of the North Island a ridge of high pressure may still extend over the South Island when the anticyclone is centred far to the east or south-east. This type of situation is shown in Figure 2. Fine, sunny weather and light winds typically prevail over Otago during such periods, although there are some exceptions. For example, fresh or strong north-easterly sea breezes can occur along the eastern coast of Otago, especially during summer. Such winds may bring areas of low cloud to those parts. Additionally, anticyclones support the development of low cloud or fog in inland parts of Otago, chiefly during April to October.

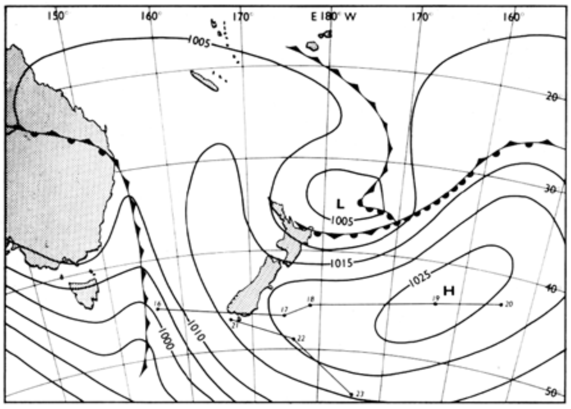


Figure 2. Mean sea level pressure analysis for 1200 hrs NZST on 19 November 1960.

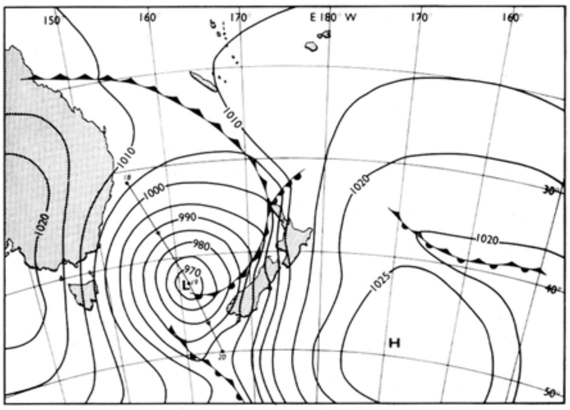


Figure 3. Mean sea level pressure analysis for 0600 hrs NZST on 19 May 1965.

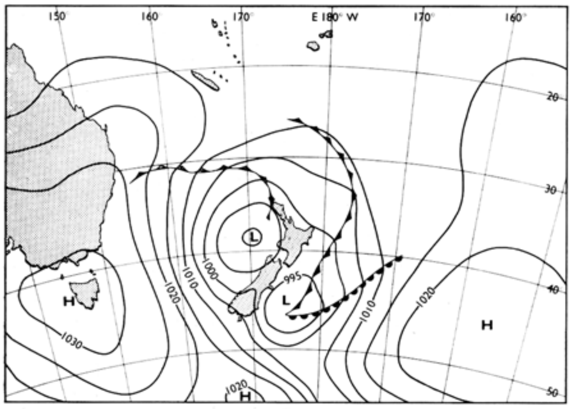


Figure 4. Mean sea level pressure analysis for 1800 hrs NZST on 20 July 1955.

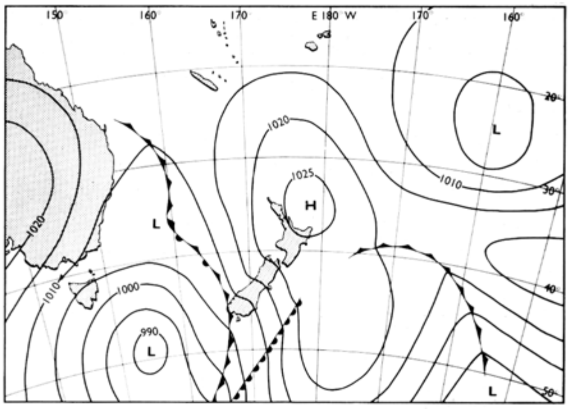


Figure 5. Mean sea level pressure analysis for 1800 hrs NZST on 26 July 1962.

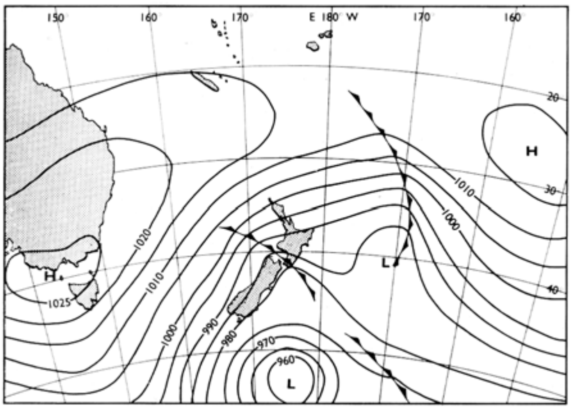


Figure 6. Mean sea level pressure analysis for 1800 hrs NZST on 26 April 1965.

Heavy rain

Heavy rain may occur on western-most parts of Otago when a strong, moist northerly to westerly air-stream is lifted over the western ranges. This orographic effect serves to intensify the rainfall along the western ranges, and the heavy rain may spill over eastwards into the headwaters of the Otago lakes and rivers. An example of this type of situation is shown in Figure 3. A deep depression moving towards the south-south-east had an occluded front which crossed Otago on 19 May 1965, and produced 100 to 125 mm of rain in the Makarora valley (north of Lake Wanaka), and 25 mm at Lake Hawea and Queenstown. A feature of this type of situation is the steady decrease in rainfall to the south-east; in this example, there was no rain at all southeast of a line from Palmerston to Lawrence.

Heavy rain also often falls in parts of Otago when a depression crosses the South Island, or becomes slow-moving to the east. Figure 4 illustrates an example of the latter situation. A complex depression lay over New Zealand on 20 and 21 July 1955, with centres west of the North Island and east of the South Island. A moist south-easterly air-stream flowed over Otago producing 50 to 100 mm of rain over the two days in a broad section along the east coast reaching as far inland as Ranfurly and Lawrence. The rainfall decreased further away from the east coast and less than 10 mm of rain was recorded at Makarora during this period.

Another situation which brings heavy rain, especially in western parts of Otago, is that of a cold front oriented in a north-south direction moving slowly eastwards across the region. An example is shown in Figure 5. The cold front was slow-moving, due in part to the blocking effect of an anticyclone centred north-east of the North Island. During 26 July and 27 July 1962, rainfall totals of 125 to 175 mm were recorded in the north-west of Otago. Little rain fell in eastern areas on 26 July, but there were rainfall totals of 25 to 50 mm over most of the region on 27 and 28 July 1962.

Showery weather

Cold unstable air associated with cold fronts from the west and south usually brings showers to Otago, but due to the irregular topography of the region, the distribution of the showers depends largely on the direction of the wind-flow. If it is from the west, showers are typically confined to the west and south of the region, with few showers reaching sheltered Central and North Otago. In contrast, a southerly air-stream typically brings showers to all parts of the region. In this instance, heaviest falls usually occur near the east coast and in the area south-west of Roxburgh, with lighter falls occurring in the north.

A common type of situation associated with showery weather over the Otago region is illustrated in Figure 6. On 24 April 1965 an intense anticyclone moved onto the area just west of Tasmania, Australia. It became almost stationary and did not reach the central Tasman Sea until 5 May, eleven days later. Pressures remained relatively low to the south and south-east of New Zealand and throughout the period a disturbed south-westerly air-stream flowed over the country, bringing widespread showery weather to Otago, particularly in the south and east. Cold fronts in the air-stream passed over the region at intervals of about two days. These fronts were accompanied by bands of more general rain. Snow, hail and thunderstorms were reported in many Otago locations between 26 April and 2 May 1965.

CLIMATIC ELEMENTS

Wind

Wind direction over New Zealand in the zone directly above the earth's surface may be interpreted from a mean sea level pressure (MSLP) map, following the general principle that, in the Southern Hemisphere, air flows in a clockwise direction around a depression, and in an anticlockwise direction around an anticyclone. As such, MSLP maps can be used to indicate the general wind direction at the earth's surface. However, actual wind direction at a particular locality is modified by the influence of friction and topography. Furthermore, wind speeds are also subject to topographical influence. Such influences are especially prevalent in Otago, where winds may be channelled by mountains, hills and valleys. The mountainous terrain means many Central Otago valleys are well sheltered and have a high percentage of calms and light winds. On the east coast the wind regime is complicated by a cool sea breeze from the easterly quarter during daylight hours in late-spring, summer and early-autumn. Sea breezes develop in Otago when synoptic-scale pressure gradients are weak (e.g. Figure 2), and are generated by air temperatures over land becoming higher than air temperatures over the sea. South-westerly winds associated with depressions to the south of New Zealand or following the passage of cold fronts across Otago are common over South Otago and the Taieri Plain. Figure 7 shows mean annual wind frequencies of surface wind based on hourly observations from selected Otago stations.

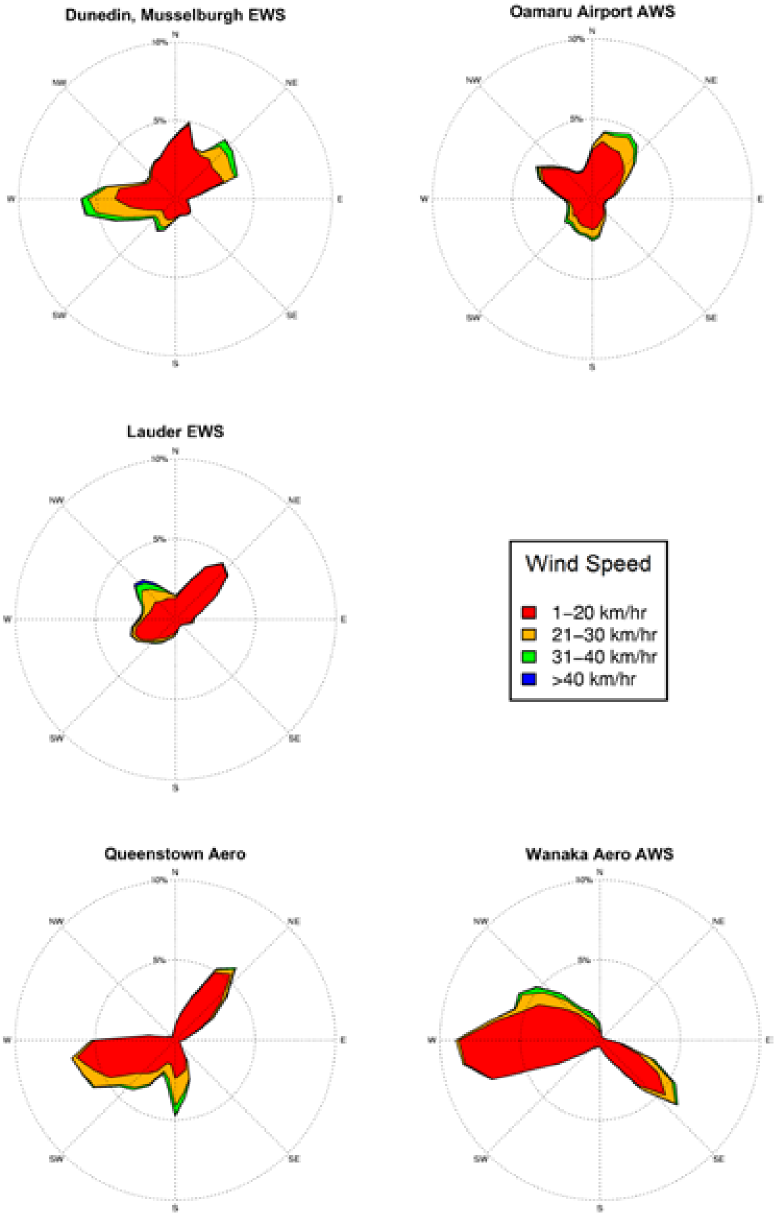


Figure 7. Mean annual wind frequencies (%) of surface wind directions from hourly observations at selected Otago stations. The plot shows the directions from which the wind blows, e.g. the dominant wind directions at Wanaka are from the west and southeast.

Mean wind speed data (average wind speeds are taken over the 10 minute period preceding each hour) are available for a number of sites in Otago, and these illustrate the several different wind regimes of the region (Table 1). Mean wind speeds are highest at the exposed coastal location of Nugget Point, and lowest at the sheltered inland location of Clyde. There is notable variability in mean monthly wind speeds over the course of a year in Otago, where wind speeds are highest from around mid-spring (October) to mid-summer (January), and lowest over the winter months (June to August). This seasonality is observed across almost all of the Otago region, and it is more pronounced at inland locations. Dunedin is typically windier than most areas of Otago throughout the year, with this difference in mean wind speeds more prominent during the winter months.

Table 1. Mean monthly and annual wind speed (km/hr) for selected Otago locations.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Nugget Point	24.2	23.3	23.3	23.0	24.0	25.4	22.9	24.1	24.2	25.7	26.5	24.3	24.2
Dunedin (Musselburgh)	14.9	14.6	13.8	13.2	13.3	13.5	12.1	13.3	14.2	15.3	15.7	15.2	14.1
Queenstown (Airport)	13.9	13.3	12.2	11.0	10.2	10.0	9.7	10.2	11.8	13.2	14.1	13.6	11.9
Wanaka (Airport)	14.9	14.1	12.9	10.4	9.3	8.0	8.0	9.0	12.4	13.5	14.6	14.9	11.8
Lauder	13.3	11.9	11.3	9.5	9.2	7.9	7.5	9.1	12.4	14.0	14.0	13.6	11.1
Oamaru (Airport)	12.4	11.6	11.2	9.8	9.5	9.7	9.4	10.2	11.3	12.5	12.6	12.8	11.1
Ranfurly	12.4	10.9	10.4	8.4	7.9	7.7	7.2	8.1	11.2	11.6	12.3	12.4	10.0
Middlemarch	10.4	9.4	9.2	7.9	8.0	8.2	7.5	7.9	10.8	10.7	11.2	10.6	9.3
Clyde	7.4	6.6	5.9	4.5	4.3	4.1	3.7	4.8	6.7	7.3	7.8	7.4	5.9

Table 2 gives the seasonal distribution and frequency of occurrence of strong winds (defined as having a daily mean wind speed of greater than 30 km/hr). For example, of all strong winds recorded at Dunedin, 29% occur in spring. In addition, during a Dunedin spring an average of 4 days have a daily mean wind speed of greater than 30 km/hr. As a further example, Nugget Point and Lauder share the same distribution of strong winds in summer, with 23% of their respective annual strong winds being recorded in that season. However, Nugget Point has an average of 22 strong wind days in summer, compared to just 2 in Lauder. This highlights that although a similar seasonal distribution of strong winds may be observed between different locations in Otago, the actual number of strong wind days per season at those locations may be considerably different. As shown in Tables 1 and 2, spring and summer are typically the windiest seasons throughout the region.

Table 2. Seasonal distribution and frequency (mean number of days) of strong winds (daily mean wind speed > 30 km/hr) recorded at selected Otago locations, from all available data.

Location	Summer		Autumn		Winter		Spring		Annual Frequency
	Distribution	Frequency	Distribution	Frequency	Distribution	Frequency	Distribution	Frequency	
Nugget Point	23%	22	25%	24	27%	26	25%	25	97
Dunedin, Musselburgh	26%	4	24%	3	21%	3	29%	4	14
Lauder	23%	2	21%	2	18%	2	38%	4	10
Wanaka (Airport)	40%	3	14%	1	7%	0.6	39%	3	8
Queenstown (Airport)	25%	1	27%	1	19%	1	29%	1	5
Oamaru (Airport)	19%	1	18%	1	22%	1	41%	2	5
Middlemarch	14%	0.6	28%	1	21%	1	37%	2	4
Ranfurly	25%	1	4%	0.2	21%	0.8	50%	2	4
Clyde	0%	0	34%	0.1	49%	0.2	17%	0.1	0.4

Diurnal variation in wind speed is well-marked, with highest wind speeds occurring mid-afternoon or early-evening before decreasing overnight. This is because heating of the land surface is most intense during the day, and stronger winds aloft are brought down to ground level by turbulent mixing. Cooling at night generally restores a lighter wind regime. Table 3 gives average wind speeds at three-hourly intervals for selected locations, whilst Figure 8 visually highlights the typical diurnal variation of wind speed observed throughout Otago.

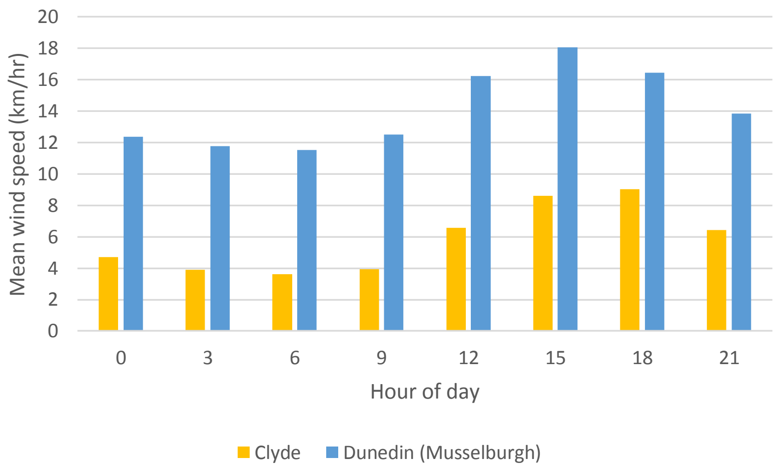


Figure 8. Mean wind speed at selected hours of the day for Clyde and Dunedin.

Table 3. Mean wind speed (km/hr) at three-hourly intervals of the day.

Location	0000	0300	0600	0900	1200	1500	1800	2100
Clyde	5	4	4	4	7	9	9	6
Dunedin (Musselburgh)	12	12	12	13	16	18	16	14
Lauder	10	9	8	9	11	14	15	13
Middlemarch	8	7	7	8	10	12	13	10
Nugget Point	24	23	23	23	25	27	28	26
Oamaru (Airport)	9	9	9	10	15	18	14	11
Queenstown (Airport)	10	9	9	9	12	14	14	13
Ranfurly	9	8	7	7	10	13	14	12
Wanaka (Airport)	11	10	9	10	13	15	15	12

Gusty winds are relatively infrequent throughout most lowland Otago locations, occurring more frequently in the mountain ranges and exposed coastal locations. Dunedin and Lauder experience an average of 65 days per year with wind gusts exceeding 61 km/hr, considerably more than Wanaka where on average 29 such days per year are recorded (Table 4). Maximum gusts recorded at different locations in Otago are listed in Table 5. Note that at the time of data collection for this publication, records only date back around 15 years for some locations (e.g. Ranfurly), and max gust records were not available for some stations (e.g. Nugget Point). The highest gust recorded in the region was 140.8 km/hr, occurring in Dunedin on 18 November 1984. Notably, Queenstown reached 24.2°C on the same day the max gust was recorded there: a particularly high temperature in October for that location.

Table 4. Mean number of days per year with gusts exceeding 61 km/hr and 94 km/hr for selected locations.

Location	Days with gusts >61 km/hr	Days with gusts >94 km/hr
Dunedin (Musselburgh)	65	2
Lauder	65	5
Middlemarch	55	5
Queenstown (Airport)	30	0.4
Ranfurly	33	0.7
Wanaka (Airport)	29	0

Table 5. Highest recorded wind gusts at selected Otago locations, from all available data.

Location	Gust (km/hr)	Direction	Date
Dunedin (Musselburgh)	140.8	W	18/11/1984
Lauder	139.0	NW	15/01/1998
Ranfurly	131.6	WNW	02/09/2006
Queenstown (Airport)	131.6	NW	03/10/1981
Middlemarch	129.7	NNW	01/09/2005
Wanaka (Airport)	92.7	NW	03/09/1993
	92.7	NNW	18/12/1997

Rainfall

Rainfall distribution

The spatial distribution of Otago's median annual rainfall is shown in Figure 9, which clearly illustrates both its dependence on elevation and exposure to the main rain bearing airflows from the west. Rainfall is highest among the western ranges which have both high elevation and western exposure. Such high rainfall is primarily a result of the orographic effect. Specifically, moisture-laden air masses arrive off the Tasman Sea and are forced to rise over the western ranges. As these air masses rise, they cool rapidly, causing the stored water vapour to condense, resulting in rainfall. These air masses continue eastwards, but they hold significantly less moisture once beyond the western ranges. As a result, there is a marked decrease eastwards in median annual rainfall beyond the Otago lakes and headwaters. Central Otago is both the driest area of Otago and New Zealand. Here, median annual rainfall totals of below 400 mm are recorded, which is approximately ten times less rainfall than that which falls in high elevation locations in the far-western ranges of Otago. The annual 'title' of New Zealand's driest centre is almost exclusively awarded to either Alexandra or Clyde.

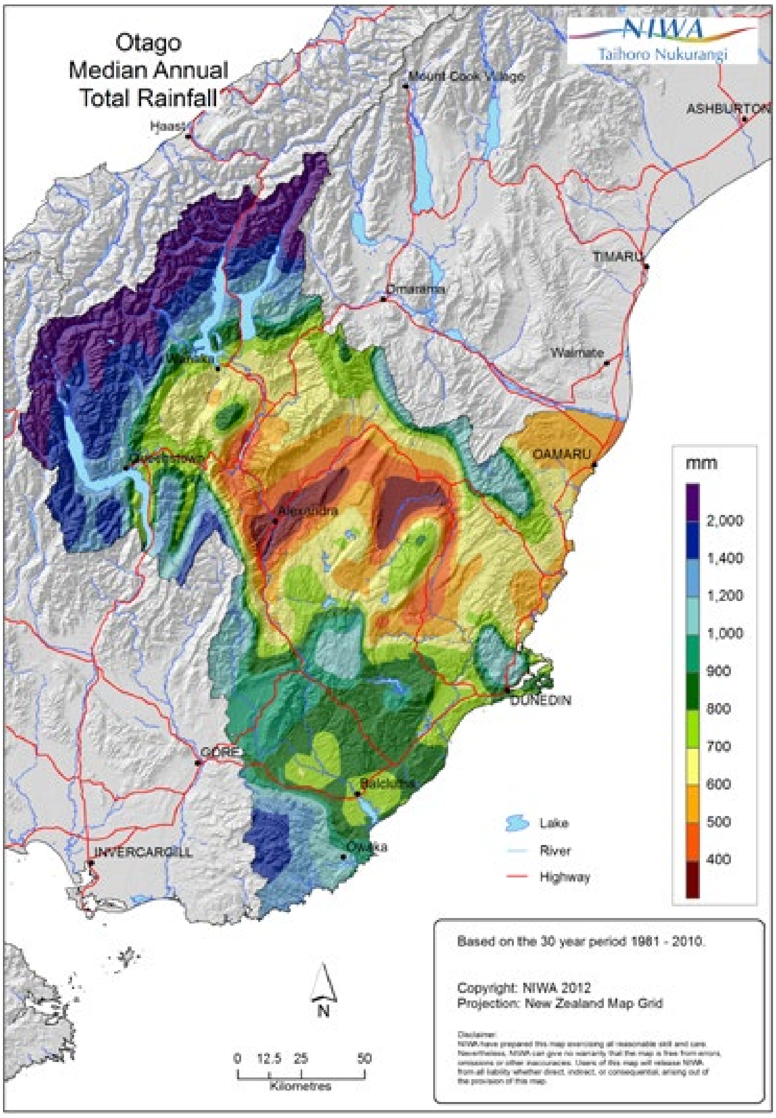


Figure 9. Otago median annual total rainfall, 1981–2010.

Table 6. Monthly and annual rainfall normal (a; mm), and monthly distribution of annual rainfall (b; %) at selected Otago locations, for the period 1981–2010.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Alexandra	a	48	36	29	24	28	31	19	23	19	31	31	47	363
	b	13	10	8	6	8	9	5	6	5	8	8	13	
Balclutha	a	78	68	62	50	68	62	50	43	48	61	53	71	713
	b	11	9	9	7	10	9	7	6	7	9	7	10	
Clyde	a	51	41	33	34	32	33	24	24	26	36	35	49	416
	b	12	10	8	8	8	8	6	6	6	9	8	12	
Cromwell	a	48	33	43	33	33	38	28	27	26	36	41	52	437
	b	11	8	10	8	7	9	6	6	6	8	9	12	
Dunedin (Airport)	a	69	63	56	48	60	47	46	40	42	58	50	72	652
	b	11	10	9	7	9	7	7	6	6	9	8	11	
Dunedin (Btl Gardens)	a	92	88	85	67	89	77	87	78	63	82	73	88	968
	b	9	9	9	7	9	8	9	8	7	8	8	9	

Table 6 continued.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Dunedin (Musselburgh)	a	73	68	64	51	65	58	57	56	48	62	56	80	738
	b	10	9	9	7	9	8	8	8	7	8	8	11	
Lauder	a	58	39	37	38	33	31	23	20	23	34	41	61	439
	b	13	9	8	9	8	7	5	5	5	8	9	14	
Makarora	a	197	134	194	175	202	228	185	217	232	241	190	251	2447
	b	8	5	8	7	8	9	8	9	9	10	8	10	
Middlemarch	a	57	51	42	35	33	31	31	24	31	47	45	68	495
	b	12	10	9	7	7	6	6	5	6	10	9	14	
Oamaru (Airport)	a	44	34	39	37	42	38	41	37	29	33	42	56	473
	b	9	7	8	8	9	8	9	8	6	7	9	12	
Queenstown (Airport)	a	64	48	53	56	70	72	49	69	67	66	68	76	757
	b	8	6	7	7	9	10	6	9	9	9	9	10	
Ranfurly	a	53	37	37	37	31	30	30	22	26	37	36	62	438
	b	12	8	8	9	7	7	7	5	6	8	8	14	
Roxburgh	a	62	60	71	44	43	42	48	35	35	57	65	55	616
	b	10	10	11	7	7	7	8	6	6	9	10	9	
Wanaka (Airport)	a	55	35	44	47	58	60	38	52	57	48	35	66	594
	b	9	6	7	8	10	10	6	9	10	8	6	11	

Table 6 lists monthly rainfall normals and the percentage of annual total for selected locations. Many Otago locations observe a maximum of rainfall in the summer months. For example, Alexandra, Lauder and Middlemarch each receive 36% of their annual rainfall during summer. In contrast, rainfall tends to be fairly evenly distributed across the year in the more western locations of Makarora, Queenstown and Wanaka. Both Lauder and Middlemarch observe a notable winter rainfall minimum, with just 17% of annual rainfall falling between June and August.

The distribution of monthly rainfall is shown in Figure 10. The 10th percentile, 90th percentile, and mean rainfall values for each month are shown along with maximum and minimum recorded values for several stations.

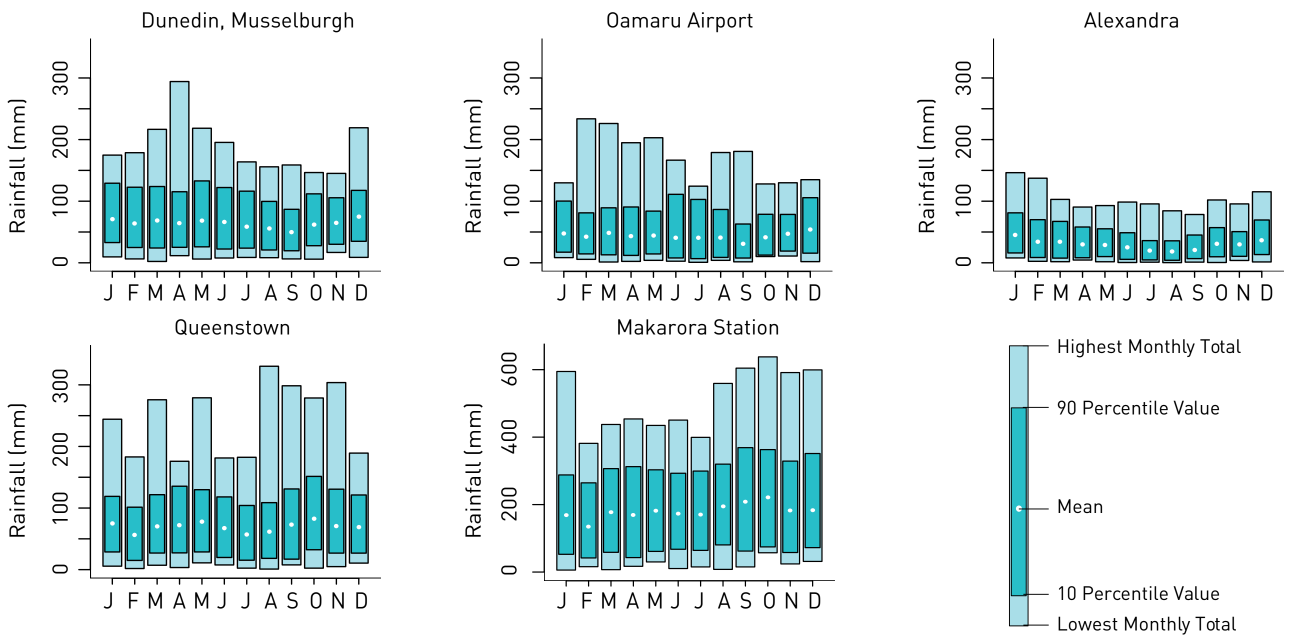


Figure 10. Monthly variation of rainfall for selected Otago locations from all available data.

Rainfall variability over longer periods is indicated by rainfall deciles, as given in Tables 7, 8 and 9. The 10th percentile values show the accumulated rainfalls that will normally be exceeded in nine out of ten years, while the 90th percentile values indicate the accumulated falls that will normally be exceeded in only one year in ten. The tables include periods from one month to twelve months (annual), with each time period that is longer than one month beginning with the month stated. For example, using the table for Alexandra (Table 7), it can be seen that in the three month period beginning in January, 63 mm or more of rainfall can be expected in nine years in ten, while a total of 162 mm or more will, on average, occur in only one year in ten.

Table 7. Rainfall means and deciles at monthly, 3-monthly, 6-monthly, 9-monthly and annual intervals for Alexandra from all available data.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Alexandra												
1 month												
90th	81	70	67	58	55	49	36	36	45	57	51	70
Mean	45	34	34	30	29	25	20	18	21	31	30	37
10th	16	9	8	8	10	6	5	4	7	10	11	13
3 months												
90th	162	147	128	119	104	90	95	110	120	153	165	169
Mean	112	97	92	84	73	62	58	71	82	98	111	114
10th	63	47	48	46	38	29	25	36	47	58	65	67
6 months												
90th	272	229	199	194	195	190	213	234	266	294	289	282
Mean	196	170	154	142	142	143	156	171	195	208	207	206
10th	132	108	109	97	89	94	100	114	136	134	144	133
9 months												
90th	335	311	306	322	327	324	352	366	391	389	369	342
Mean	253	239	235	239	253	257	265	277	287	292	279	267
10th	182	167	171	170	184	178	184	198	211	214	208	202
Annual												
90th	431											
Mean	348											
10th	269											

Rainfall frequency and intensity

The average number of days each year on which 0.1 mm or more of rain is recorded (a rain day) varies from 101 days at Middlemarch to 178 days at Dunedin (Botanical Gardens). Alexandra and Clyde experience the lowest number of wet days (> 1.0 mm of rain) in the region, with 65 wet days recorded there on average, compared with 137 wet days at Makarora. Table 10 lists the average number of days per month with at least 0.1 mm and 1 mm of rain for selected locations. The number of rain and wet days recorded at a given station tends to decrease as distance from the coast increases. As such, inland locations experience fewer rain and wet days than coastal and western-most locations. The seasonal variation of rain days and wet days in Otago is relatively small. Therefore, the summer maximum of rainfall observed in some areas of Otago may be largely attributed to there being more heavy falls of rain, as opposed to more total days of rain.

Table 8. Rainfall means and deciles at monthly, 3-monthly, 6-monthly, 9-monthly and annual intervals for Dunedin from all available data.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dunedin (Musselburgh)												
1 month												
90th	129	123	124	115	133	122	116	100	87	112	106	118
Mean	71	64	69	64	68	66	59	56	50	62	65	75
10th	33	25	24	25	26	22	24	21	20	28	30	35
3 months												
90th	300	291	299	315	303	266	262	243	247	280	300	304
Mean	204	197	202	200	194	180	165	168	177	201	211	210
10th	113	102	110	114	114	101	90	87	118	135	141	124
6 months												
90th	557	558	511	496	478	477	463	490	500	525	535	551
Mean	403	392	380	360	359	357	367	378	386	405	409	412
10th	250	271	260	249	257	249	266	274	289	293	288	271
9 months												
90th	723	708	706	712	732	693	715	758	758	788	814	774
Mean	565	557	556	563	570	567	571	576	589	605	602	590
10th	409	398	436	431	438	419	436	418	452	452	444	430
Annual												
90th	942											
Mean	768											
10th	600											

Table 9. Rainfall means and deciles at monthly, 3-monthly, 6-monthly, 9-monthly and annual intervals for Makarora from all available data.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Makarora												
1 month												
90th	288	264	307	313	303	293	299	320	369	363	329	351
Mean	169	135	178	169	182	173	170	195	209	221	183	183
10th	53	42	59	43	61	68	64	80	62	75	58	72
3 months												
90th	737	726	765	707	746	757	837	987	928	827	810	783
Mean	478	481	528	526	525	537	573	625	613	588	535	485
10th	251	250	288	336	338	358	330	353	295	328	273	242
6 months												
90th	1342	1308	1346	1444	1538	1508	1628	1603	1533	1444	1416	1395
Mean	1005	1010	1070	1098	1148	1148	1161	1159	1098	1066	1014	1023
10th	648	707	782	747	753	721	698	647	639	647	624	705
9 months												
90th	2056	2120	2180	2237	2204	2095	2153	2180	2109	2068	2062	2101
Mean	1577	1634	1681	1687	1684	1631	1634	1637	1625	1593	1540	1554
10th	1057	1110	1139	1132	1077	1059	1032	1052	1094	1091	1050	1092
Annual												
90th	2769											
Mean	2163											
10th	1501											

Table 10. Average monthly rain days (a; days where at least 0.1 mm rainfall is measured) and wet days (b; days where at least 1 mm rainfall is measured) at selected Otago locations.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Alexandra	a	9	8	8	9	10	9	9	8	8	9	9	10	107
	b	6	5	5	5	6	5	5	4	5	6	6	7	65
Balclutha	a	14	11	13	13	15	14	14	13	14	14	15	13	163
	b	9	8	9	9	11	10	9	8	9	10	10	10	113
Clyde	a	10	9	8	10	13	12	10	11	10	12	10	12	127
	b	6	5	4	5	6	5	4	5	5	7	6	7	65
Cromwell	a	11	9	10	10	13	14	12	12	10	13	10	13	138
	b	6	5	6	6	6	7	5	5	5	7	5	7	70
Dunedin (Airport)	a	14	11	12	13	15	16	15	15	13	15	15	15	171
	b	9	8	8	8	9	9	8	8	8	11	10	11	107
Dunedin (Btl Gardens)	a	15	13	15	14	16	15	15	15	14	16	16	16	178
	b	11	9	10	10	11	10	10	10	10	12	12	12	128
Dunedin (Musselburgh)	a	14	12	13	13	14	14	14	14	13	15	15	15	166
	b	10	8	9	9	10	10	10	9	9	11	11	12	118
Lauder	a	9	8	7	9	11	13	11	9	7	9	9	10	113
	b	7	6	5	5	6	6	5	5	4	6	7	7	69
Makarora	a	13	10	13	12	14	14	13	15	15	16	14	15	165
	b	10	8	10	10	12	11	11	12	13	14	12	13	137
Middlemarch	a	10	8	8	8	8	7	7	7	8	10	10	11	101
	b	8	7	7	6	6	5	5	5	6	8	8	9	80
Oamaru (Airport)	a	10	8	9	10	10	9	9	9	8	10	10	11	114
	b	7	6	6	6	6	5	6	6	5	7	8	8	76
Queenstown	a	10	8	9	10	11	10	9	10	10	12	11	11	121
	b	8	6	8	8	9	8	7	7	8	9	8	8	95
Ranfurly	a	9	8	8	8	9	8	8	8	8	10	9	10	102
	b	7	6	6	6	6	5	5	5	5	7	6	7	70
Roxburgh	a	10	8	9	9	9	9	8	8	8	10	10	10	108
	b	8	7	7	7	7	7	6	6	7	8	8	9	87
Wanaka (Airport)	a	8	7	8	8	11	13	11	10	10	11	8	11	114
	b	6	5	6	6	7	7	6	7	7	8	6	8	78

Heavy short period rainfalls in the western ranges often occur during persistent west/northwesterly airflows as a trough approaches the South Island. For remaining areas of Otago, heavy short period rainfalls occur with the passage of a depression over or close to the region, or in association with slow moving fronts. High intensity rainfall, particularly at sub-hourly periods, is typically associated with thunderstorm activity. Eastern areas of Otago typically experience heavy rainfalls over 12- to 72-hour periods when a depression is centred to the east of the South Island (e.g. Figure 4), due to the prevalence of moisture-laden easterly-quarter winds under such circumstances. In Table 11, maximum short period rainfalls for periods of 10 minutes to 72 hours with calculated return periods are given for Dunedin and Queenstown. Also listed in this table are the maximum rainfalls expected in 2, 5, 10, 20, and 50 years. Depth-duration frequency tables for Otago locations are available from NIWA's High Intensity Rainfall Design System (HIRDS). HIRDS uses the index-frequency method to calculate rainfall return periods. For more information on methods and to use the tool, see http://hirds.niwa.co.nz/.

Table 11. Maximum recorded short period rainfalls and calculated return periods from HIRDS.

Location		10min	20min	30min	1hr	2hrs	6hrs	12hrs	24hrs	48hrs	72hrs
Dunedin (Musselburgh)	a	17.9	26.9	28.5	28.8	29.4	53.0	89.9	120.7	162.3	175.0
	b	Feb 2005	Feb 2005	Feb 2005	Feb 2005	Feb 2005	Jun 2015	Jun 2015	Jun 2015	Mar 1968	Mar 1968
	c	100+	100+	100+	100+	20	26	65	60	95	80
	d	4.1	5.8	7.2	10.3	14.8	26.5	38.2	55.2	67.2	75.5
	e	5.6	8.0	9.9	14.1	20.0	34.8	49.4	70.1	85.4	95.9
	f	6.9	9.9	12.2	17.4	24.4	41.8	58.6	82.1	100.1	112.3
	g	8.4	12.1	14.9	21.4	29.6	49.7	68.9	95.6	116.5	130.7
	h	10.9	15.7	19.4	27.8	37.9	62.3	85.1	116.4	141.8	159.1
Queenstown	a	8.1	11.7	13.8	21.8	30.1	58.8	81.3	120.5	176.3	242.6
	b	Jul 1990	Jul 1990	Mar 1969	Mar 1969	Mar 1969	Jun 1983	Mar 1987	Nov 1999	Nov 1999	Nov 1999
	c	100	60	37	33	30	61	60	90	100+	100+
	d	3.2	5.1	6.8	10.9	15.7	28.0	40.3	58.0	69.1	76.5
	e	4.1	6.6	8.7	14.1	20.0	35.1	49.9	71.0	84.6	93.6
	f	4.8	7.8	10.3	16.6	23.5	40.7	57.5	81.2	96.7	107.0
	g	5.6	9.1	12.1	19.5	27.4	46.9	65.8	92.3	109.9	121.7
	h	6.9	11.2	14.9	24.0	33.4	56.3	78.4	109.0	129.8	143.7

a: highest fall recorded (mm)
b: month and year of occurrence
c: calculated return period of a (years)
d: max fall calculated with ARI 2 years (mm)
e: max fall calculated with ARI 5 years (mm)
f: max fall calculated with ARI 10 years (mm)
g: max fall calculated with ARI 20 years (mm)
h: max fall calculated with ARI 50 years (mm)

Recent extreme events in Otago

Otago has experienced numerous extreme weather events, with significant damage and disruption caused in particular, by heavy rain and flooding. The events listed below are some of the most severe rainfall and flooding events to have affected the Otago region between 1980 and 2015.

4–7 June 1980: Heavy rain in Otago caused widespread flooding, with at least 8370 hectares of land flooded, including 124 homes. Stock losses comprised 1680 sheep, 151 dairy cows and 79 yearling cattle, whilst 7500 cattle and 6200 sheep were evacuated from the region. A Civil Defence emergency was declared in Tuapeka County, the Taieri Plain, Clutha County and Silverpeaks County. The weather pattern was typical of heavy easterly rain in Otago, featuring a large, slow-moving depression to the east of the South Island. Dunedin recorded 119.3 mm of rain in 24 hours to 9 a.m. on 5 June. At least 60 St Clair residents were evacuated from their hillside homes as a mudslide threatened to knock several houses off their foundations. Numerous other slips were reported, especially about the Otago Peninsula. SH 1 south of Dunedin was closed between Mosgiel and Balclutha by flooding, and railway lines into and out of the city were blocked by flooding. Major damage was caused to the pasture on the Taieri Plain, with land there unproductive for up to three months. Dunedin Airport (located on the Taieri Plain) was under water for six weeks. North of Dunedin, SH 1 was open to Hampden but closed from there to Herbert.

14–18 November 1999: Heavy rain was caused by a front that stalled over the area as a broad, active trough approached from the Tasman Sea. The original frontal cloud band remained almost stationary over Fiordland for two-and-a-half days. A Civil Defence Emergency was declared for the Central Otago District, the Clutha District and Queenstown. The Clutha River was in high flood, and at one point was flowing at six times its normal volume (3200 cumecs, compared to a normal flow of 500 cumecs). The river peaked at 142.5 metres above sea level at Alexandra on 18 November, 7.5 m above normal. Around 200 homes and businesses in Alexandra were evacuated due to flooding, and nine homes were destroyed due to floodwaters reaching up to their eaves.

Some Balclutha properties were inundated by floodwater, with 110 people evacuated there. Queenstown received 243 mm of rain in 72 hours: establishing a new record 72-hour rainfall for Queenstown (the previous record was in 1871). The central business area of Queenstown was engulfed by Lake Wakatipu on 17 November, with some buildings inundated for an entire week. Lake Wakatipu reached a peak of 312.7 metres above sea level on 18 November. This was its highest level on record, surpassing the record set in 1878 by half a metre. Farther north, Lake Wanaka reached a level of 281.3 metres above sea level: its highest level since September 1878. The central business area of Wanaka was inundated by Lake Wanaka on 17 November, with around 60 businesses affected by the floodwaters.

24–31 May 2010: A front carrying heavy rain moved down the North Island on 24 May and stalled over Canterbury, contributing to heavy rain and flooding which predominantly affected eastern parts of Otago. In addition, a cold southerly flow brought snow to low levels in Otago on 26 and 27 May, exacerbating the flooding situation. Rivers in eastern parts of Otago flooded due to persistent rainfall, combined with snowmelt which occurred in river catchments. Oamaru was completely isolated for a time, with flooding forcing the closure of SH 1 north and south of the town, as well as the SH 1 bypass roads. Oamaru recorded 146 mm of rain from midday on 24 May to 9 p.m. on 25 May. The army was called in to help North Otago residents stranded by flooding: soldiers and two Unimogs accessed areas cut off by heavy rain and delivered supplies. Dunedin recorded 77 mm of rain in 24 hours to 9 p.m. on 25 May, and Dunedin Airport recorded 243 mm of rain from 24 May to 31 May. Floodwater covered the railway line south of Allanton for five days. On 30 May a sizeable landslip swept through Berwick Forest campground (near Outram), shifting a building where 42 people were sleeping. These people were transferred to the caretaker's premises before being evacuated to Dunedin.

3–4 June 2015: Dunedin was inundated by very heavy and prolonged rainfall, which resulted in significant flooding, loss of electricity, evacuations and road closures throughout the city and nearby areas. Numerous slips were reported along Otago Peninsula, while New Zealand Army's Unimog trucks were involved in evacuating pupils from Abbotsford School. The normally placid Leith Stream was a raging torrent and proved popular with local kayakers. The Fire Service responded to 345 callouts, with the vast majority of those in the South Dunedin area. Dunedin (Musselburgh) received 113 mm of rainfall in the 24 hours to 9 a.m. on 4 June – its second-highest 1-day rainfall total for June on record.

Periods of low rainfall

Periods of fifteen days or longer with less than 1 mm of rain on any day are referred to as 'dry spells'. Dry spells are not particularly common towards coastal areas of Otago, however they do occur more frequently in inland areas. Dry spells throughout Otago typically occur when a persistent (blocking) anticyclone becomes established over the South Island. Additionally, the western ranges provide a great deal of sheltering for eastern areas, such that dry spell conditions can occur in north or northwesterly airstreams. Table 12 outlines the dry spell frequency and duration for selected Otago locations. On average, a dry spell occurs once every three months in Alexandra, and once every thirteen months in Dunedin. The longest dry spell was 59 days, recorded in Queenstown from 21 July 1952 to 17 September 1952. Table 13 shows the seasonal distribution of dry spells at selected Otago locations. Dry spells occur most frequently during winter in Dunedin and Queenstown, and in autumn in Alexandra.

Table 13. Seasonal distribution (%) of dry spells at selected Otago locations, from all available data.

Location	Summer	Autumn	Winter	Spring
Alexandra	18%	31%	27%	24%
Dunedin (Musselburgh)	17%	31%	39%	13%
Queenstown	25%	22%	34%	19%

Table 12. Dry spell (at least 15 consecutive days with less than 1 mm rainfall per day) frequency and duration for selected Otago locations, from all available data.

Location	Frequency	Mean duration (days)	Max duration (days)	Max duration date
Alexandra	One every 3 months	21	40	18/2/2003 to 29/3/2003
Dunedin (Musselburgh)	One every 13 months	18	36	26/2/2001 to 2/4/2001
Queenstown	One every 6 months	19	59	21/7/1952 to 17/9/1952

Temperature

Sea surface temperature

Monthly mean sea surface temperature off the south-eastern coast of Otago is compared with mean air temperature for Alexandra and Dunedin in Figure 11. There is a lag in the increase of sea surface temperatures when compared to air temperatures from July to September. This may be at least in part attributed to the greater heat capacity of the sea compared to land, which results in the sea surface temperatures taking longer to increase and decrease in response to changing seasons compared to land-based areas. Figure 11 highlights the influence of the sea on air temperatures at coastal locations in Otago. Dunedin records lower mean air temperatures in summer and higher mean air temperatures in winter compared to the inland location of Alexandra. Figure 12 shows the mean sea surface temperatures for the New Zealand region for February and August, which are the warmest and coolest months with respect to sea surface temperatures.

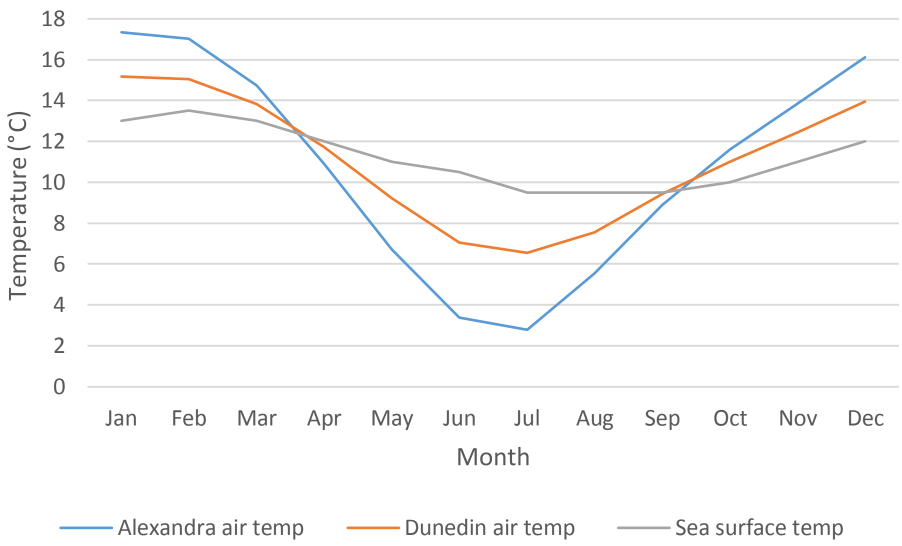


Figure 11. Mean monthly air temperature (Alexandra and Dunedin) and estimated sea surface temperature (off the south-eastern coast of Otago).

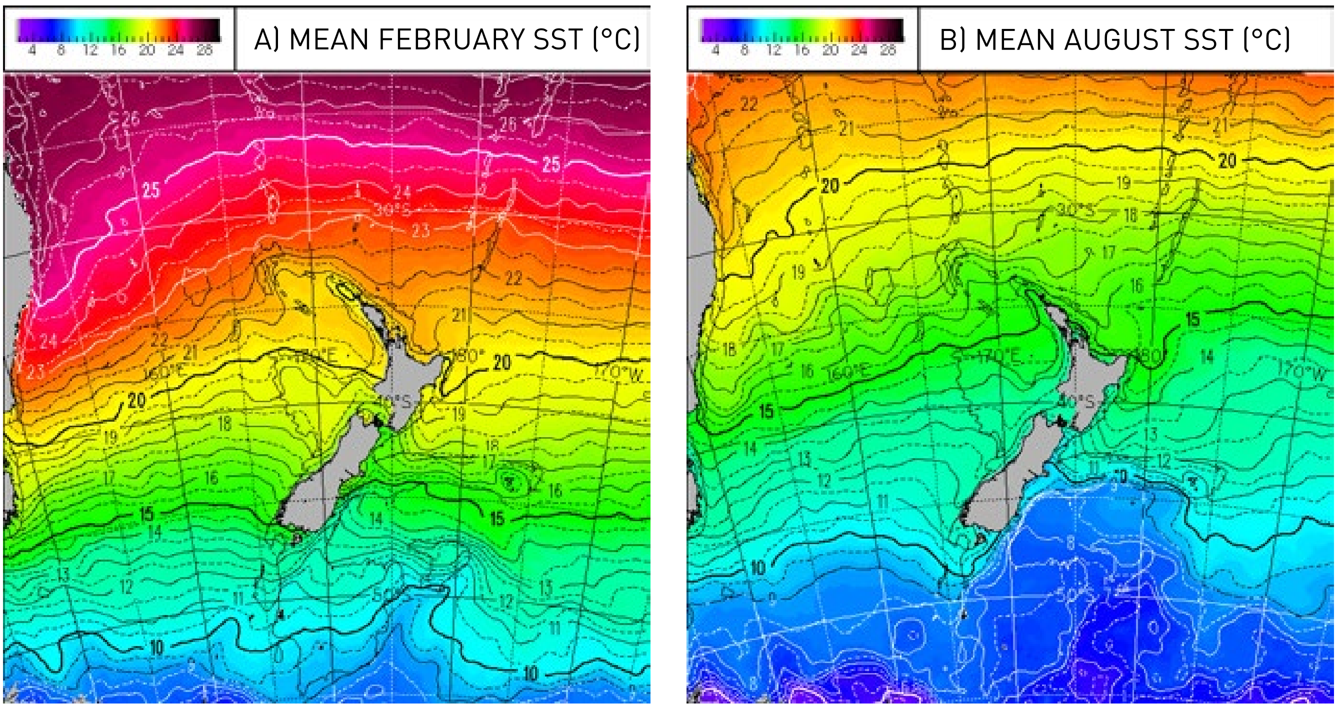


Figure 12. Monthly mean sea surface temperatures (°C) for: a) February; b) August. Source: NIWA SST Archive, Uddstrom and Oien (1999).

Air temperature

Otago typically observes afternoon temperatures reaching between 18°C and 24°C in summer, and overnight temperatures falling to between -2°C and 3°C in winter (Figure 13). Inland areas of Otago typically record higher daily maximum temperatures in summer and lower daily minimum temperatures in winter compared to areas nearer the coast. The notable exception is relatively high elevation hills and mountains, where temperatures are lower throughout the year. This is because temperatures generally decrease with elevation, reducing by about 6°C for every 1000 m increase in elevation. Figure 14 shows the median annual average temperature in the Otago region, and clearly demonstrates that lower temperatures are recorded at higher elevation locations. Many relatively low elevation locations throughout Otago have a mean annual temperature of between 10°C and 11°C, although some inland areas about Central Otago observe a slightly lower mean annual temperature of between 9°C and 10°C. Mean annual temperatures of below 2°C occur in the western ranges about Mt Earnslaw, Mt Aspiring and Mt Brewster, which contributes to the perennial snow and glaciers at high elevations in those areas. Figure 15 gives the monthly temperature regime (highest recorded, mean monthly maximum, mean daily maximum, mean, mean daily minimum, mean monthly minimum, and lowest recorded) for selected locations in Otago.

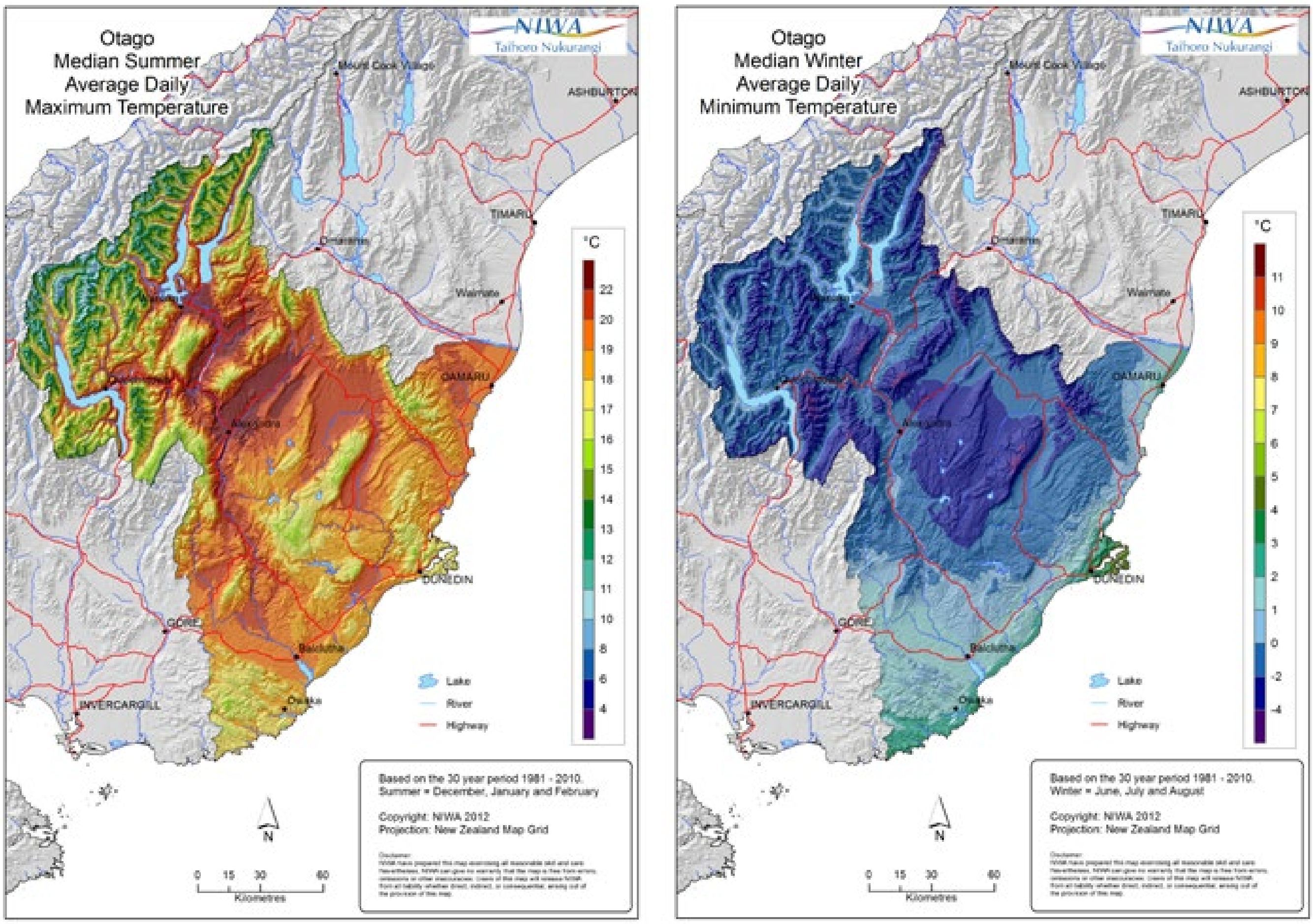


Figure 13. Left: Otago median summer (December, January and February) average daily maximum temperature; Right: Otago median winter (June, July and August) average daily minimum temperature.

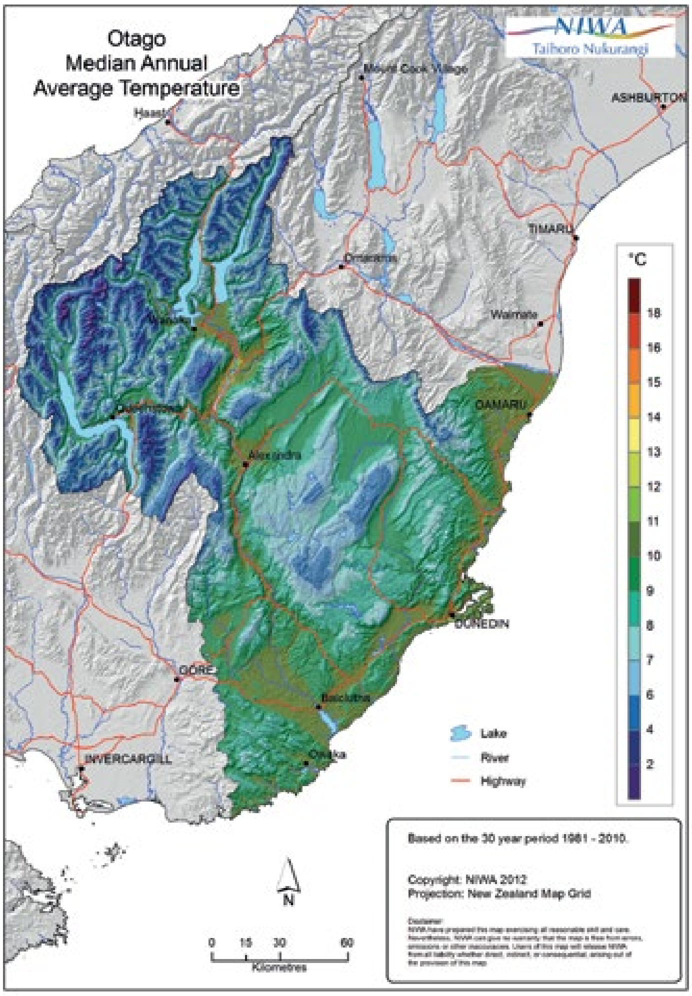


Figure 14. Otago median annual average temperature, 1981–2010.

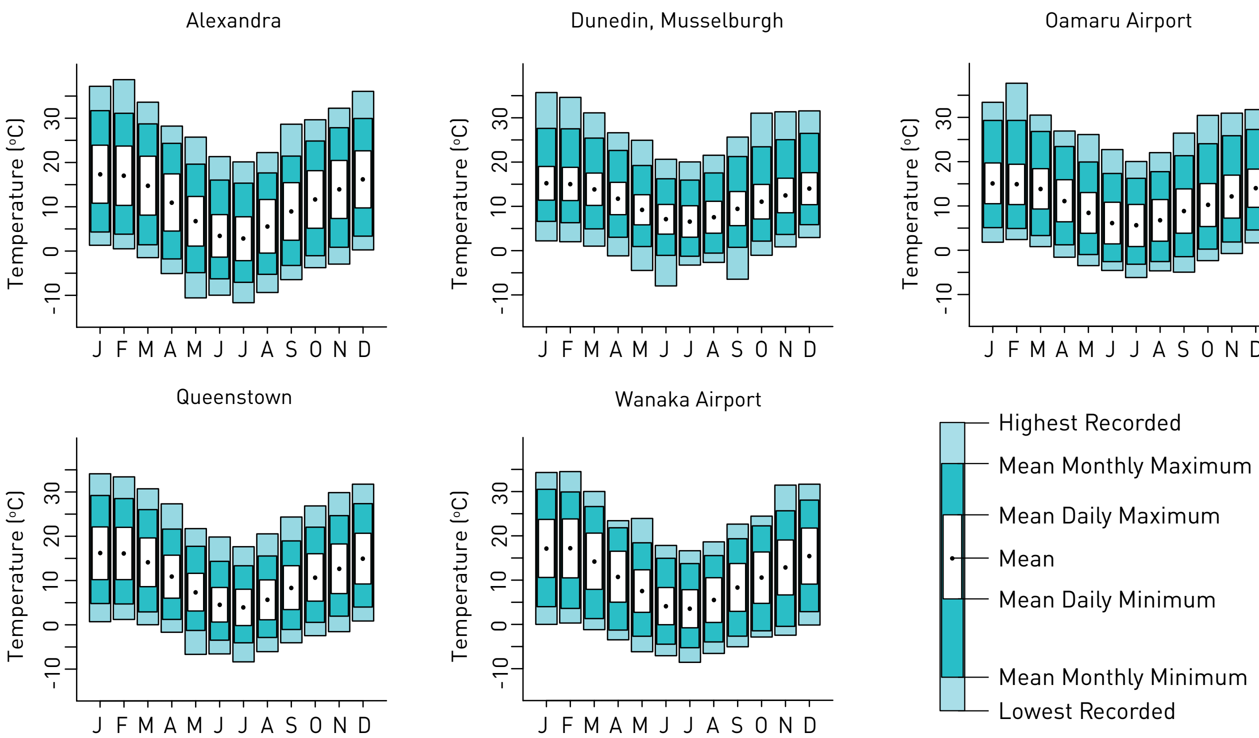


Figure 15. Monthly variation in air temperatures for selected Otago locations.

Table 14 shows that the average daily temperature range, i.e. the difference between the daily maximum and minimum temperature, is smaller at the coast (e.g. Dunedin and Oamaru) than in inland areas (e.g. Alexandra). This is the case throughout the year, however the difference is most prominent during spring, summer and autumn. Central Otago consistently observes the highest average daily temperature range in Otago. Such diurnal variation can be attributed to its inland location, which isolates the area from the moderating influence of the sea on air temperatures.

Table 14. Average daily temperature range (Tmax–Tmin, °C) for selected Otago locations.

Location	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann**
Alexandra	13.2	13.4	13.3	12.9	11.3	9.6	9.9	12.1	13.0	13.0	13.1	12.9	12.3
Dunedin (Musselburgh)	7.6	7.6	7.3	7.3	6.9	6.8	7.0	7.2	7.7	7.8	7.8	7.2	7.4
Oamaru (Airport)	9.2	9.1	9.0	9.5	9.2	9.5	9.4	9.4	10.0	9.7	9.6	8.6	9.4
Queenstown	11.9	11.9	11.0	9.7	8.5	7.8	8.2	9.0	9.9	10.7	11.1	11.4	10.1
Wanaka (Airport)	13.1	13.3	12.7	11.5	9.6	8.4	8.7	10.1	10.8	11.6	12.4	12.7	11.2

Table 15 and Figure 16 further highlight the diurnal temperature range, showing the median hourly mean air temperature for January and July at Alexandra and Dunedin. Air temperatures at Alexandra remain lower than Dunedin at all hours of the day in July. In January, air temperatures in Alexandra are similar to Dunedin in the early hours of the morning, but considerably higher during the afternoon. Note that hourly mean air temperature at a given time is calculated as the mean of the maximum and minimum air temperature recorded over the previous hour. As such, both the daily maximum and minimum air temperatures are damped, resulting in a reduced diurnal temperature range (e.g. Table 15) compared to the absolute daily temperature range (Table 14) recorded at Alexandra and Dunedin.

Table 15. Median hourly mean air temperatures for January and July at Alexandra and Dunedin.

		00	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**
Alexandra	**January**	14.9	14.3	13.9	13.3	12.8	12.6	12.3	12.8	14.1	15.6	17.4	18.7
	July	0.3	-0.1	-0.1	-0.2	-0.5	-0.5	-0.3	-0.7	-0.9	-1.1	-0.2	1.6
		12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
	January	19.8	20.6	21.4	22.2	22.3	22.4	21.9	21.1	19.6	17.8	16.8	15.7
	July	3.3	5.1	6.5	7.4	7.8	6.9	5.4	3.9	2.6	1.7	1.1	0.8
		00	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**
Dunedin (Musselburgh)	**January**	13.5	13.3	13.3	13.0	12.7	12.6	12.5	13.2	14.2	15.2	15.7	16.3
	July	6.2	5.9	5.8	5.5	5.4	5.3	5.5	5.4	5.3	5.4	6.2	7.5
		12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
	January	16.5	16.8	17.0	16.8	16.4	16.2	15.7	15.3	14.8	14.3	14.1	13.8
	July	8.4	9	9.5	9.6	9.3	8.6	7.8	7.2	6.8	6.5	6.6	6.3

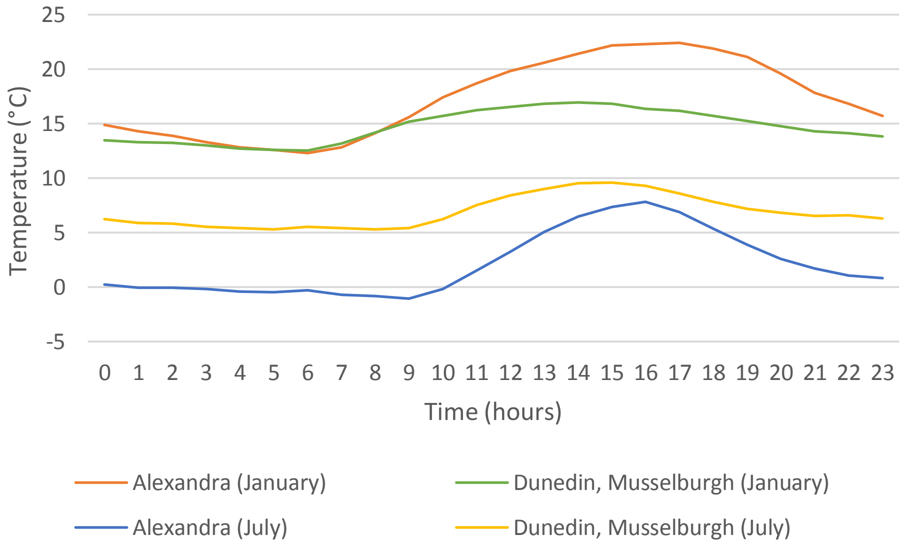


Figure 16. Median hourly mean air temperatures at Alexandra and Dunedin in January and July.

Maximum air temperatures in excess of 25°C occur relatively frequently throughout inland Otago, particularly in Clyde, where an annual average of 41 such days occur (Table 16). Furthermore, Central Otago locations reach maximum air temperatures in excess of 30°C relatively frequently when compared to remaining parts of New Zealand. Inland parts of Otago typically record a greater number of days with a maximum air temperature above 25°C and a minimum temperature below 0°C compared to locations closer to the coast. Indeed, Central Otago locations frequently observe New Zealand's highest daily maximum temperature during summer and New Zealand's lowest daily minimum temperature during winter. The highest air temperature recorded in Otago to date is 38.7°C at Alexandra on 5 February 2005. This temperature occurred towards the end of an extremely hot spell in Alexandra between 22 January 2005 and 10 February 2005. During this time, the average daily maximum temperature was 31.6°C, with 30°C exceeded on 12 out of the 20 days. The town reached a maximum temperature of at least 34°C on six consecutive days from 1 February 2005 to 6 February: a truly extraordinary occurrence for a New Zealand location. Ranfurly recorded the lowest air temperature in Otago; -25.6°C on 17 July 1903. This is additionally the lowest ever temperature recorded in New Zealand.

Table 16. Highest and lowest recorded air temperatures, average number of days per year where maximum air temperature exceeds 30°C and 25°C, and average number of days per year where the minimum air temperature falls below 0°C, for selected Otago locations from all available data.

Location	**Highest recorded (°C)**	**Annual days max temp > 30°C**	**Annual days max temp > 25°C**	**Lowest recorded (°C)**	**Annual days min temp < 0°C**
Alexandra	38.7	7	35	-11.7	86
Clyde	36.0	6	41	-9.8	93
Dunedin (Airport)	34.9	2	20	-8.8	66
Dunedin (Musselburgh)	35.7	0.6	7	-8.0	8
Lauder	35.0	3	33	-19.7	104
Middlemarch	36.0	4	33	-11.7	90
Nugget Point	33.0	0.1	3	-5.0	3
Oamaru (Airport)	37.7	0.9	11	-6.2	41
Queenstown	34.1	1	23	-12.2	47
Ranfurly	33.5	2	25	-25.6	118
Wanaka (Airport)	34.5	3	35	-8.6	73

Earth temperatures

Earth (soil) temperatures are measured once daily at 9 a.m. at several Otago locations. Earth temperatures are measured at varying depths and are important for determining the growth and development of plants. Different plants have different rooting depths and as such, earth temperatures are routinely monitored at 10, 20, 30, 50, and 100 cm depths. Table 17 lists mean monthly earth temperatures for a number of standard depths. At the coastal Dunedin location, lower summer earth temperatures and higher winter earth temperatures are observed when compared to the inland location of Clyde.

Figure 17 shows how earth temperatures change throughout the year at Dunedin, compared with mean air temperature. The 10 cm earth temperatures are lower than the mean air temperature except during summer. The annual earth temperature cycle at 100 cm depth is more damped and lagged than at shallower depths. As a result, earth temperatures at 100 cm remain above mean air temperature throughout winter, but fall slightly below mean air temperatures during spring, before returning to higher temperatures than the mean air temperature in summer. Diurnal variation of earth temperatures (not shown) decreases with increasing depth, such that earth temperatures may show little-to-no diurnal variation at 100 cm depth.

Table 17. Monthly and annual mean 9 a.m. earth temperatures (°C) at varying depths from the ground surface for selected Otago locations.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Clyde													
10 cm	18.4	17.6	14.1	9.2	5.4	2.1	1.0	2.5	6.4	9.9	14.0	17.4	9.8
20 cm	20.2	19.8	16.1	10.9	6.6	3.1	1.7	3.5	7.5	11.4	15.6	18.9	11.3
30 cm	21.3	21.0	17.3	12.0	7.6	3.7	2.2	4.1	8.1	12.1	16.4	19.8	12.1
100 cm	18.9	19.4	17.7	14.3	10.6	7.0	4.5	5.1	7.8	10.8	14.3	17.2	12.3
Dunedin (Musselburgh)													
10 cm	15.7	15.3	13.3	10.4	7.7	5.3	4.2	5.2	7.5	9.9	12.4	14.5	10.1
20 cm	16.5	16.3	14.3	11.4	8.6	6.1	5.0	5.9	8.2	10.6	13.1	15.1	10.9
30 cm	17.6	17.1	14.9	11.8	8.5	6.3	5.0	6.0	8.7	11.3	14.0	15.9	11.4
50 cm	16.8	17.0	15.6	13.2	10.5	7.9	6.6	7.2	9.0	11.2	13.5	15.5	12.0
100 cm	15.8	16.3	15.5	13.7	11.5	9.3	7.8	7.8	9.0	10.7	12.7	14.4	12.0
Ranfurly													
10 cm	15.5	14.9	12.9	9.4	6.0	3.1	1.7	3.2	6.0	8.4	11.9	14.8	9.0
20 cm	16.3	16.1	14.2	10.7	7.3	4.1	2.5	4.0	6.6	9.1	12.3	15.2	9.9
50 cm	16.4	16.5	15.0	12.1	8.9	5.8	3.8	4.8	7.1	9.4	12.3	15.2	10.6
100 cm	15.2	15.8	15.0	13.1	10.6	7.8	5.7	5.7	7.1	8.9	11.2	13.6	10.8

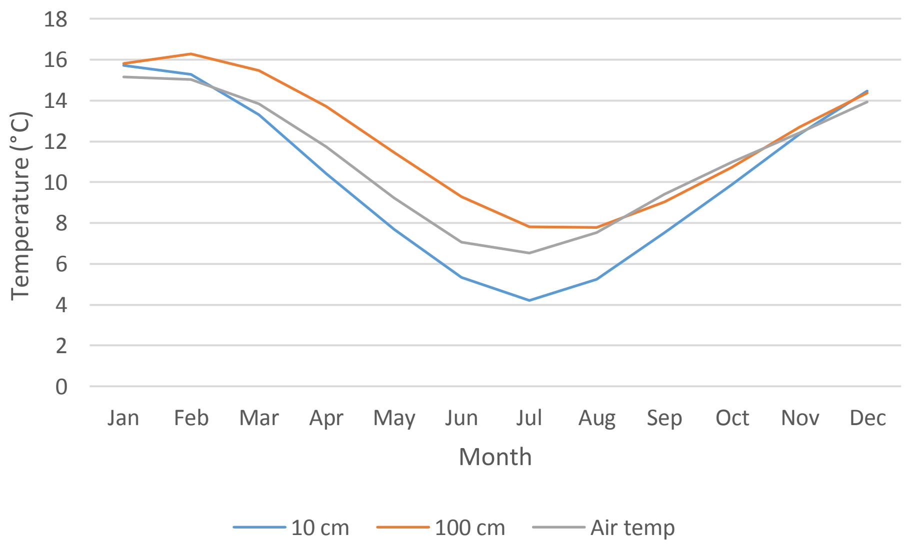


Figure 17. Monthly mean 9 a.m. earth temperature at different depths from the ground surface, and monthly mean air temperature, from all available data at Dunedin (Musselburgh).

Frosts

Frost is a local phenomenon and both its frequency of occurrence and intensity can vary widely over small areas. Frosts occur most frequently in winter during periods of anticyclonic conditions, primarily for two reasons. Firstly, clear skies associated with anticyclones enhance the rate of radiative cooling during the night. Secondly, anticyclones are associated with light winds, which reduces the amount of turbulent mixing of air. Cold air is relatively dense, so when there is a lack of turbulent mixing it tends to sink towards the earth surface. Therefore, areas most likely to experience frost are flat areas, where relatively cold air is not able to drain away on calm nights, and in valleys, where relatively cold air pools after descending from higher elevation areas nearby. Under such conditions, temperature inversions (where the air temperature increases with elevation) are common.

There are two types of frost recorded. Air frosts occur when air temperature measured in a screen 1.3 m above the ground falls below 0°C. Ground frosts are recorded when the air temperature 2.5 cm above a closely cut grass surface falls to -1.0°C or lower. Both types of frost are common in Otago in the cooler months. Table 18 lists for selected locations the mean daily grass minimum and extreme grass minimum temperatures, and the average number of days each month with ground and air frosts. Ground frosts occur more frequently than air frosts, and air frosts occur most frequently at the inland location of Alexandra.

Hoar frost is another form of frost which occurs infrequently, and its occurrence in Otago is typically limited to Central Otago. Hoar frost occurs when water vapour in the air comes into contact with features at the Earth's surface (e.g. tree leaves, branches, fences) that are below 0°C. The water vapour condenses and freezes upon contact, enabling ice crystals (frost) to form on the individual features, making for a scenic phenomenon.

Table 18. Frost occurrence and grass minimum temperatures at selected Otago locations.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Alexandra	a	7.5	7.2	4.9	1.3	-1.9	-3.9	-4.6	-3.5	-1.2	1.2	3.7	6.6
	b	-4.3	-7.5	-7.8	-11.9	-13.9	-13.9	-14.4	-15.0	-11.9	-10.6	-7.8	-5.2
	c	1	1	4	11	19	25	27	24	17	11	5	1
	d	0	0	0.3	3	12	20	24	19	7	2	0.5	0
Dunedin (Musselburgh)	a	8.7	8.5	7.2	4.5	2.1	-0.1	-0.9	0.1	1.7	3.6	5.4	7.8
	b	-2.7	-2.6	-3.5	-5.5	-8.9	-10.1	-11.1	-9.0	-9.4	-6.5	-5.5	-2.8
	c	0.1	0.1	0.4	2	7	13	16	13	8	4	1	0.2
	d	0	0	0	0	0.4	2	3	2	0.3	0.1	0	0
Queenstown	a	6.3	6.2	4.4	1.9	-0.8	-3.1	-4.0	-2.9	-1.1	0.9	2.9	5.3
	b	-5.6	-4.4	-7.1	-8.7	-11.7	-12.6	-13.4	-12.6	-10.6	-8.0	-10.0	-6.0
	c	1	1	3	8	16	22	26	23	16	11	5	1
	d	0	0	0	0.1	4	13	16	10	2	0.1	0	0
Wanaka (Airport)	a	8.2	8.1	5.3	2.0	0.0	-2.4	-3.1	-2.2	0.0	1.9	3.9	6.7
	b	-5.0	-3.1	-3.8	-8.5	-11.0	-10.3	-10.7	-10.1	-10.2	-6.8	-5.5	-3.1
	c	0.3	1	2	7	13	20	22	20	13	8	4	1
	d	0	0	0.2	2	7	17	20	14	7	3	1	0.1

a: Mean daily grass minimum (°C)
b: Lowest grass minimum recorded (°C)
c: Mean number of ground frosts per month
d: Mean number of air frosts per month

Sunshine and solar radiation

Sunshine

Sunshine hours typically increase as distance from the coast increases (Figure 18), with the notable exception of some mountainous areas (e.g. The Remarkables near Queenstown and Pisa Range near Cromwell) where increased cloudiness reduces sunshine totals experienced there. South-eastern parts of Otago receive relatively low annual sunshine hours compared with much of the rest of New Zealand. Coastal South Otago is particularly cloudy, and this area receives less than 1500 hours of bright sunshine annually. Other locations near the east coast receive between 1600 and 1800 hours of sunshine annually, compared to many inland locations which receive in excess of 2000 hours of annual sunshine. Figure 19 shows the monthly mean, maximum, and minimum recorded bright sunshine hours for selected locations in Otago. Note that the lower sunshine hours recorded in the winter months tends to reflect the northerly declination of the sun, as opposed to signalling an increase in cloudiness during those times.

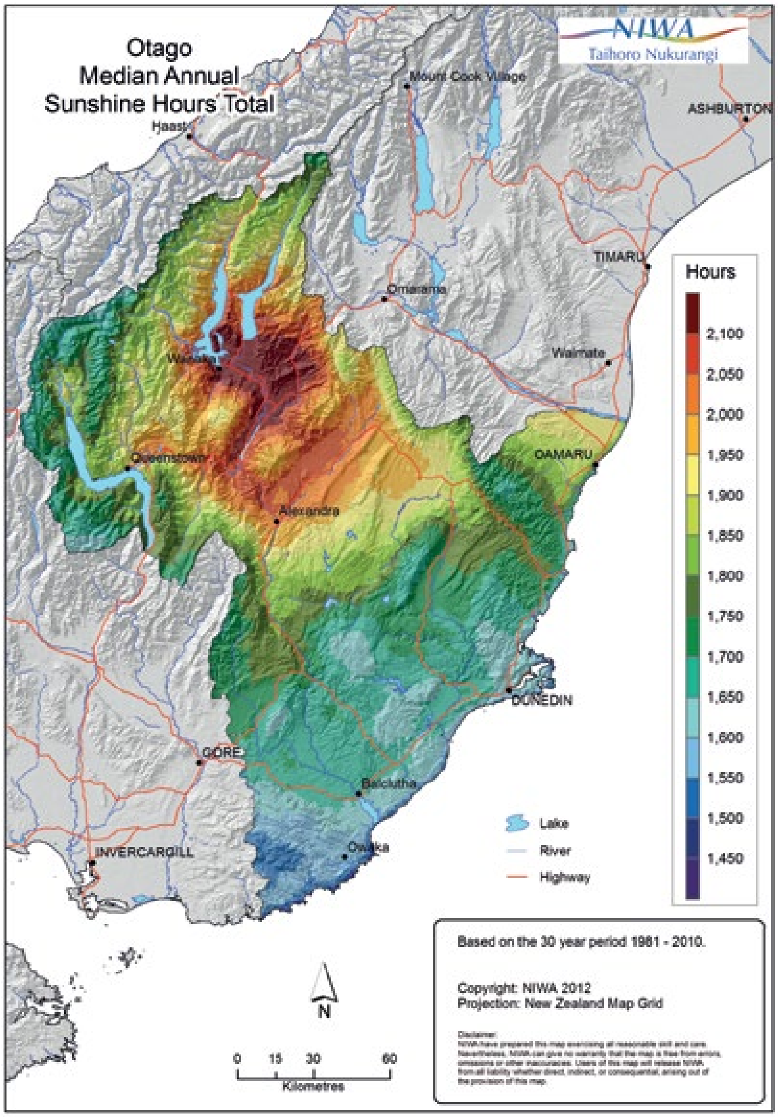


Figure 18. Median annual sunshine hours for Otago, 1981–2010.

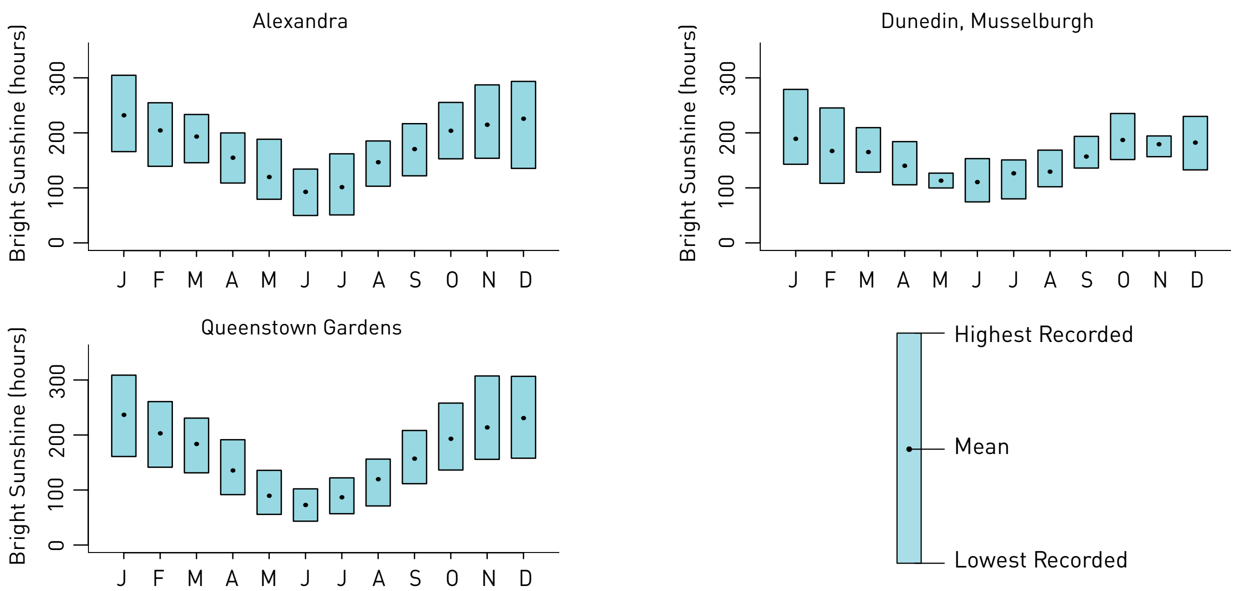


Figure 19. Mean, highest and lowest recorded monthly bright sunshine hours for selected locations in Otago.

Solar radiation

Solar radiation records of greater than 10 years are available for only a few sites in Otago. Table 19 presents the mean daily solar radiation (global) for Alexandra, Dunedin and Queenstown. Insolation is at a maximum in December and a minimum in June.

Table 19. Mean daily global solar radiation (MJ/m²/day) for selected Otago locations.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Alexandra	21.3	18.9	14.1	9.2	5.5	4.1	4.8	7.7	12.0	16.6	20.8	21.7	13.1
Dunedin (Musselburgh)	19.3	17.0	12.6	8.2	4.9	3.7	4.5	6.6	10.9	15.3	18.4	19.7	11.7
Queenstown (Airport)	23.8	20.7	15.6	10.4	6.2	4.8	5.8	8.6	12.9	18.3	22.2	24.2	14.5

UV (ultra-violet) radiation

The mean daily ultra violet radiation (UV) index recorded at Lauder (Central Otago) is compared to that recorded at Leigh (a site in northern Auckland) in Figure 20. Lauder records lower UV levels than Leigh throughout the year due to its southern location. Both sites record significantly higher UV levels in summer than in winter, with maximum UV levels recorded in January and minimum UV levels recorded in June. Figure 21 shows an example of a UV forecast for Dunedin, indicating the UV levels and times of the day where sun protection is required.

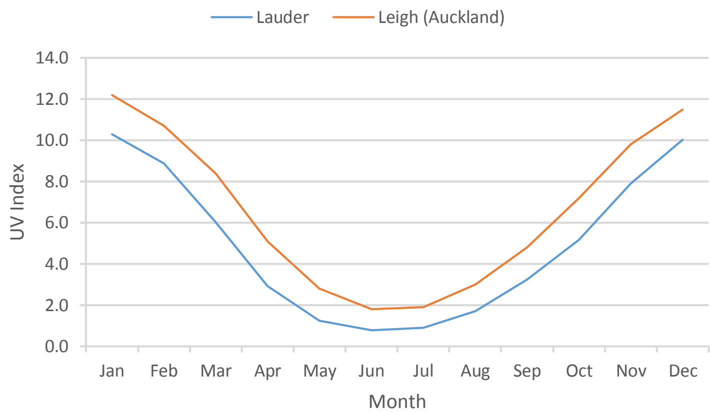


Figure 20. Mean monthly maximum UV index at Lauder and Leigh.

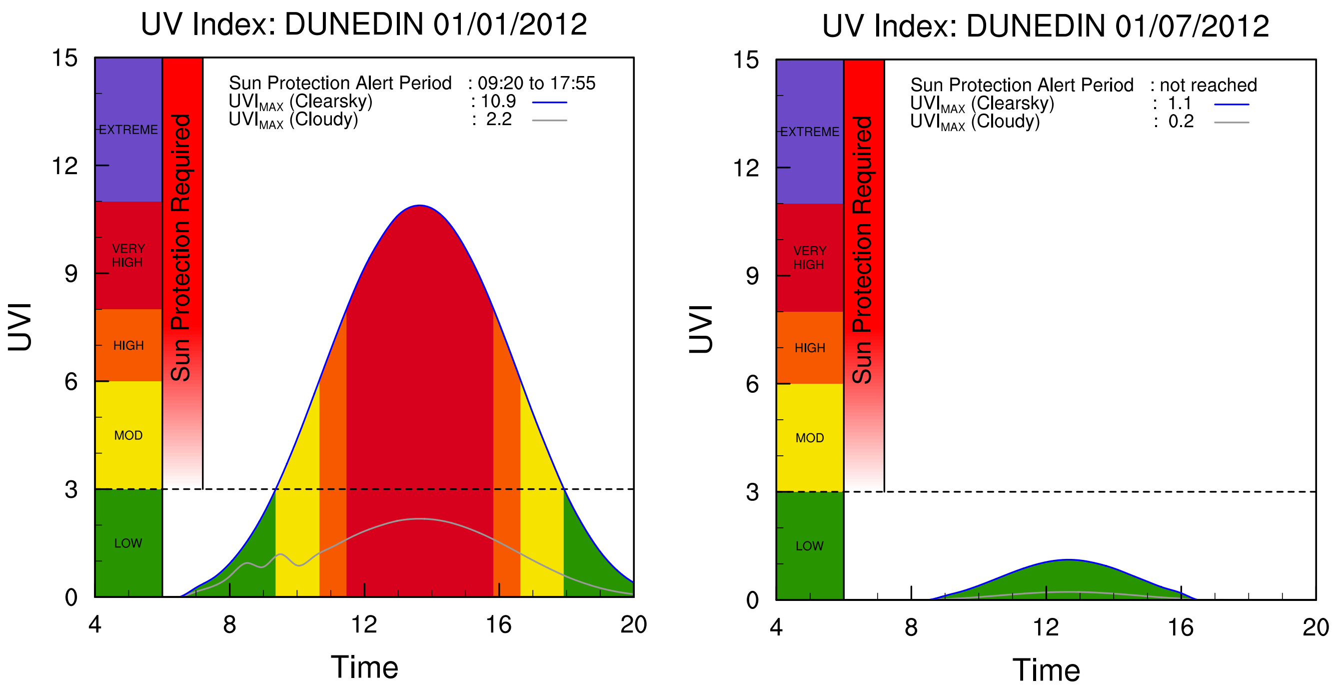


Figure 21. UV Index forecast for Dunedin, January and July. Source: https://www.niwa.co.nz/our-services/online-services/uv-ozone

Other elements

Snow

Snowfalls occur frequently in Otago relative to other parts of New Zealand. Table 20 shows the average number of days each year that snowfall occurs at selected Otago locations. Snow doesn't tend to settle for longer than a day or two at a time, except after particularly heavy snowfall events or in shaded inland locations. The exception is mountainous terrain, where extensive seasonal snowfields typically begin to accumulate in late autumn, and persist through to early summer. Considerable snowfalls occur in the far western ranges of Otago which contributes to the perennial snow and glaciers at high elevations in those areas. A single winter storm cycle can deposit 2 - 3 m of snow in the Fiordland mountains farther south (Conway et al., 2000), and it is likely that similar totals would be recorded in the western-most mountains of Otago. The alpine passes over the Crown Range and Lindis Pass are often subject to snowfall in winter, requiring the use of chains by motorists and forcing closure of those roads from time to time. Snow has an important role to play for the economy of the Otago region. Commercial skifields and heli-ski companies operate near Queenstown and Wanaka, attracting thousands of visitors each winter.

Table 20. Average number of days each year with snow, thunder, hail and fog recorded at selected Otago locations, from all available data. The elevation of each station above mean sea level is also shown.

Location	Snow	Thunder	Hail	Fog
Alexandra (141 m)	4	2	1	25
Dunedin Airport (1 m)	8	7	12	63
Dunedin, Musselburgh (2 m)	4	5	5	6
Queenstown (329 m)	12	5	3	1

Thunderstorms

Thunder occurs relatively infrequently in Otago compared to other regions of New Zealand, with 7 or fewer days of occurrence per year in Alexandra, Dunedin and Queenstown (Table 20.) However, it is likely that thunder occurs more frequently in the west of the region. Furthermore, due to the localised nature of thunderstorm occurrence, it is possible that not all thunderstorms are detected at each station. Thunderstorms in Otago are associated with bouts of high intensity rainfall, lightning, hail, and wind squalls which sometimes cause considerable localised flooding and damage to vegetation and buildings.

On 7 February 2005, Dunedin was hit by a severe thunderstorm which caused flash flooding in the city streets and resulted in millions of dollars of damage. At the peak of the thunderstorm, Dunedin city recorded 34 mm of rain in just 20 minutes. Floodwaters were knee-high in some areas and flooded many houses, shops and properties. Roads and city streets were flooded. Insurance industry payouts for the flooding reached $5,000,000 (in 2005 dollars).

Hail

Table 20 gives the average number of days per year on which hail is reported at selected locations. Hail occurs considerably more often at Dunedin Airport than any of the other locations shown. As with thunder, hail can be a localised event, meaning some falls may escape detection. Severe hailstorms may be classified as those which cause damage and/or have hailstones of at least 0.5 cm in diameter. One such severe hailstorm occurred in Roxburgh between 7.30 p.m. and 8.15 p.m. on 23 November 1992. Flash flooding caused problems in the Roxburgh area, and hail severely damaged stone fruit and berry crops at Orchards. It was estimated that the total loss of fruit production was over $3,000,000 (in 1992 dollars), with $2,500,000 damage done to the apple crop alone.

Fog

The most common type of fog in Otago is radiation fog, formed when the air cools to its dew-point on clear nights, allowing the water vapour in the air to condense. The average number of days per year with fog for selected locations in Otago is listed in Table 20. The frequency of fog varies widely over the Otago region, ranging from an average of 1 day with fog per year at Queenstown to an average of 63 days per year at Dunedin Airport. Although fog can occur at any time of the year in Otago, it is recorded most frequently during autumn and winter. For example, of the annual average of 25 days with fog at Alexandra, 24 days (96%) are recorded between March and August. Similarly at Dunedin Airport, of the annual average of 63 days with fog there, 41 days (64%) are recorded between these same months.

DERIVED CLIMATOLOGICAL PARAMETERS

Apart from elements such as temperature and rainfall which are measured directly, it has been found that parameters calculated from several elements have some important uses, especially in industry. Parameters which define the overall suitability of the climate for agriculture, horticulture, architectural and structural designs, and contracting, etc., are vapour pressure, relative humidity, evapotranspiration (leading to soil water balance), degree-days (thermal time), and rainfall extremes. Some of these and their uses are discussed in the following paragraphs. Note that short-term high intensity rainfalls have already been addressed in this publication.

Vapour pressure and relative humidity

Vapour pressure and relative humidity are the two parameters most frequently used to indicate moisture levels in the atmosphere. Both are calculated from simultaneous dry and wet bulb thermometer readings, although a hygrograph may be used to obtain continuous humidity readings.

Vapour pressure is the part of the total atmospheric pressure that results from the presence of water vapour in the atmosphere. It varies greatly with air masses from different sources, being greatest in warm air masses that have tropical origins and lowest in cold, polar-derived air masses. Vapour pressure can be important in determining the physiological response of organisms to the environment (very dry air, especially if there is a pre-existing soil moisture deficit, can cause or increase wilting in plants). Mean monthly 9 a.m. vapour pressures for several locations are given in Table 21, which shows that vapour pressures are lowest in the winter months.

Relative humidity relates the amount of water present in the atmosphere to the amount of water necessary to saturate the atmosphere. Unlike vapour pressure, relative humidity is dependent on the air temperature. This is because as air temperature increases, the capacity of the atmosphere to hold water also increases. Therefore, relative humidity often displays large diurnal variation. Table 22 highlights this diurnal variation, showing 9 a.m. relative humidity is higher than that recorded at 3 p.m. at corresponding times of year. Highest relative humidity is experienced in the winter months due to lower air temperatures.

Table 21. Mean monthly and annual 9 a.m. vapour pressure (hPa) at selected Otago locations.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Alexandra	12.0	12.0	10.5	8.8	7.3	6.0	5.7	6.4	7.3	8.4	9.3	11.1	8.7
Dunedin (Musselburgh)	12.1	12.3	11.6	10.2	8.7	7.5	7.2	7.6	8.3	9.1	9.9	11.3	9.7
Oamaru (Airport)	13.0	13.2	11.8	10.1	8.4	6.9	6.5	7.4	8.6	9.6	10.5	12.3	9.9
Queenstown	11.6	11.7	10.6	8.9	7.3	6.1	5.8	6.2	7.2	8.4	9.4	10.8	8.7
Wanaka (Airport)	10.9	11.1	10.0	8.9	7.7	6.4	5.9	6.5	7.4	7.9	8.6	10.0	8.5

Table 22. Mean monthly and annual 9 a.m. (a) and 3 p.m. (b) relative humidity (%) at selected Otago locations.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Alexandra	a	69	77	80	84	87	89	89	85	74	72	67	68	77
	b	38	43	41	44	59	64	63	52	41	39	36	35	46
Dunedin (Musselburgh)	a	73	77	77	77	79	79	80	78	72	71	70	73	75
	b	66	67	64	65	69	66	62	68	58	61	63	65	65
Oamaru (Airport)	a	77	82	80	80	81	80	79	79	75	77	74	76	79
	b	71	72	68	69	74	68	65	74	62	69	67	70	69
Queenstown	a	72	76	77	79	82	84	83	79	72	71	70	71	76
	b	48	50	53	56	66	66	65	62	56	50	46	44	55
Wanaka (Airport)	a	63	68	72	77	83	87	86	82	73	70	63	63	74
	b	42	42	47	50	64	70	70	60	49	47	38	38	51

Evapotranspiration and soil water balance

Evapotranspiration is the process where water held in the soil is gradually released to the atmosphere through a combination of direct evaporation and transpiration from plants. A water balance can be calculated by using daily rainfalls and by assuming that the soil can hold a fixed amount of water with actual evapotranspiration continuing at the potential rate until total moisture depletion of the soil occurs. The calculation of water balance begins after a long dry spell when it is known that all available soil moisture is depleted or after a period of very heavy rainfall when the soil is at field capacity. Daily calculations are then made of moisture lost through evapotranspiration or replaced through precipitation. If the available soil water becomes insufficient to maintain evapotranspiration then a soil moisture deficit occurs and irrigation becomes necessary to maintain plant growth. Runoff occurs when the rainfall exceeds the field capacity (assumed to be 150 mm for most New Zealand soils).

Mean monthly and annual water balance values for a number of locations in Otago are given in Table 23. Soil moisture deficit peaks in summer throughout Otago, with highest soil moisture deficit observed in Central Otago, whereas runoff peaks in the winter months. Compared to the remainder of New Zealand, mean soil moisture deficit observed throughout the year in Central Otago is relatively high. Figure 22 shows region-wide variability in days of soil moisture deficit per year, which further illustrates the dryness of Central Otago compared to other areas of Otago.

Potential evapotranspiration (PET) has been calculated for Alexandra, Dunedin and Queenstown using the Penman method (Penman, 1948). The monthly mean, minimum, and maximum PET values for these locations are listed in Table 24.

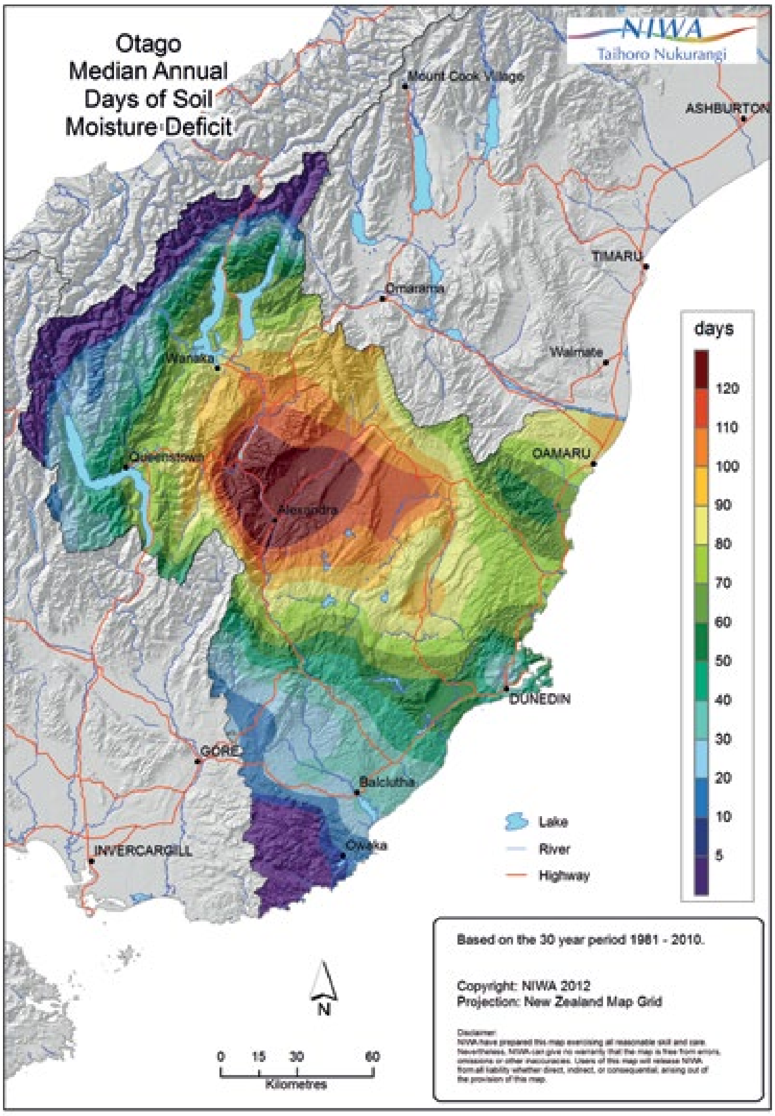


Figure 22. Median annual days of wilting point deficit for Otago, 1981–2010.

Degree-day totals

The departure of mean daily temperature above a base temperature which has been found to be critical to the growth or development of a particular plant is a measure of the plant's development on that day. The sum of these departures then relates to the maturity or harvestable state of the crop. Thus, as the plant grows, updated estimates of harvest time can be made. These estimates have been found to be very valuable for a variety of crops with different base temperatures. Degree-day totals indicate the overall effects of temperature for a specified period, and can be applied to agricultural and horticultural production. Growing degree-days express the sum of daily temperatures above a selected base temperature that represent a threshold of plant growth. Table 25 lists the monthly totals of growing degree-day totals above base temperatures of 5°C and 10°C for locations in Otago.

Table 23. Mean monthly and annual water balance summary for a soil moisture capacity of 150 mm at selected Otago locations.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Alexandra	DE	98	75	46	18	2	1	0	3	20	54	88	100	505
	ND	21	19	18	14	4	2	1	3	11	19	22	22	157
	RO	0	0	0	0	0	0.1	0.5	0.6	0.1	0	0	0	1.3
	NR	0	0	0	0	0	0	0.2	0.2	0	0	0	0.0	0.4
Dunedin (Musselburgh)	DE	50	39	20	6	1	0	0	0	1	7	29	44	198
	ND	13	12	8	4	1	0	0	0	0.4	2	8	11	59
	RO	1	1	4	6	18	36	37	27	9	3	2	1	145
	NR	0.1	0.1	0.4	1	2	6	6	5	2	0.6	0.4	0.1	23
Oamaru (Airport)	DE	68	52	30	12	2	1	1	2	5	19	45	60	295
	ND	19	17	13	9	2	1	2	2	3	7	14	17	105
	RO	0	0	1	2	5	8	13	12	2	1	0.2	0.2	45
	NR	0	0	0.1	0.1	0.4	1	2	2	0.5	0.1	0.1	0	5
Queenstown	DE	65	51	23	6	1	0	0	0	0	3	31	59	238
	ND	14	13	9	4	1	0	0	0	0	1	8	13	63
	RO	1	1	4	7	31	51	48	48	35	21	10	1	258
	NR	0.1	0.1	0.3	1	4	7	7	6	4	2	1	0.2	31
Wanaka (Airport)	DE	107	86	47	21	3	0.2	0	0	2	23	86	96	470
	ND	20	19	15	13	3	0.3	0	0	1	7	19	19	116
	RO	0	0	0	0.2	2	12	13	18	10	3	0	2	59
	NR	0	0	0	0.1	0.3	2	2	3	1	0.4	0	0.1	8

DE: average amount of soil moisture deficit (mm)
ND: average number of days on which a soil moisture deficit occurs
RO: average amount of runoff (mm)
NR: average number of days on which runoff occurs

Table 24. Penman calculated maximum, mean, and minimum monthly potential evapotranspiration (mm), and mean annual total potential evapotranspiration, for selected Otago locations.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Alexandra	Max	181	131	92	51	20	8	11	30	70	102	139	158	
	Mean	136	103	75	36	14	5	6	22	49	84	112	133	776
	Min	105	83	63	29	8	1	3	17	36	67	85	112	
Dunedin (Musselburgh)	Max	155	115	91	59	44	32	36	51	78	107	133	149	
	Mean	126	98	79	47	29	20	22	35	61	91	112	124	856
	Min	95	79	69	38	21	14	11	25	44	76	91	107	
Queenstown (Airport)	Max	189	147	106	56	36	17	20	36	74	112	157	181	
	Mean	158	122	91	46	24	12	15	31	59	98	125	151	933
	Min	137	106	76	36	16	9	13	25	50	86	101	127	

Table 25. Average growing degree-day totals above base 5°C and 10°C for selected Otago locations.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Alexandra	5°C	381	340	301	178	72	18	12	42	119	205	267	346	2279
	10°C	226	199	148	52	8	1	0	2	19	66	121	191	1023
Dunedin (Musselburgh)	5°C	315	283	274	202	131	67	55	82	133	186	223	277	2228
	10°C	160	142	120	61	18	3	2	5	21	49	80	123	785
Oamaru (Airport)	5°C	310	277	270	186	106	44	36	59	114	159	210	277	2048
	10°C	155	136	117	49	11	2	1	3	16	33	69	123	715
Queenstown	5°C	346	314	283	176	80	23	15	39	102	175	229	308	2091
	10°C	192	173	131	47	7	1	0	1	10	42	87	155	844
Wanaka (Airport)	5°C	376	343	286	172	86	24	17	40	102	170	234	321	2172
	10°C	221	202	134	47	10	1	0	1	13	41	93	167	932

Table 26. Average cooling (CDD) and heating (HDD) degree-day totals with base 18°C for selected Otago locations.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Alexandra	CDD	33	25	7	0	0	0	0	0	0	0	4	18	87
	HDD	55	53	109	212	350	438	471	386	273	199	127	75	2749
Dunedin (Musselburgh)	CDD	7	7	3	0	0	0	0	0	0	0	1	3	22
	HDD	96	91	131	189	273	328	355	323	258	218	168	129	2559
Oamaru (Airport)	CDD	8	6	2	0	0	0	0	0	0	0	1	3	21
	HDD	101	96	136	205	299	358	383	352	277	245	181	129	2760
Queenstown	CDD	16	13	2	0	0	0	0	0	0	0	1	6	37
	HDD	73	66	123	214	331	404	438	383	290	228	162	100	2813
Wanaka (Airport)	CDD	25	24	4	0	0	0	0	0	0	0	2	9	63
	HDD	52	48	120	219	325	416	450	386	290	233	158	91	2788

Cooling and heating degree days are measurements that reflect the amount of energy that is required to cool or heat buildings to a comfortable base temperature, which in this case is 18°C. Table 26 shows that the number of cooling degree days reach a peak in mid-late summer in Otago, when energy required to cool building interiors to 18°C is highest. Conversely, heating degree days reach a peak in winter, where the energy required to heat buildings to 18°C is highest. Figure 23 shows region-wide variability in the number of heating degree days per year. The number of heating degree days tends to be lower in low elevation coastal areas, compared with areas further inland and at higher elevations.

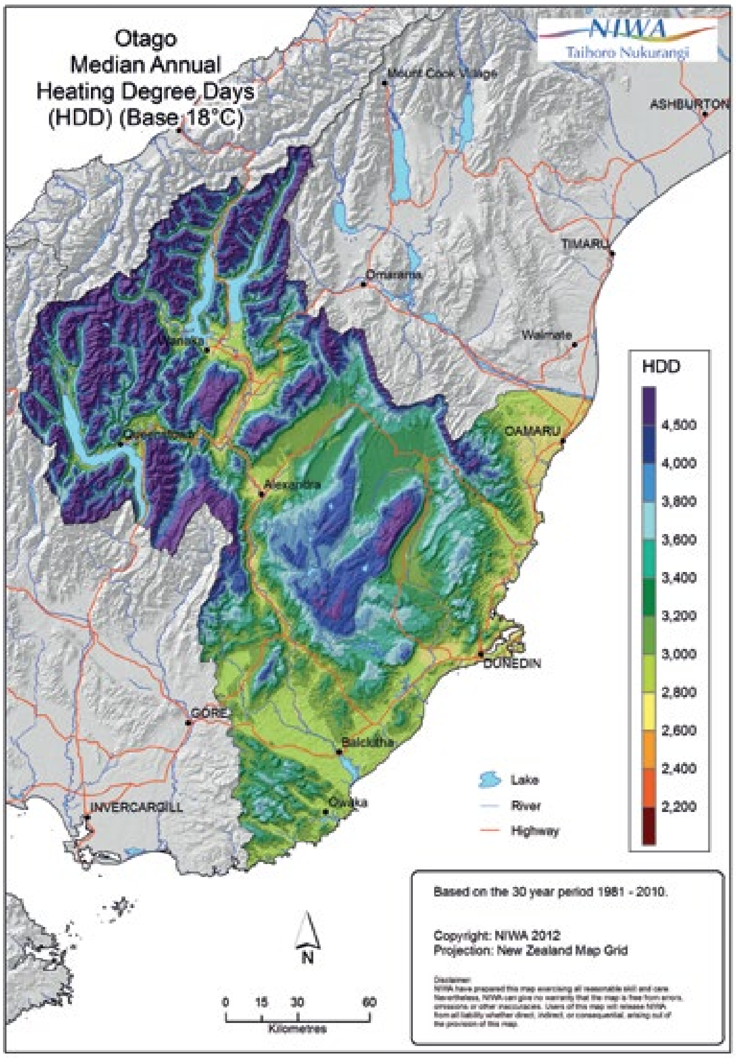


Figure 23. Median annual heating degree days for Otago, 1981–2010.

ACKNOWLEDGEMENTS

The following people from NIWA are acknowledged for their contribution to the preparation of this publication: Dr Andrew Tait, Petra Chappell, Erika Mackay, James Sturman, Dr Elizabeth Somervell and Dr Michael Uddstrom.

Photo credits:

Contents page, page 6, 8, 30, 34, 37, 39, 40, 41, Gregor Macara, NIWA
Page 12, Erika Mackay, NIWA

REFERENCES

NIWA databases used:

The National Climate Database cliflo.niwa.co.nz

HIRDS (High Intensity Rainfall Design System) hirds.niwa.co.nz

New Zealand Historic Weather Events Catalogue hwe.niwa.co.nz

NIWA Sea Surface Temperature Database

References:

CONWAY, H., CARRAN, W. & CARRAN, A. 2000. The timing, size and impact of avalanches on the Milford Highway, New Zealand. *Proceedings of the International Snow Science Workshop, Big Sky, Montana USA*, 167-172.

PENMAN, H. L. 1948. Natural evaporation from open water, bare soil, and grass. *Proceedings of the Royal Society of London A*, 193, 120-145.

UDDSTROM, M. J. & OIEN, N. A. 1999. On the use of high resolution satellite data to describe the spatial and temporal variability of sea surface temperatures in the New Zealand Region. *Journal of Geophysical Research (Oceans)*, 104, 20729-20751.