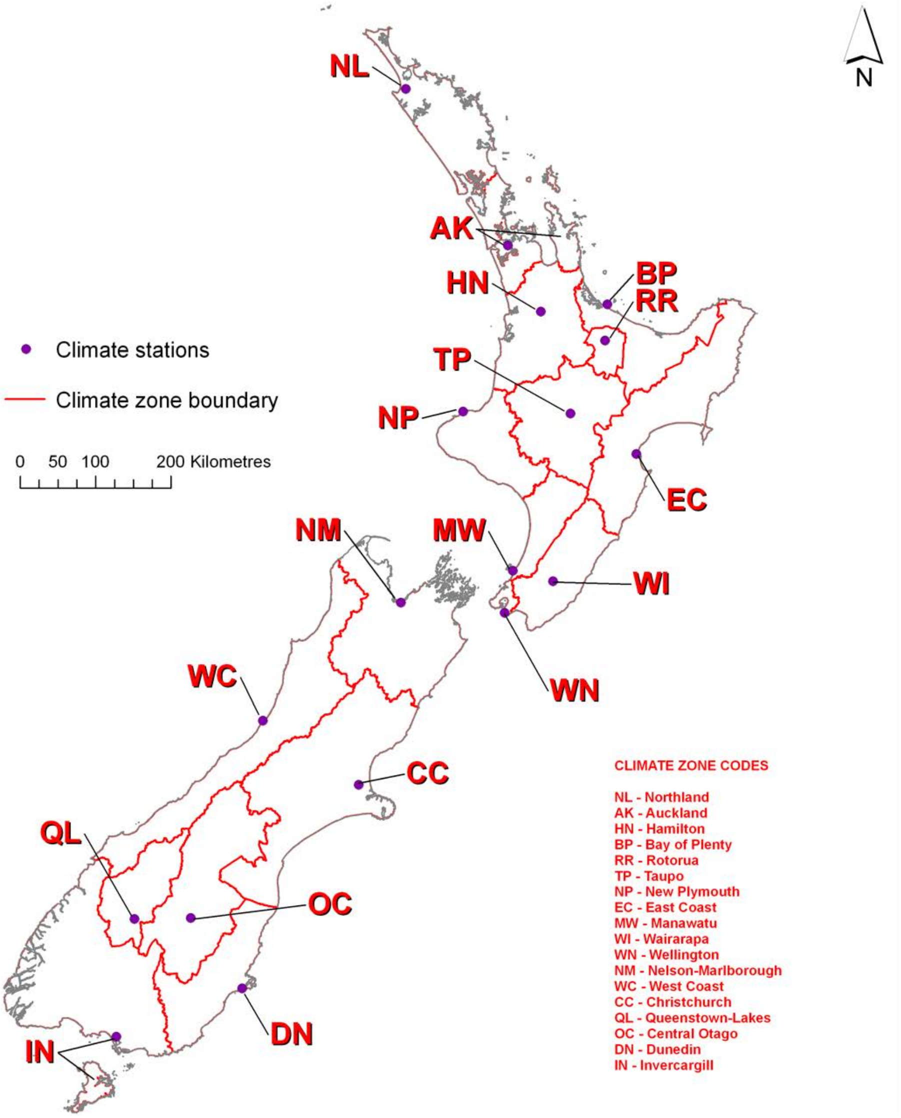
NIWA
Taihoro Nukurangi

Weather Files for Energy Modelling



Prepared for MBIE

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Contents

Executive summary

On contract to Building System Performance in the Ministry of Business, Innovation, and Employment, NIWA has completed updates to the Typical Meteorological Years (TMYs) first developed for the Home Energy Rating Scheme (HERS) of the Energy Efficiency and Conservation Authority in 2008.

The updated TMYs apply to the same 18 climate zones identified for HERS, which mostly align with boundaries of Territorial Local Authorities. The time series on which the TMYs are based were extended by 16 years of data, and rainfall is now quantified as a separate field.

We have developed and implemented a modified version of the statistical algorithm for selecting a year to represent each month in the TMY. The new algorithm allows a defined trend to be specified for any climate variable, and we apply this to dry bulb and dew point temperatures so that the new TMYs are representative of climate conditions in 2024.

Moisture Design Reference Years for all 18 climate zones have been derived from the same time series of climate data. They are selected by estimating annual totals of wind-driven rain onto south-facing walls and the solar radiation onto the same surfaces. The selected years are output in a text format specific to WUFI (Wärme Und Feuchte Instationär) software.

Design Summer Years are specified by the Chartered Institute of Building Services Engineers (CIBSE) in London as a way to assess the risk of overheating in buildings. The temperature records for each location are used to derive a threshold temperature that characterises uncomfortably hot conditions for those accustomed to the climate of that site. Prolonged periods above the threshold constitute a heat wave, and the DSY1s that we derive are a standard representation of such conditions. They are produced in TMY3 format for use in EnergyPlus or compatible simulation software.

In addition to the TMYs allowing for trends in temperature and humidity to 2024, we have developed TMY3s and DSY1s for projected future climates. They are based on downscaled data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) used by the Intergovernmental Panel on Climate Change. Six of those models had been selected for their representation of NZ climates, and the data downscaled to an 8-10 x 12 km grid over NZ at monthly, daily, and hourly resolution. We compared distributions of daily data in the historical test set to the measured distributions to derive monthly shifts of dry bulb and dew point temperature.

For all 18 climate zones, TMY3s and DSY1s were derived for approximate temperature increases from present day by 0.5, 1.0, and 2.0 °C centred on 2040, 2050, and 2070 under IPPC Shared Socioeconomic Pathways 1, 2, and 3 respectively. The output files are in TMY3 format, with Design Conditions, Typical/Extreme Periods, and Earth Temperatures adjusted accordingly. The Design Conditions conform to the ASHRAE 2013 prescription, but should be used instead of values from the ASHRAE Handbook.

For ready reference, the file names and purpose are summarised in Table 1.

Reference Summer Weather Years (RSWYs) are another approach to the risk of overheating, defined in terms of a physiological model of human temperature regulation by transpiration and perspiration subject to activity level, clothing, and environmental conditions. Work is under way to derive RSWYs for seven of the 18 climate zones. It will be reported separately.

Table 1. Datasets delivered, and their purpose. There are 18 of each type, identified by zone ‘xx’.

File Name	Intended Purpose
TMY3_NZ_xx.epw	General simulations of building performance in 18 climates typical for 2024
MDRY_NZ_xx.WAC	Simulating moisture ingress, mould and damp, in 18 climates typical of recent past
DSY1_NZ_xx.epw	Testing risk of overheating to recognised criteria, in 18 recent climates
TMY3_NZ_M1_xx.epw	Simulating buildings at ~0.5 °C above present, or ~1.5 °C above pre-industrial
TMY3_NZ_M2_xx.epw	Simulating buildings at ~1.0 °C above present, or ~2.0 °C above pre-industrial
TMY3_NZ_M3_xx.epw	Simulating buildings at ~2.0 °C above present, or ~3.0 °C above pre-industrial
DSY1_NZ_M1_xx.epw	Assessing overheating risk at ~0.5 °C above present, or ~1.5 °C above pre-industrial
DSY1_NZ_M2_xx.epw	Assessing overheating risk at ~1.0 °C above present, or ~2.0 °C above pre-industrial
DSY1_NZ_M3_xx.epw	Assessing overheating risk at ~2.0 °C above present, or ~3.0 °C above pre-industrial

1 Introduction

1.1 Background

In 2008, NIWA developed a set of 18 climate files for the Energy Efficiency and Conservation Authority (EECA) to use in the incipient Home Energy Rating Scheme (HERS) (Liley et al. 2008). Each of the files represented a climate zone, delineated in terms of Territorial Local Authority (TLA) boundaries, that was sufficiently uniform in terms of average temperature, humidity, wind, and incident solar radiation. Those parameters, as hourly measurements or estimates, are the key elements in modelling energy balance in houses or small buildings.

The standard procedure is to use hourly time series of all parameters for at least 10 years, and preferably 30 or more, to construct Typical Meteorological Years (TMYs). Each TMY is a synthetic year of hourly data constructed from the 'most typical' version of each month, according to an established prescription (Marion and Urban 1995).

For HERS, the files were required in a specific format developed by CSIRO for software used by the parallel Nationwide House Energy Rating Scheme (NatHERS) in Australia and adapted to HERS. In addition, the 18 TMY files were produced in EnergyPlus format, which is readable by much of the software used globally for building energy simulation, both in research and industry. The TMYs for Aotearoa have been correspondingly widely used, and shared internationally.

In 2020, NIWA produced an update of the TMYs, using the additional 13 years of data then available, again on a contract to EECA. That update used the full time series to establish the mean distributions of variables, but the TMY months were selected from the most recent decade.

1.2 MBIE update

We understand that, in addition to their own work, the Ministry of Business, Innovation & Employment is assisting work by many groups, including Kāinga Ora, the Building Research Association of New Zealand (BRANZ), Victoria University of Wellington School of Architecture, and others in working on aspects of building design for comfort, energy efficiency, and climate resilience. For this purpose, they need to represent the range of NZ climates both now and over the lifetime of structures now being planned. In this context, MBIE originally requested four products, as cited below with some discussion regarding our capability and the approach that we proposed.

"1) Update 18 x TMY2, including warming trend, as well as updates to ground temperatures and design temps."

The original TMYs for HERS used data up to the end of 2007, but a third of the primary climate stations had less than 15 years' data. With data now available to the end of 2023 for the same sites or their replacements, all zones can now be represented with the preferred 30 years' data.

As HERS did not require the 'design conditions', 'typical/extreme periods', and monthly ground temperatures that appear in the header of EnergyPlus files, these were derived or estimated by Weather Converter software from the TMY data. As 16 of the 18 sites have measured ground temperatures, we can include these directly, and derive them for the other two sites by a model of ground heat conductivity. The typical/extreme periods are derived for the TMY in question. Design conditions refer to the full time series according to the ASHRAE definitions (http://ashrae-meteo.info/v2.0/help.php) but the ASHRAE tables would be inconsistent with the warming trends considered in our analysis. They required a modified procedure as described further below.

The 2008 TMYs are in the TMY2 form described by Marion and Urban (1995), which include ‘Present Weather Elements’ by a series of codes. In fact those data are somewhat piecemeal, and will be more so now with declining numbers of human climate observers. Precipitation is expressed as a range of rates to match human perception, rather than as accumulated depth. The TMY3 prescription of Wilcox and Marion (2008) adds new fields for surface albedo and liquid precipitation and removes the fields for present weather, snow-depth, and days since last snowfall that were present in the TMY2. It is also explicitly in comma-separated-variable (CSV) format as used for EnergyPlus. From subsequent discussion, we conclude that TMY3 files are the preferred product for this work.

“2) Create 18 x TRYs for design moisture years (for WUFI modelling, internal moisture in constructions).”

For this component MBIE requires, for each climate zone, a Moisture Design Reference Year (MDRY) as defined in ANSI/ASHRAE Standard 160-2021. The specification combines air temperature, humidity, cloud index, vapour pressure, plus solar radiation and wind-driven rain onto a south-facing wall (for the southern hemisphere). Rather than a composite of months selected from individual years, an MDRY is, like a Test Reference Year (TRY) as originally conceived, a complete year of hourly data. The MDRY is to be in ‘WAC’ format used by WUFI (Wärme Und Feuchte Instationär) software, with the addition of fields for irradiance and driven rain onto a south-facing wall (https://wufi.de/en/service/downloads/creating-weather-files/).

“3) Create 18 x TRYs for overly hot years (according to CIBSE TM49 method where CIBSE call overly hot TRYs, DSY1s).”

In designing to avoid overheating risk in buildings, Kāinga Ora have recommended a Design Summer Year (DSY1) for each of the 18 climate zones. A DSY is again a full year of data, the selection of which is defined in CIBSE (2014) and Virk and Eames (2016). The latter reference identifies several versions of the Weighted Cooling Degree Hour (WCDH), the cumulative square of the hourly temperature excess above a predefined level, as the index used to select the TRY. Virk and Eames (2016) describe three types of DSY, and a DSY1, as specified, represents a moderately hot year with a return period of 7 years. Year selection of a DSY1 uses the Static Weighted Cooling Degree Hour (SWCDH), for which a threshold temperature is derived for each climate zone as the 93rd percentile.

A further consideration is that the work by CIBSE (Chartered Institution of Building Services Engineers, London) applies primarily to the northern hemisphere, where summer occurs in a single calendar year. To better capture the cumulative overheating risk through a southern hemisphere summer, it would seem preferable to select a July-to-June DSY, though this consideration would be greater for the DSY2 and DSY3 prescriptions of Virk and Eames (2016) than for a DSY1 as requested.

Also from discussion, we understand that the risk of overheating in NZ homes may be better characterised by an alternative criterion based on the Standard Effective Temperature (SET), as used by Laouadi et al. (2020) to select a Reference Summer Weather Year (RSWY). For assessment of its suitability, MBIE requested derivation of RSWYs as a distinct part of the proposal.

“4) Create modified versions of (2) and (3) to represent future climate scenarios e.g. 1.5 °C warming, 2.0 °C warming RCP8.5 50th Percentile (for example).”

In simulating how building performance responds to weather, there is obvious need to have data that represent climates of the future rather than the present, let alone the past. Air temperatures in Aotearoa already average around 1.1 °C warmer than a century ago, and they are expected to increase throughout this century. The difficulty is to match conditions to projected future temperatures while preserving the physical relationships that tie the different parameters together. One approach, described by CIBSE (2014) as ‘morphing’, is to shift and stretch the past weather data to match the mean monthly projections but preserve the historical variation around those means. In the UK, UKCP09 projections of future climate provide a range of changes with associated estimates of likelihood. We have applied this approach using recent work by NIWA to downscale Coupled Model Intercomparison Project Phase 6 (CMIP6) data, but with some differences arising from analysis of the model data.

We proposed this work as a separate component to proceed on completion of parts 1) – 3). In particular we noted from subsequent discussion that the above should read “modified versions of (1) and (3)”, as the requirement is for simulated future TMY3s and DSY1s, not MDRYs as described in 2) above.

It was also agreed from discussion that the future versions of the TMY3s and DSY1s should be for three scenarios, corresponding to low, medium, and higher emissions and projected temperature rise. For regulatory purposes, and for use by building researchers, there was a preference that there be only one file of each type for each climate zone and scenario; a total of 2 x 18 x 3 = 108 files.

1.3 Scope of the project

We have produced TMY3 files including hourly data to the end of August 2023 for the 18 climate zones as delineated for HERS and represented by the same climate stations or their update. As noted above, the TMY3 files replace the present weather codes of TMY2s with precipitation amount in millimetres. Of the defined TMY3 fields, some are marked as missing because there is no suitable source at most sites; precipitable water, aerosol optical depth, and surface albedo. Visibility data are provided if available for that site and year, but otherwise are marked as missing. Since 1996, cloud cover (required in tenths) can generally only be inferred from the present WMO categorisation of ‘clear’ (0 tenths), ‘few’ (2), ‘scattered’ (5), ‘broken’ (8), and ‘overcast’ (10). The precision and accuracy of cloud information varies with source: human observers give good estimates of areal cover, but mostly just by day, and ceiling height is imprecise; ceilometers give precise height, and hourly measurements, but can only estimate cover from temporal averaging over the zenith. To provide mostly complete hourly records, we have used ceilometer data but overwritten cloud cover from observers where and when available.

The separate diffuse and direct components of global solar irradiance are only measured at four of the 18 representative climate stations. For the others, and at those stations for periods where data are missing or fail quality control, the components are estimated from global irradiance using algorithms derived for the above four sites and extensively used in NZ and Australia. Luminance data are estimated using published relationships established for New Zealand conditions.

We have similarly produced 18 MDRYs following the selection procedure in ANSI/ASHRAE Standard 160-2021. Unlike the TMYs, these are each a full calendar year of hourly data. We can assume moisture control to be a greater concern over winter months, and this period is contiguous in the southern hemisphere in a calendar year. As the data are to be used with WUFI software, the preferred format is the WAC file type defined by WUFI.

To select DSY1s based on SWCDH, we first need to derive 93rd percentile values for temperature for each representative site. The selection procedure is then straightforward, and the output files are again in the EnergyPlus format.

A suggested departure from the representation for TMYs and MDRYs was that the DSY1 would not be a calendar year but a year beginning on 1 July and ending on 30 June the following year. This would seem to better represent the cumulative effect of overheating over a single hot season, but it required confirmation that the simulation software is not limited to a calendar year. We understand that is not the case, so the DSY1 has to be a calendar year.

This restriction might still allow files with the data written out of order, so that the first six months of a July-to-June year were appended to the last six to look like a single calendar year. We implemented this capability in the software but have not deployed it here. The DSY1 files described herein are each just for a standard January-to-December year. Overheating analysis of NZ’s summer might be better served by simulation software customised for southern hemisphere seasons, but anyway the hottest periods in Aotearoa occur from January through to early March, within a single calendar year.

As described in Section 1.2, item 3) above, we have worked to implement the calculation of SET to select RSWYs as described by Laouadi et al. (2020). The resultant RSWYs will be in the same file format as the DSY1s. This work involves algorithms that are less mature than the others listed below, and it is incomplete at the time of this report.

For item 4) of Section 1.2, we have used the results of six of the CMIP6 models. Whereas the UKCP09 datasets include a probabilistic component, by providing figures at the 10th, 50th, and 90th percentile for indicative climate variables, our best source is a NIWA project to downscale CMIP6 projections for the six models that had previously been found to represent Aotearoa climate reasonably well. To reduce the six simulations down to one, as required, it would not make physical sense to simply average a set of free-running models. Instead, we have reviewed the differences in climate for each model and adjusted our analysis for what differences are consistent between them.

2 Methods

Items 1) – 3) all require the initial creation of time series for all the required parameters from the NIWA Climate Database (http://cliflo.niwa.co.nz). For the 18 zones, 25 climate stations are needed because some lack the full set of required parameters. In particular, the requirement for regular cloud observations or ceilometer data means that many of the stations are at airports.

From the time series, merged into a combined set with the structure of the TMY3 records, three different selection procedures are applied to create the distinct TMYs, MDRYs, and DSYs.

For item 4), projections of future NZ climate were needed. A separate NIWA project has downscaled historical (1960-2014) simulations and projections for 2015-2100 from six of the CMIP6 General Circulation Models (GCMs) used in IPCC AR6 analysis (https://niwa.co.nz/climate/research-projects/updated-national-climate-projections-for-aotearoa-new-zealand). That project was funded by MBIE to extend work previously undertaken for the Ministry for the Environment.

The projections are for the four different Shared Socioeconomic Pathways (SSPs) that supersede the Representative Concentration Pathways (RCPs) of IPCC AR5. Each SSP describes a scenario of technological, industrial, and social developments, which in turn give rise to emissions profiles as described by RCPs. For clarity, the SSPs are regularly identified as SSP-RCP.

The six models downscaled for NZ were found in a previous NIWA study (MfE 2018) to represent NZ climates well under past and expected climate change. Of the SSP-RCP combinations, a 2020 commentary (Hausfather and Peters) described SSP5-8.5 as highly unlikely, SSP3-7.0 as unlikely, and SSP2-4.5 as likely. On the other hand, RCP8.5 is the best match to the cumulative emissions from 2005 to 2020 (Schwalm et al. 2020). The NIWA downscaling project is for SSP1-2.6, SSP2-4.5, and SSP3-7.0, and all three were used here.

2.1 Data collection

All required historical data are obtained from the NIWA Climate Database. Eight of the 18 primary stations, and one of the additional seven, are owned and operated by MetService NZ. For those sites, hourly data are accessible for research but are not otherwise available except by express permission of MetService. For the purpose of the present work, MetService has given such permission, subject to acknowledgement in the data files and interdiction against use other than for the stated purpose.

Although the TMYs, MDRYs, and FSYs are all extracted from the full time series of hourly data, the MetService restrictions and other considerations mean that the complete time series are not provided as a deliverable. One limitation is that the full series have many gaps where data are missing or fail quality control. Those gaps are largely avoided in the selection of representative data, and any residual missing values are imputed from nearby sites or by temporal interpolation over short intervals. Those corrections are applied only to the selected files, not the initial time series.

For item 4), downscaled CMIP6 data are available at hourly, daily, and monthly resolution. The morphing procedure only calls for shifting climate values by mean values for the month, but the selection procedure for TMYs in particular is based on the distribution of daily values within a month. To confirm that this was correctly treated we downloaded the files of daily mean, minimum, and maximum temperature, and daily mean humidity; 345 GB of data for the NZ grid and the six models. From these we extracted values for the 18 representative sites.

2.2 Typical Meteorological Years

The creation of TMY2s is described by Marion and Urban (1995), and in 2008 we largely followed that prescription, adapted to resolve some ambiguity. Here we describe our method in full both to contrast it with the other representative year types and to show how TMYs can be adapted to allow for changing climate. For each month in a time series of at least 10 years' duration, the procedure selects a year for which that month was most typical over the long term.

2.2.1 Our 2008 method for TMYs

Step 1 requires calculation of Finkelstein-Schafer (F-S) statistics for each of 10 specified climate variables. The F-S statistic is illustrated in Figure 1 for global irradiance in Auckland, from the report for HERS in 2008. The distribution function for the full time series is shown in red, and those for each year in black. Also highlighted are the worst (crimson) and best (blue) for that variable, and the year selected (green) by the full procedure across all 10 parameters.

The statistic for closeness of a month's data to the mean distribution is:

$$FS^{x}{}_{ym} = \frac{1}{n}\sum_{d=1}^{n} \left| D^{x}{}_{ym}(X_d) - D^{x}{}_{m}(X_d) \right| \tag{1}$$

where

X_d is the value of parameter x on day d,

$D^{x}{}_{ym}$ is the distribution of parameter x in month m of year y (black, Figure 1),

$D^{x}{}_{m}$ is the combined distribution of parameter x in month m (red, Figure 1),

n is the number of days in month m of year y with valid data.

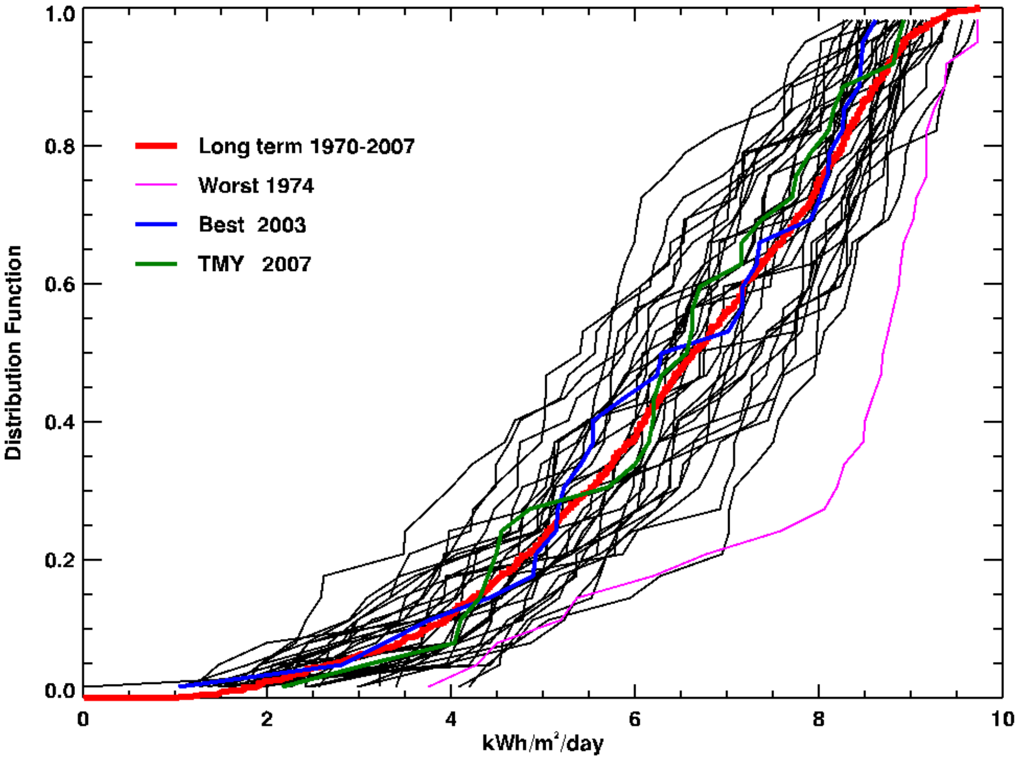

Figure 1. Distribution functions of January daily global irradiance in Auckland to 2008. The best match to long-term distribution for irradiance alone is 2003 (blue), and the worst 1974 (crimson); the HERS (2008) TMY year for January (2007, green) was chosen from a weighted mean of 10 parameters, as in Table 2.

An advantage of the F-S statistic is that, as a mean in probability space, it is dimension-free. Thus, it is directly comparable between different physical measures, so that a weighted sum of the F-S statistics for several quantities correctly reflects their specified importance without the need for prior normalisation. The weights w_x are used in the obvious way to compute the combined F-S statistic of each year y for month m:

$$FS_{ym} = \sum_{x} w_x FS^{x}{}_{ym} \tag{2}$$

In accordance with Marion and Urban (1995) and Wilcox and Urban (2008), the weightings in this work are as listed in Table 2.

Table 2. Weightings for Finkelstein-Schafer statistics in TMYs.

Index	Weight
Max Dry Bulb Temperature	1
Min Dry Bulb Temperature	1
Mean Dry Bulb Temperature	2
Max Dew Point Temperature	1
Min Dew Point Temperature	1
Mean Dew Point Temperature	2
Max Wind Speed	1
Mean Wind Speed	1
Global Radiation	5
Direct Radiation	5
Total (denominator)	20

Note that the F-S statistic can be computed even for months with missing data for some days, and such months still contribute sensibly to the combined distribution functions and to the sorted set of weighted F-S values. Months with some missing data are thus still of value in establishing what is ‘typical’, but at the stage of selecting years for each month of the TMY we omit any with whole days missing for any parameter.

Step 2 in the prescription of Marion and Urban (1995) and Wilcox and Urban (2008), is to select the five months with lowest combined F-S score, and rank them in order of “closeness of the month to the long-term mean and median”. Neither report says how they compare these two measures, nor how they weight them for the different parameters as both mean and median are expressed in physical units. Unlike the F-S statistic, that seems to require normalisation, such as division by standard deviation or interquartile range, and consideration of the different distributions.

Our technique was developed for consistency with Step 1, and we have used it both for HERS in 2008 and for all subsequent updates of NatHERS in Australia.

With the same notation as in Equation (1), we simultaneously compute a ‘signed’ F-S value as:

$$FSs^{x}{}_{ym} = \frac{1}{n}\left|\sum_{d=1}^{n}\left(D^{x}{}_{ym}(X_d) - D^{x}{}_{m}(X_d)\right)\right| \tag{3}$$

Referring to Figure 1, the true FS measures the mean absolute deviation of a month's distribution function (DF) from the combined DF, but a curve lying entirely above or below the reference curve can score equally with one that crosses it. In contrast, FSs is smallest for a curve that lies equally above and below the reference and will consequently have a median close to the overall median.

The FSs values have the further advantages that they can be computed simultaneously with FS and weighted in the same way, they are again independent of physical units, and skewness of the underlying distribution is accommodated.

Step 3 in the standard prescription for TMY2s or TMY3s is that "persistence of mean dry bulb temperature and daily global horizontal radiation are evaluated by determining the frequency and run length above and below fixed long-term percentiles." Marion and Urban (1995) use both terciles (33rd and 67th percentiles) for temperature, and the lower tercile for radiation. Applying the persistence criteria to candidate months from Step 2, they exclude "the month with the longest run, the month with the most runs, and [any] month with zero runs." The implication of this description is that the most and least persistent of just the candidate months are excluded, without reference to whether those months are more or less persistent than usual for the long-term record. If, for example, all five months are more persistent in weather patterns than the long-term average, then surely the least persistent of those five should be preferred.

Marion and Urban (1995) are also less than clear what constitutes a 'run', but two consecutive values in the same tercile (high, medium, or low temperature; or low radiation or not) seems to be the criterion. This gives three separate run measures, and the question of whether they are to be tested separately or in combination; for example, whether runs for high temperature compensate for many runs of low radiation. With some difficulty interpreting the prescription, we developed a technique somewhat analogous to the F-S statistic. Histograms of sequential days within the above terciles are computed, and their cumulative sum gives the distribution function of run lengths of each type, analogous to Figure 1. The combined distribution of run lengths enables evaluation of each month's distribution, as previously, with a statistic, FSr, defined as:

$$\begin{gathered} FSr_{ym} = \frac{1}{10}\sum_{l=1}^{10} \sqrt{l}\left|N_{ym}(l) - \bar{N}_m(l)\right| \\ N_{ym}(l) = \sum_t w_t {N^t}_{ym}(l) \end{gathered} \tag{4}$$

where

${N^t}_{ym}(l)$ is the cumulative number of runs of length l in month m of year y for test t (parameter and tercile criterion),

$N_{ym}(l)$ is the weighted sum of the ${N^t}_{ym}(l)$, as expressed in the second line of (4),

$\bar{N}_m(l)$ is the mean of $N_{ym}(l)$ across all years.

For similarity to the earlier weightings for the 10 parameters, we separately considered runs of low global or direct radiation, and then with equal weightings w_t. The distribution of these FSr statistics across all years at several sites shows a long tail of high values in less than about 10% of cases. Selection of TMY-month years was thus restricted to below the 90th percentile for FSr.

Step 4 for TMY construction is the concatenation of selected months into a synthetic year, with parameters smoothed over six hours either side of the joins. Our method varies the smoothing according to the size of the step so that the rate of change in any variable is not outside the range of rates in the time series, and we smooth from the end of December into January so the typical year is effectively cyclical. For example, December-January-February from the TMY can be regarded as a contiguous summer.

2.2.2 Revised TMY method for climate trends

We include the detail of TMY2 or TMY3 selection and our interpretation of it partly to facilitate review, but more because we have applied an amended version of Steps 1 and 2. Testing the DF of a month in any particular year against the DF for that month in all years implicitly assumes that the time series is stationary, so that all year-to-year variation is random, with no secular trend. This assumption may be false for any of the parameters, but for most of them any such trend is likely to be uncertain, possibly local to that zone, and inadequately characterised by the one time series.

On the other hand, we know that mean air temperature everywhere has risen over the last century, and the rate of temperature rise has increased in recent decades. To make allowance for this, we have modified the calculation of FS to include a time component, so that Equation (1) now becomes:

$$FS^{x}{}_{ym} = \frac{1}{n}\sum_{d=1}^{n} \left| D^{x}{}_{ym}(X_d) - \widehat{D}^{x}{}_{m}\big(X_d - \tau_x(y)\big) \right| \tag{5}$$

where

$\tau_x(y)$ is the trend in parameter x evaluated in year y

$\widehat{D}^{x}{}_{m}$ is the modified distribution of x - τ for month m.

The concept is illustrated in Figure 2, for mean daily February temperatures in Auckland.

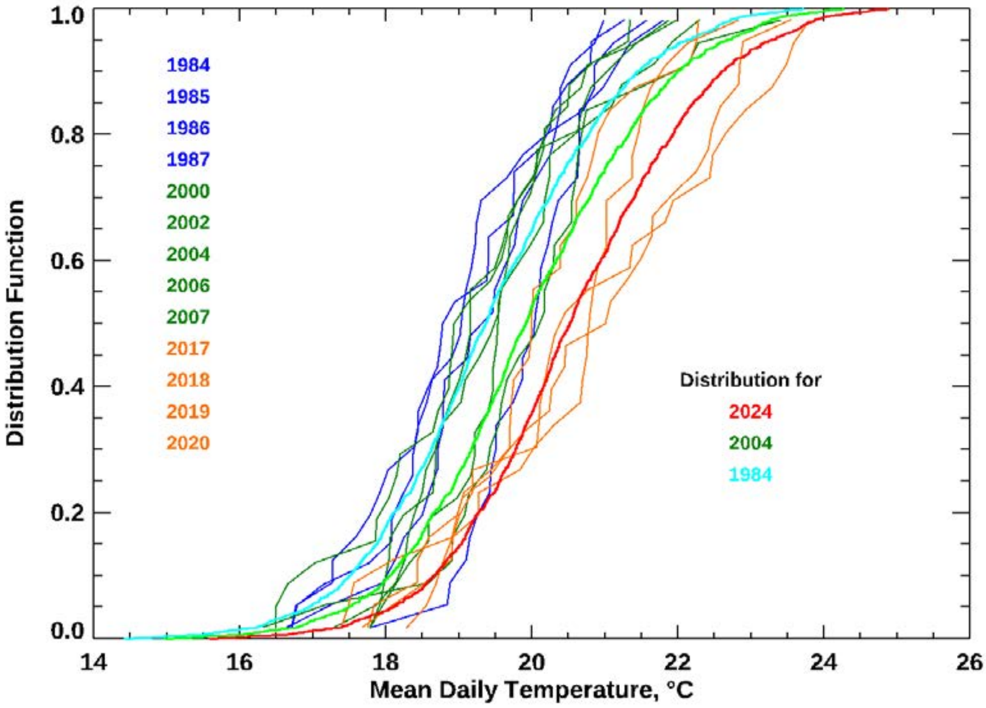

Figure 2. Distribution functions of February daily mean temperatures in Auckland. A selection of early (blue), mid-term (green); and recent (orange) years for February show a warming trend. The combined $\widehat{D}^{x}{}_{m}$, adjusted as illustrated for 1984, 2004, and 2024, is used in Equation (5).

This analysis recognises that a warmer year than average in 2000 might only be average in 2020.

Equation (5) can be used in place of Equation (1) for any of the variables listed in Table 1, but we expected, and could find in the data, reasonably consistent trends only for the first six; maximum, minimum, and mean daily values of both air temperature ('dry bulb') and dew point. We analysed daily values of these six parameters for all NZ sites with at least 10 years of data, fitting to each a linear model including trend and two sinusoidal pairs for annual and semi-annual cycles. We also explored any clear effect of latitude and annual cycle by latitude.

Unsurprisingly, the fits are 'noisy', in that other variation dominates the trends, as illustrated in Figure 3, which plots the fitted linear trend against the standard error of the fit. Values to the left of the plot show stations where the trend is well-characterised statistically, and it is apparent that trends for daily mean temperature cluster around values in the range +0.2 – +0.5 °C per decade. It is also reassuring that all but one of the reference sites for the 18 climate zones sit in this cluster.

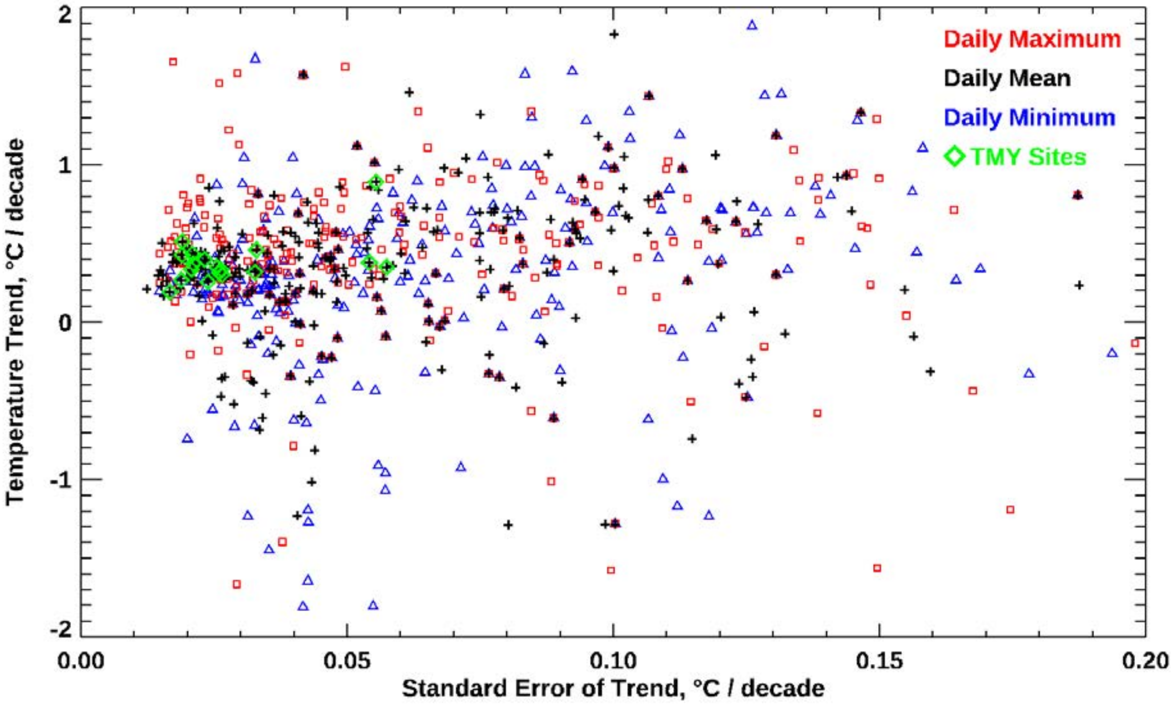

Figure 3. **Temperature trends for climate stations in Aotearoa.** Fitting a multilinear model (constant, trend, annual- and semiannual-cycles) at 275 NZ climate stations with more than 10 years of recent data gives decadal trends for daily maximum (red squares), mean (black '+'), and minimum (blue triangles) temperatures. Trends are plotted here against the standard error of the trend from the fit. Trends for mean temperature at stations representing the 18 climate zones are highlighted with larger green diamonds.

Any dependence of the trends on latitude was small, and inconsistent in sign between daily maxima, minima, and mean. Trends for dew point (not shown) were similar, and again there was little variation with latitude. Overall, the scatter as in Figure 3 seemed too great to justify ascribing any other dependence, such as with season, but this topic may warrant further investigation. For the present work, we adopted as representative for all sites the trends given in Table 3. These values were calculated as the mean of individual trends (ordinate of Figure 3) weighted by the inverse of its squared standard error (abscissa of Figure 3), and the corresponding figures for dew point trends. The values are also close to the modes (peak frequency) of the distributions of trends.

It is well-established that average temperatures in NZ have increase by 1.1 °C over the last century, and this figure would suggest only 0.11 °C per decade, so the much higher values of Table 3 show the trend has been non-linear; a rise of 0.3 °C per decade would be 3 °C over a century, though our time series only extend back to around 1970. Somewhat arbitrarily, we reconcile these different rates by assuming that the function τ_x of Equation (5) is quadratic, increasing from zero six decades ago (1964) to the present value for each parameter.

Table 3. **Present trends in dry bulb and dew point temperatures.**

	Trend in °C / Decade	
Daily Statistic	**Air Temperature**	**Dew Point**
Minimum	0.22	0.30
Mean	0.30	0.34
Maximum	0.40	0.38

In the application of Equation (5) for FS, and its corresponding formulation for FSs, we have sought representative values of all variables, with trends in T and T_d, for 2024, as illustrated by the red curve in Figure 2. Potentially, the same trend could be extrapolated, so that a TMY for 2040, for example, might be built from some of the warmest versions of each month in the past. This would have the benefit that all values were real, intrinsically respecting the physical relationships between them. It would not work for a distant future scenario if temperatures had shifted to the extent that no historical months could now be considered typical.

For the selection of TMY months, no actual adjustment of temperature or dew point values is necessary; it is just their DF that is changed. On the other hand, the TMY header contains "Design Conditions", as defined by ASHRAE, that are intended to represent the overall distribution of values. To compute these values, as defined for example in http://ashrae-meteo.info/v2.0/help.php, we have applied the shifts given by the functions τ_x for daily values. To estimate the effect on hourly values, we shift them by the trend in daily mean and then stretch the range by the difference between trends in maxima and minima.

2.3 Moisture Design Reference Years

As noted above, each MDRY is a full year of hourly data selected on the basis given by ANSI/ASHRAE Standard 160-2021. The specification is to calculate average yearly weather parameters for:

T	Air temperature (°C),
RH	Relative humidity (0 – 1),
C_8	Cloud index values (0 – 8),
P_W	Water vapour pressure (Pa),
I_S	Solar radiation on a south-facing wall (W m^{-2}),
R_S	Wind-driven rain on a south-facing wall (kg h^{-1} m^{-2}).

Note I_S and R_S here are redefined from ANSI/ASHRAE 160-2021 for the Southern Hemisphere.

Then the Predicted Damage Function is estimated by the (regression-derived) equation (Salonvaara and Corning 2011):

$$\begin{aligned} DTDRH_{70} = 108307 - 241 \cdot I_S - 1391 \cdot C_8 - 312326 \cdot RH + 183308 \cdot R_S \\ + 15.2 \cdot P_W + 27.3 \cdot T^2 + 261079 \cdot RH^2 - 0.00972 \cdot {P_W}^2 \end{aligned} \tag{6}$$

Equation (6) is used to calculate the damage function values for each year, which are then ranked in descending order. The selected weather year for hygrothermal analyses would be the 10th percentile year in ranking. Hourly data for the year have been produced in WAC format of WUFI, which allows for the extra hourly fields I_S and R_S as above.

2.4 Design Summer Years

As noted in Section 1.3, the selection of DSY1s is based on Static Weighted Cooling Degree Hour (SWCDH), for which a threshold temperature is derived for each climate zone as the 93rd percentile of mean temperature for the summer months. For the southern hemisphere, summer extends from one year into the next, but the relevant software seems to require a calendar year. We allowed that might be supported by folding a July-to-June year to appear as January to December, but we are unsure whether this may lead to any confusion for little benefit. At this time, we have just used calendar years, as for MDRYs.

For calculating the 93rd percentile of dry-bulb temperature, Virk and Eames (2016) cite the work of Armstrong et al. (2014). They had used “all available monitoring station data on minimum and maximum dry-bulb temperature” to estimate daily mean. They “also estimated daily mean relative humidity and daily mean and maximum apparent temperature, an index designed to reflect the combined effect of humidity and temperature on heat stress.”

We can readily compute these parameters at each zone’s representative site, but that is not quite the same as what Armstrong et al. (2014) describe; using all available climate stations within a zone. On the other hand, only data from the representative site are used to select the DSY1, and restriction to the 93rd percentile means that in a 30-year record the choice is likely to be between two or three years. Thus, we have determined the threshold just from the representative site, subject to that analysis being consistent with known climatology.

As given by Virk and Eames (2016), the required formula is then:

$$SWCDH = \sum_{all\ hours} \left(T - T_{Threshold,region}\right)^2, T - T_{Threshold,region} > 0 \qquad (7)$$

The DSY1 is intended to “represent a moderately warm summer year, defined as a year with a SWCDH return period closest to 7 years.” This expectation was checked against the distribution over all years.

The resulting data files are again in TMY3 format as CSV files to be checked with Weather Converter. The DSY1 is a non-leap year regardless of the selected year. There do not appear to be any other parameters required in addition to those included in the TMYs of 2.2.1, but the values of $T_{Threshold,region}$ for the zone and SWCDH for the selected year are listed in the file header.

2.5 Modified TMY3s and DSY1s for future scenarios

Virk and Eames (2016) describe the creation of future weather files by the ‘morphing methodology’ used in TM49 (CIBSE 2014). Morphing is used “to adjust the sequence of historical years, 1977–2004, under the climate change projections. This method involves ‘shifting’ and ‘stretching’ the observed weather data so that it has the mean monthly statistics given in the climate change projections but retains the observed hourly and day-to-day weather variability.” The description in TM49 notes that the scenarios in UKCP09 projections are given in probabilistic terms, allowing calculation of the 10th, 50th, and 90th percentiles.

2.5.1 Downscaled CMIP6 models

For this purpose we have relied on recent work by NIWA to downscale six of the CMIP6 models that have been found in previous work by NIWA to represent Aotearoa consistently and to span the expected uncertainty. The downscaling is to a grid of 0.10733° in latitude and longitude, so that a downscaled grid cell is just under 12 km in N-S extent, and ranges from 10 down to 8 km in W-E extent over the country from north to south. The models include historical simulations, from 1960 to 2014, that can be used as a 'training set'. By comparison of the actual historical data with the training set, we establish the difference in mean and standard deviation averaged over a decade, and then shift and scale the data to match the corresponding mean and s.d. in the target decade(s).

The available future scenarios from the NIWA project are SSP1-2.6, SSP2-4.5, and SSP3-7.0, as elaborated in Table 4. As shown by the estimated warming for 2041-2060, the first two correspond approximately to the 1.5 °C and 2.0 °C cited in Section 1.2 4).

Table 4. Shared Socioeconomic Pathways in the IPCC Sixth Assessment Report.

SSP-RCP	Scenario	Estimated warming (2041-2060)	Estimated warming (2081-2100)	Very likely range in °C (2081-2100)
SSP1-2.6	Low GHG emissions: CO_2 emissions cut to net zero around 2075	1.7 °C	1.8 °C	1.3 – 2.4
SSP2-4.5	Intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	2.0 °C	2.7 °C	2.1 – 3.5
SSP3-7.0	High GHG emissions: CO_2 emissions double by 2100	2.1 °C	3.6 °C	2.8 – 4.6

We have morphed the historical TMY3s and DSYs for the 18 climate zones for the three SSP-RCPs using the mean response of the six models. For each SSP-RCP we selected a future period for which annual mean temperature rises approximate 1.5, 2.0, and 3.0 °C above pre-industrial values. For each model, we computed the difference from the 1995-2014 simulations and the projections for the three SSP-RCPs over two decades around the future times of 2040, 2050, and 2070 respectively relative to the with the same model. The annual mean shifts for each of the six zones representing the largest population centres is shown in Table 5.

As found in the analysis of station data summarised in Table 3 for our algorithm (Section 2.2.2), trends for dry bulb and dew point temperatures are similar in the CMIP6 model results. They are slightly less for dew point than air temperature in the model projections, rather than slightly greater, but the difference is small in either instance.

The actual morphing is calculated separately for each month, as illustrated in Figure 4. Within each month, the plot shows shifts for the six zones ordered from North to South. Thus the downward slope in the points in most months indicates that southern centres have somewhat lower projected temperature rises than northern cities, though the difference is mostly less than between SSPs. Any such latitudinal dependence applies mainly to the larger trends in the warmer months.

Table 5. **Projected future mean annual changes for the six most populous NZ climate zones.**

	SSP1-2.6		SSP2-4.5		SSP3-7.0	
From 2005 to:	**2040**		**2050**		**2070**	
Climate Zone	**ΔT**	**ΔT_d**	**ΔT**	**ΔT_d**	**ΔT**	**ΔT_d**
Auckland	0.56	0.55	0.99	1.00	1.91	1.85
Hamilton	0.57	0.52	1.03	0.97	1.99	1.82
Tauranga	0.58	0.54	1.00	0.97	1.90	1.83
Wellington	0.46	0.45	0.90	0.90	1.75	1.71
Christchurch	0.61	0.38	1.02	0.86	2.00	1.58
Dunedin	0.44	0.38	0.82	0.77	1.70	1.53

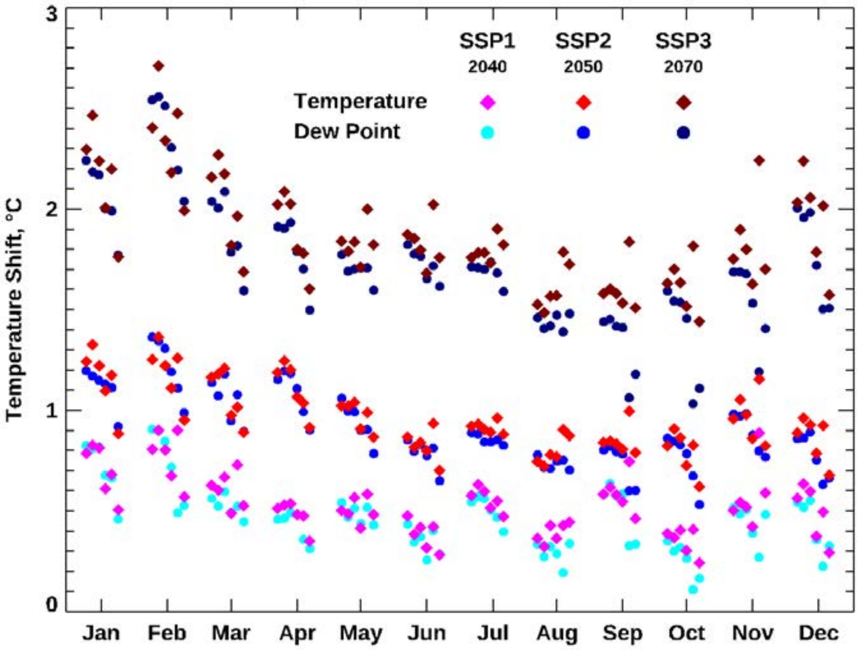

Figure 4. **Temperature shifts for morphing.** The shift by month from 2005 for temperature and dew point, to the respective SSP-RCP projections in the associated year, are shown for the six zones of Auckland, Hamilton, Tauranga, Wellington, Christchurch, and Dunedin, in that order from left to right within each month.

Of the six CMIP6 models, one denoted 'CCAM' has served as the archetype for the downscaling, and it could be used on its own with some justification. On the other hand, the morphing process does not directly use the actual sequences of projected future climate variables; it just shifts past data to match their distribution. We instead sought to combine the statistics of the separate models to effectively morph to their collective distribution, as described by Troup and Fannon (2016).

In particular, the method of Virk and Eames (2016) describes shifting and stretching month by month, and they take some trouble to correct for the way that a stretch derived from maximum minus minimum differences might not be symmetrical, so changing the kurtosis of the distribution. We concluded that to preserve the distributions within months that are the basis of F-S analysis, we needed to examine the daily, rather than just monthly, downscaled data. The daily datasets are roughly 30 times larger; 345 GB rather than just 12 GB for the monthly data. The historical data are for 1960 to 2014, and the future projections are from 2015 to 2100, but as above we compared the last 20 years of historical data with 20-year periods around 2040, 2050, and 2070 to approximate temperatures 0.5, 1.0, and 2.0 °C above present conditions.

With the daily data, we looked at the change in monthly distribution function from historic to projected future, for each month, zone, and parameter. The analysis is illustrated in Figure 5 for Auckland from 2005 to 2050 under SSP2-4.5 with the six models distinguished by colour. Solid curves denote the daily average, with short and long dashes for daily minima and maxima.

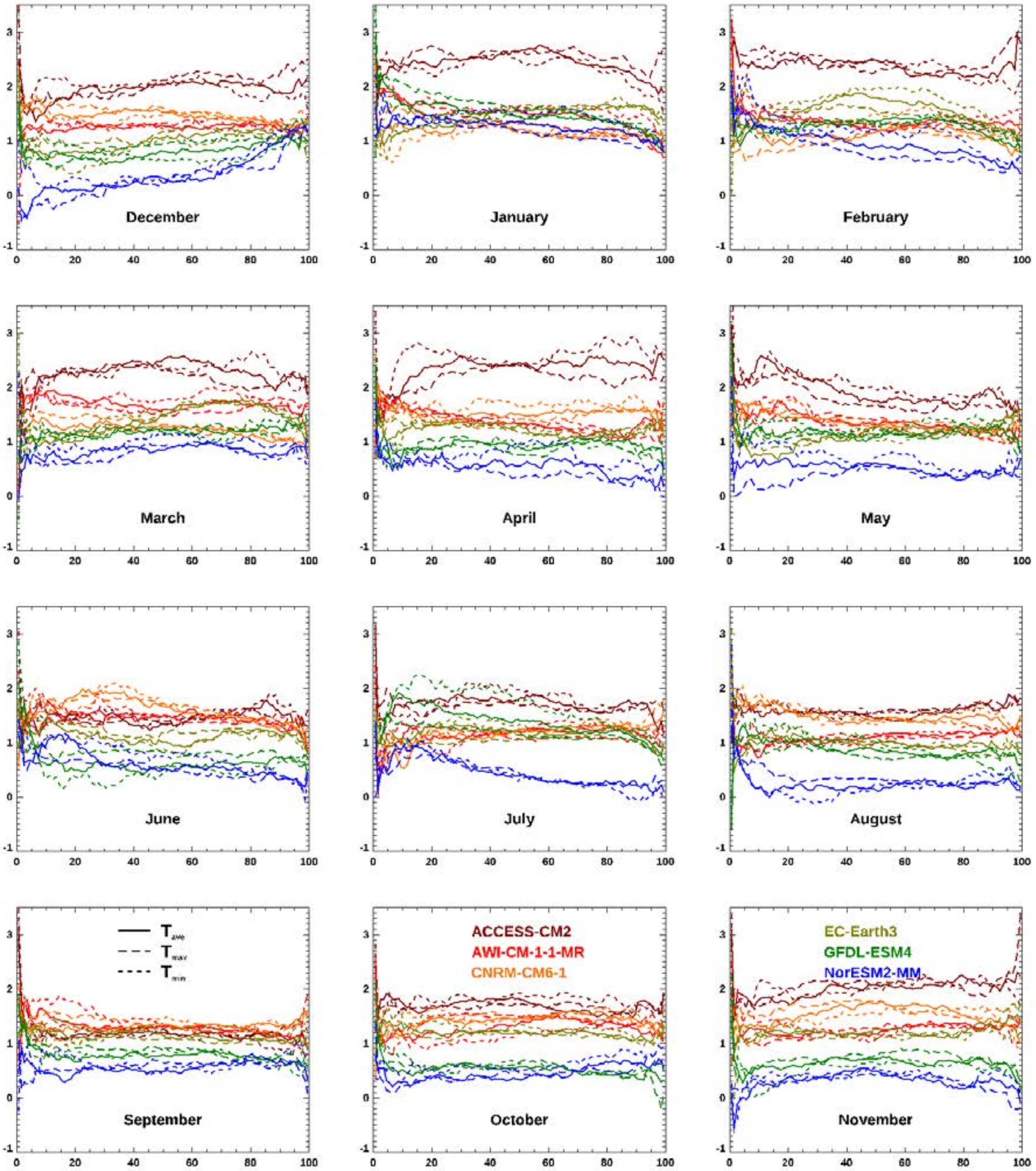

Figure 5. Shift in monthly temperature distributions in Auckland to 2050 for SSP2 in each model. The abscissa in each plot is the percentile in historical and future periods, with the ordinate showing the temperature shift. Upward or downward trends indicate stretch or contraction in range respectively.

For each month, the ordinate is the change in temperature, and the abscissa is the percentile in the monthly DF; effectively the ordinate of Figure 1 or Figure 2 expressed as per cent rather than a decimal fraction. A curve increasing from left to right would indicate stretch of the distribution; a downward slope would be contraction.

From this example, and the other 17 plots for the three SSP-RCP scenarios at the six sites, and the corresponding 18 plots for dew point, we see no clear effect of stretch (high temperatures increasing more than low) or contraction in temperature range. Thus, the shifts illustrated in Figure 4, and summarised in Table 5, are applied uniformly to shift the dry bulb and dew point temperatures in the hourly time series, without any stretch. Against this, Figure 4 does show larger shifts for the warmer months, so that there is some effective stretch within a year, but not within a day or a month.

We similarly depart from the work of Virk and Eames (2016) in making no adjustment to other parameters; solar radiation, wind speed and direction, or cloud cover. Though it is established that global irradiance at NZ climate stations diminished from the 1960s to around 1990, and subsequently increased (Liley 2009), it is unclear whether the latter trend continues, and neither effect is captured by models. As exemplified by the variability between models in Figure 5, we do not expect enough agreement on changes in other variables to justify their inclusion. Cloud cover is the main determinant of solar irradiance at any given time of day, but instantaneous cloud cover and local wind are perhaps the least accurately predictable weather and climate variables, and they will not be resolved adequately in the downscaled models.

2.5.2 Why we don’t use the model projections directly

Further to the last point, it might be asked whether we could use the downscaled data from the IPCC AR6 models directly as the source for deriving future TMY3s and DSY1s. The problem is the expectation that weather files for building simulation will capture the details of real variation in variables, including any correlations or anticorrelations from physical relationships. These are present in the GCMs and mesoscale models, but only at spatial scales of tens of kilometres and corresponding time scales. The downscaled projections from the large NIWA project for MfE are trustworthy instead for their statistical distributions, for use in the morphing described above.

2.6 Reference Summer Weather Years

Laouadi et al. (2020) analyse a range of indices for heat events and conclude that the only one that meets all of their criteria is the Standard Effective Temperature (SET), as proposed by Gagge et al. (1986) and defined in ANSI/ASHRAE Standard 55-2017 (ASHRAE 2017). Laouadi et al. (2020) use a ‘transient’ version (t-SET) that they describe as based on the work of Schweiker et al. (2016) to include the effect of both “past and present thermal conditions.” In essence, that work relates human thermal comfort to the exergy (Gibbs free energy) required for bodily thermoregulation.

It is apparent that this is a developing field, with some uncertainty how best to combine physical and physiological models for generic analysis. The models apply to a person of specified metabolic rate, clothing, and exertion in a given setting of air and radiative temperature, humidity, and air flow, whereas the RSWY is intended to be optimally chosen for a wide range of such situations.

We will follow the approach of Laouadi et al. (2020), including possible modifications suggested by research in this area at CIBSE and University College, London. The RSWYs will be in the same file format as the DSYs, for seven of the representative sites: Auckland, Hamilton, Tauranga, Wellington, Christchurch, Nelson, and Queenstown.

3 Results

3.1 Climate Zones

The present work uses the same 18 climate zones for Aotearoa determined for HERS (Liley et al. 2008), as reproduced in Figure 6 and on the cover of this report. For administrative reasons the zones were delineated in terms of Territorial Local Authorities, but the grouping of those, and the choice of 18 zones, was based on climate maps for the country. Those maps had been produced in previous NIWA work, and they can be found in the 2008 report.

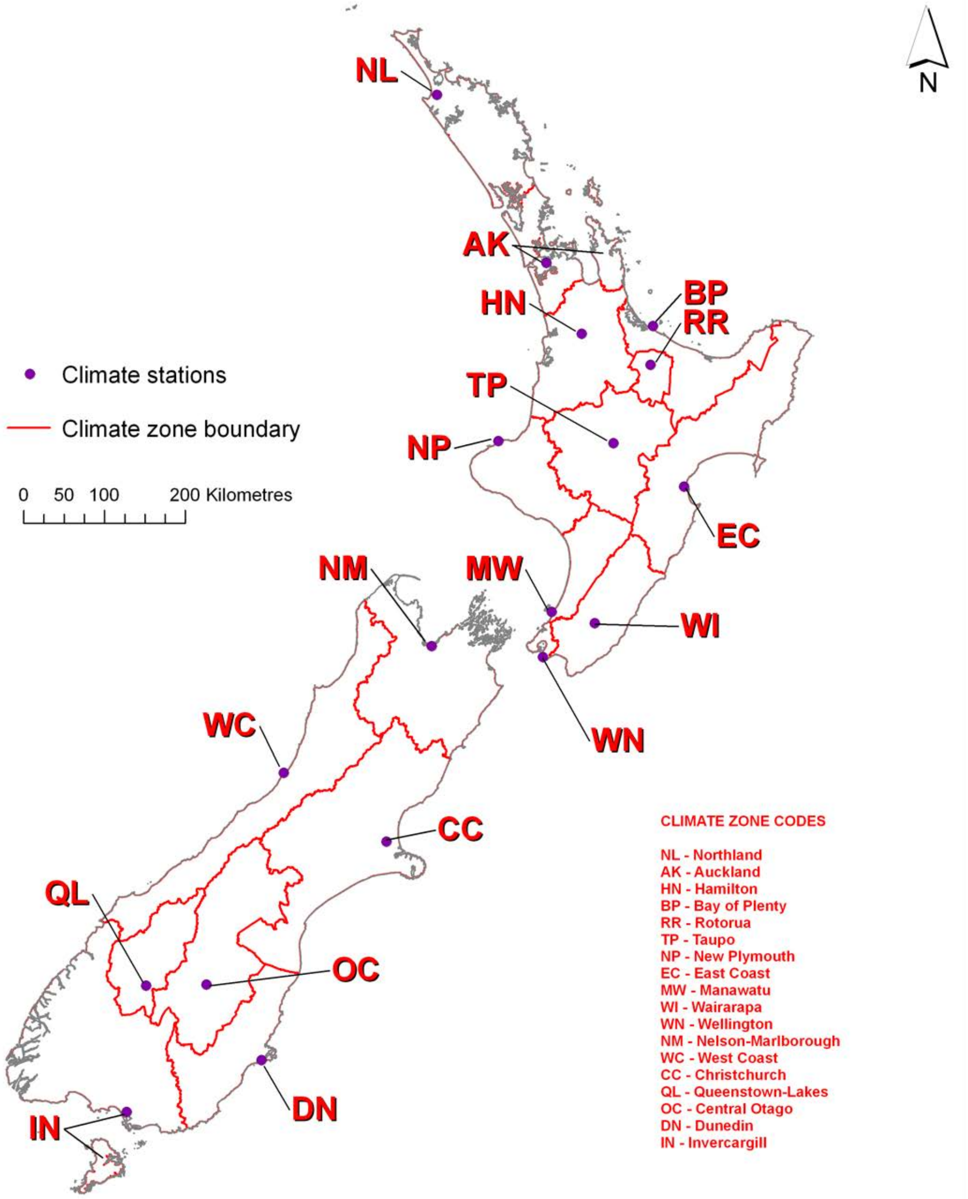

Figure 6. Climate zones for Aotearoa-New Zealand. The zones were selected in 2008 for similarity in solar flux, temperature, humidity, and wind according to NIWA climate maps. For administrative convenience in HERS, the zones were expressed in terms of TLAs, with the additional refinement that Rangitikei and Waitaki were split to better match the distinction of coastal and inland climates.

The allocation of TLAs to climate zones is shown in Table 6. Since the 2008 work, the new Auckland (Super)City has subsumed the former Rodney DC, North Shore CC, Waitakere CC, Auckland CC, Manukau CC, Papakura DC, and most of Franklin DC. The southern part of Franklin became part of Waikato, and north-eastern Franklin joined Hauraki. This means that both areas would now be represented by the HN climate zone, rather than AK, and from re-examination of the climate maps used for the original assignment of climate zones this change in fact seems apposite. Though shown separately in the 2008 report, Banks Peninsula DC had merged in 2006 with Christchurch, with which it was already in the same climate zone.

Table 6. **Climate zones for Aotearoa and associated TLAs.**

Zone	Station	Territorial Local Authorities
NL	Kaitaia	Far North DC, Whangārei DC, Kaipara DC
AK	Auckland	Auckland Council, Thames-Coromandel DC
HN	Ruakura (Hamilton)	Hauraki DC, Waikato DC, Matamata-Piako DC, Hamilton CC, Waipa DC, Otorohanga DC, South Waikato DC, Waitomo DC
BP	Tauranga	Western Bay of Plenty DC, Tauranga CC, Whakatāne DC, Kawerau DC, Ōpōtiki DC
RR	Rotorua	Rotorua DC
TP	Turangi	Taupō DC, Ruapehu DC, *northern* Rangitikei DC
NP	New Plymouth	New Plymouth DC, Stratford DC, South Taranaki DC, Whanganui DC
EC	Napier	Gisborne DC, Wairoa DC, Hastings DC, Napier CC, Central Hawke's Bay DC
MW	Paraparaumu	*Southern* Rangitikei DC, Manawatu DC, Palmerston North CC, Horowhenua DC, Kāpiti Coast DC
WI	Masterton	Tararua DC, Upper Hutt CC, Masterton DC, Carterton DC, South Wairarapa DC
WN	Wellington	Porirua CC, Hutt CC, Wellington CC
NM	Nelson	Tasman DC, Nelson CC, Marlborough DC, Kaikōura DC
WC	Hokitika	Buller DC, Grey DC, Westland DC
CC	Christchurch	Hurunui DC, Waimakariri DC, Christchurch CC, Selwyn DC, Ashburton DC, Timaru DC, Waimate DC
QL	Queenstown	Queenstown-Lakes DC
OC	Lauder	Mackenzie DC, *western* Waitaki DC, Central Otago DC
DN	Dunedin	*Eastern* Waitaki DC, Dunedin CC, Clutha DC
IN	Invercargill	Southland DC, Gore DC, Invercargill CC

One constraint on the selection of climate zones is that each needs a representative climate station with at least 10 years of data for all the required parameters. The inclusion of cloud cover in the list means that many of the stations are at airports, or a nearby airport is used for cloud data. It should be noted that the quoted latitude and longitude of a site are for the location of the pyranometer because the calculation of solar position depends on that information. This has apparently caused confusion for some users of the data, particularly in Wellington where the pyranometer is at Baring Head so that is the nominal location of the site. The data should nevertheless be considered representative of the entire climate zone, and indeed cloud data are for Wellington airport. The data are especially more appropriate for simulations of Wellington buildings than some past alternatives like IWEC, for which the radiation data were not even from measurements but inferred from other parameters such as humidity through its imprecise effect on cloudiness.

The representative climate stations for the 18 NZ climate zones are given in Table 7. Improvements in meteorological instruments and automated data logging mean that more recent data in the NIWA Climate Database are more reliable and more complete. Some earlier temperature and radiation data were stored to lower precision. Cloud layers have been reported for many years at airports around New Zealand, often hourly, but usually only for daylight hours. Automated Weather Stations (AWS) in the climate network record cloud layers hourly both day and night, so these data are used where possible.

The reference sites, including NIWA Climate Database 'agent number', nearest WMO code, latitude, longitude, and altitude are listed in Table 7. In our analysis, data for the full number of 'Years' from 'Start', as denoted in Table 7, establish the distribution of values and persistence for climate parameters at each site, but the choice of years for use in TMYs is limited to those after 'Use from'. Data series from 26 to 54 years' duration are used to establish distributions, while the data series considered for the TMY run from the year/month shown up to 2023/09 when this work began.

Table 7. Reference sites, locations, record length, and preferred period for the NZ climate zones.

Zone	Station/s	CliDB	WMO	Lat	Lon	Alt	Start	Years	Use from
NL	Kaitaia	17067	930120	-35.134	173.263	85	1987	37	1994/07
AK	Auckland	1962	931190	-37.008	174.789	7	1970	54	1994/11
HN	Ruakura	26117	931730	-37.774	175.305	45	1996	27	1996/11
BP	Tauranga	1615	931850	-37.673	176.196	4	1995	29	1995/01
RR	Rotorua	1770	932470	-38.106	176.315	283	1991	32	1991/12
TP	Turangi	25643	932450	-38.974	175.791	360	1996	27	1996/06
NP	New Plymouth	2283	933090	-39.008	174.184	30	1991	32	1991/11
EC	Napier	2980	933730	-39.459	176.858	3	1995	29	1995/01
MW	Paraparaumu	12442	934170	-40.904	174.984	5	1987	36	1993/11
WI	Masterton	36735	934710	-40.975	175.638	138	1995	29	1995/01
WN	Wellington	18234	934370	-41.408	174.871	79	1991	23	1991/06
NM	Nelson	4271	935460	-41.302	173.219	4	1991	32	1993/05
WC	Hokitika	3910	936150	-42.712	170.984	38	1991	32	1991/11
CC	Christchurch	4843	937800	-43.493	172.537	37	1970	54	1994/08
QL	Queenstown	5451	938310	-45.018	168.740	354	1991	32	1991/11
OC	Lauder	5535	938510	-45.040	169.684	375	1985	38	1996/01
DN	Dunedin	15752	938910	-45.901	170.515	4	1997	26	1997/09
IN	Invercargill	12444	938450	-46.417	168.330	1	1970	54	1993/12

The same 18 climate zones, and the data records for their representative sites, are used for the TMY3s, MDRYs, and DSY1s below. All 18 zones are morphed to simulate future climates in TMY3 and DSY1 files. The RSWY files will be produced for Auckland, Hamilton, Tauranga, Wellington, Christchurch, Nelson, and Queenstown.

3.2 TMY3s

A Typical Meteorological Year (TMY) consists of hourly records for an artificial year created from twelve representative months. The chosen months are each typical of that month from data records over a period of ten years or more. The 24 x 365 = 8760 records include figures for:

- Global (horizontal) irradiance,
- Direct radiation (on a sun-tracking surface),
- Diffuse irradiance,
- Air temperature,
- Moisture content / Dew point,
- Pressure,
- Wind speed,
- Wind direction,
- Cloud cover.

The definition of 'typical' is implied by the algorithm given in Section 2.2.1, using radiation, temperatures, and wind with the weightings in Table 2. We have allowed for trends in dry bulb and dew point temperatures as described in Section 2.2.2, but note that the two measures of radiation account for half the weighting, while dry bulb and dew point temperatures are accorded only one fifth each. Warmer years are more likely to be selected, but not if they are anomalous in radiation.

Our procedure for considering trends necessarily includes choosing a target year for which the changing variables are typical. In this work, that year is 2024.

We could as readily choose another, and a future year such as 2030 or 2040 would be appropriate as central to the period over which a new building will be occupied, perhaps before it is modified for even more extreme future climate. A potential difficulty is that our allowance for trends still relies just on past data, by finding previous years that typify present or future conditions. It requires that the future distribution still overlaps the past enough to find representative month-years in the intersection of the two. It is however quite conceivable that in future even average climate conditions will lie beyond present or past extremes.

The morphing technique that we have also implemented does not have this limitation, but it does carry the risk that taking historical climate data and changing values upsets the physical relationships that underlie them. As noted in Section 2.5.2, the downscaled models are not sufficient to check or confirm this, and Figure 5 illustrates the wide variation between models in mean monthly distribution even of daily values, so averaging over models would destroy any hourly connections between model projections. Thus, neither our method for trend adjustment, nor morphing, can give much assurance for a future climate far outside the range of present or past conditions.

As shown in Table 5, the morphed results for future scenarios each have a reference year central in the decade to which they apply, and the shift is calculated relative to the last two decades of the historical simulations, centred on 2005. For comparison with morphed results, we could have a created TMYs selected for 2005, rather than 2024. Note instead the revision in Section 3.5.2.

The choice of past month-years for the 2024 TMYs is shown in Table 8. They are supplied in TMY3 format, and the header contains Design Conditions, Extreme/Typical Periods, and monthly mean

Ground Temperatures calculated for the adjusted time series, TMY dataset, and region respectively, in accordance with the ASHRAE 2013 prescription. We recommend that these figures be used in preference to ASHRAE tables for any purpose that assumes consistency with the TMY file.

Table 8. Selected month-years for trend-aware TMYs for the 18 climate zones.

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NL	2008	2008	2007	2011	2018	2018	2021	2021	2021	2011	2018	2018
AK	2006	2017	2007	2021	2010	2016	2007	2020	2014	2011	2017	2007
HN	2021	2009	2007	2008	2005	2011	2007	2015	2007	2014	2018	2012
BP	2009	2005	2008	2021	2006	2018	2017	2007	2014	2016	2016	2018
RR	2007	2009	2005	2011	2006	2010	2020	2020	2022	2016	2016	2013
TP	2006	2009	2007	2021	2018	2016	2008	2020	2013	2016	2017	2014
NP	2006	2023	2005	2010	2021	2008	2018	2021	2014	2011	2018	2008
EC	2008	2006	2005	2016	2021	2016	2005	2020	2007	2019	2017	2013
MW	2023	2020	2008	2023	2014	2010	2007	2010	2017	2016	2018	2012
WI	2016	2017	2016	2015	2013	2010	2017	2018	2013	2019	2016	2014
WN	2016	2011	2021	2015	2005	2011	2017	2015	2008	2019	2016	2010
NM	2016	2020	2007	2008	2013	2010	2020	2018	2014	2013	2018	2013
WC	2010	2005	2023	2016	2014	2013	2006	2018	2017	2011	2018	2012
CC	2011	2018	2005	2015	2013	2013	2005	2021	2008	2016	2019	2014
QL	2009	2008	2016	2009	2014	2017	2017	2018	2013	2016	2011	2013
OC	2019	2020	2021	2007	2010	2019	2005	2005	2012	2020	2019	2013
DN	2021	2008	2023	2015	2014	2008	2020	2021	2009	2020	2011	2012
IN	2022	2020	2018	2017	2014	2021	2006	2017	2013	2000	2018	2013

It should be borne in mind that the algorithms of Sections 2.2.1 and 2.2.2, in their basis on the Sandia method, are intended to be representative of climates in the specific context of building simulation. The resulting TMY will have climate statistics similar to those of the full time series, but actual values will vary. The objectivity of the year-month selection method that allows it to be automated also means that a minimal change in one value can result in a different year selection, with different maxima and minima for the various parameters even though both years are almost identically typical by the criteria. By the assumptions, this should have minimal effect on simulated building performance, but that assurance does not extend to other uses of the data.

3.3 MDRYs

As contracted and described in Section 2.3, the MDRYs are produced in the **W**UFI **A**SCII **C**limate (WAC) format described in the WUFI software. The file consists of tab-delimited columns for the different weather elements. The number, content and sequence of the columns are not fixed and may be chosen as needed, but their meaning is denoted by prescribed column headers. This flexibility allows the omission of parameters that are not needed for any specific application.

A further flexibility is in the data that are supplied. If measured, the solar radiation on a given surface, and the rain flux on it, can be supplied directly. In the absence of either or both, they are estimated by WUFI from other elements, as we have done for the presumed south-facing wall.

In our data, direct beam (R) and diffuse (F) radiation for each hour are already estimated from global (G) irradiance, except when measured at four of the 18 sites. The calculated radiation flux onto a south-facing wall I_s for use in Equation (6) is then given by:

$$I_S = -R \cos \alpha_s \cos \phi_s + 0.5F + 0.5\xi G \tag{8}$$

where

α_s	is the solar elevation angle,
ϕ_s	is the solar azimuth angle, positive east from north,
ξ	is the albedo of surrounding surfaces, with a value of 0.15 assumed.

Rain rate on a south-facing wall is calculated from the southerly wind component and the effective fall speed for the range of droplet sizes. To estimate these we rely on the report of Cornick et al. (2002), and specifically their description of "Straube's Method", from which the wind-driven rain rate R_S of Equation (6) is:

$$R_s = A \frac{W \cos \phi_w}{V(D)} \tag{9}$$

where

W	is the wind speed,
ϕ_w	is the wind direction of origin, positive east from north,
$V(D)$	is the fall speed for rain droplets of diameter D,
A	is a rain admittance factor, with 0.9 assumed.

Following Cornick et al., rather than the Straube's suggested median diameter D_{50}, we use the predominant droplet diameter D_{pr} given in millimetres by:

$$D_{pr} = 1.3(1 - 1/2.25)^{1/2.25}\, {r_h}^{0.232} \tag{10}$$

where

r_h	is rainfall intensity on a horizontal surface, in mm h^{-1} or equivalently kg h^{-1} m^{-2}.

In fact the multiplier $1.3(1 - 1/2.25)^{1/2.25} = 1.0013$, which is unity to better than the precision of any measurements of hourly rainfall.

Of the various formulations of terminal velocity available, we again follow Cornick et al. in using their polynomial approximation for a raindrop of diameter D in mm, giving V in m s^{-1} as:

$$V = -0.16603 + 4.91884D - 0.888016D^2 \leq 9.20 \tag{11}$$

Following the prescription of Section 2.3, hourly values of all variables including I_s and R_s are averaged over each year to compute the damage function of Equation (6), and the year nearest the first decile (worst year in ten) is selected.

The WAC files have 12 header lines, largely self-explanatory. The third line gives the site and selected year, as listed for all sites in Table 9. The MDRY is a single year of data, so selection is more sensitive to missing values than for TMYs selected month by month. For MDRYs, we required there be at least 350 days of complete data, and consequently start years differ from those of Table 7 for some sites.

Table 9. **Reference sites, start year, record length, and selected MDRY for the 18 climate zones.**

Zone	Station/s	Start	Years	MDRY
NL	Kaitaia	1987	37	2012
AK	Auckland	1970	54	2010
HN	Ruakura	1996	27	1997
BP	Tauranga	1995	29	2005
RR	Rotorua	1991	32	2011
TP	Turangi	1996	27	2022
NP	New Plymouth	1991	32	2011
EC	Napier	1995	29	1997
MW	Paraparaumu	1987	36	2013
WI	Masterton	1995	29	2022
WN	Wellington	2000	23	2017
NM	Nelson	1991	32	2022
WC	Hokitika	1991	32	2019
CC	Christchurch	1970	54	2008
QL	Queenstown	1991	32	2011
OC	Lauder	1985	38	2018
DN	Dunedin	1997	26	2006
IN	Invercargill	1970	54	1994

The last header line of the MDRY file gives the column identifiers and order of hourly data for a year (365 days regardless of selected year), which follow as tab-delimited values of:

TA	Air temperature (°C)
HREL	Relative humidity (0 – 1)
PSTA	Pressure at station (hPa)
WS	Wind speed (m s^{-1})
WD	Wind direction (° through E from N)
ISGH	Global horizontal irradiance (W m^{-2})
ISDH	Direct horizontal irradiance (W m^{-2})
ISD	Diffuse horizontal irradiance (W m^{-2})
CI	Cloud index (0-1)
RN	Rain rate (mm h^{-1} ≡ kg m^{-2} h^{-1})

For the 18 climate zones and genericity of situations, we have estimated I_s and R_s for each hour of the climate record. However the WAC format allows that they might have been measured for the specific location and orientation of interest, and those values can be input directly to WUFI software by including them in the WAC format as:

ISM	Solar irradiance measured on a south-facing wall (W m^{-2})
RM	Wind-driven rain on a south-facing wall (kg h^{-1} m^{-2})

If these values are not supplied, WUFI calculates them internally, presumably with formulae similar to those above. Because inclusion our calculated values of ISM and RM would, if included, supplant WUFI's own, we have not written them to the file, but we could readily do so if that were required.

3.4 DSY1s

As described in Section 2.4, the selection of DSY1s is based on the initial determination of a temperature threshold for each region as the 93rd percentile of mean summer temperature. A 'Summer Year' for the southern hemisphere might better run from July to June, especially if a target hot spell ran over New Year. We implemented this idea in the code, but understand that EnergyPlus software requires the data as a conventional calendar year. A file written as January to June of the second year followed by July to December of the first might work, especially as in TMY format we smooth across all month joins including from December to January, so that they are effectively cyclic. The benefit was uncertain, as the hottest summer periods are around February rather than the change of year. Thus the DSY1 files as supplied are single calendar years, but this could be revisited if preferred for software customised for southern hemisphere seasons.

Table 10. Reference sites, usable years between first and last, threshold temperature, and selected DSY1.

Zone	Station/s	No. of Years	First	Last	Threshold °C	DSY1
NL	Kaitaia	11	2010	2022	24.5	2019
AK	Auckland	27	1995	2022	24.5	1998
HN	Ruakura	17	1998	2022	25.6	2022
BP	Tauranga	12	2005	2022	25.0	2019
RR	Rotorua	11	2007	2022	23.6	2020
TP	Turangi	10	2012	2021	24.4	2019
NP	New Plymouth	11	2010	2022	22.8	2016
EC	Napier	12	2001	2022	25.9	2020
MW	Paraparaumu	11	2010	2022	22.1	2018
WI	Masterton	10	2012	2022	26.0	2016
WN	Wellington	9	2011	2022	21.8	2018
NM	Nelson	15	2004	2022	23.2	2005
WC	Hokitika	11	2010	2022	20.9	2022
CC	Christchurch	17	1997	2022	24.5	1998
QL	Queenstown	10	2010	2022	23.8	2018
OC	Lauder	5	2010	2017	25.2	2015
DN	Dunedin	23	1998	2022	21.2	2019
IN	Invercargill	7	1995	2022	20.7	1998

Table 10 shows the results of the analysis and our final DSY1 selections (note Section 3.5.4). The limited number of usable years reflects tighter restrictions on missing values than for the MDRYs. We required at least 364 days with sufficient temperature, humidity, and radiation; at least 363 days with wind speed; and 360 days of rainfall and cloud. All years could be used to determine the 93rd percentile threshold temperature, and they could also be ranked by *SWCDH* of Equation (7), so the restriction to years with very few days of missing data is not too onerous for the selection.

It is noteworthy that the DSY1s for most sites are from the decade since 2015, except at three sites where the renowned El Niño year of 1998 was selected, and 2005 for Nelson. Unlike our procedure for TMY3s, or the morphing of both TMY3 and DSY1s in the following section, the prescription for the historical DSY1s makes no allowance for trends in temperature. To do so would require us to redefine both the threshold temperature and the idea of a 7-year return period.

3.5 Morphed climate files

The procedure described in Section 2.5 was used to shift dry bulb and dew point temperatures in historical data to match the corresponding distributions in future scenarios.

3.5.1 Morphed TMY3s

For this purpose, the TMY3 selection would necessarily differ from that described in Section 3.2, wherein each past month's sorted data were compared, via F-S statistics, with the fitted distribution for 2024. There, an early year would only be selected if it was much warmer than typical for its time, and indeed selection was restricted to years from 2005 onwards without loss of generality.

For the morphing, we are instead shifting temperatures, rather than just finding warmer years, so each month-year is compared with the fitted distribution for its own era. For this reason, in our initial approach, we extended the allowed range back to 1990, or effectively to the year/month pairs listed in the last column of Table 7, which all post-date 1990.

A further difference arises in that dry bulb and dew point temperatures are shifted by different amounts for each month, as illustrated in Figure 4. As shown there, the shifts are generally larger in the warmer months, with the effect that there is some stretch in the annual range of temperatures even though we do not stretch (or shrink) the range in each day.

Within each zone, only temperature and dew point are changed for the different SSP-RCPs, and only by the difference in linear trend from 2005 to the central years of 2040, 2050, and 2070. The annual means of those trends, derived from Table 5, are shown in Table 11 for the major cities.

Table 11. Projected annual mean trends for NZ climate zones. Trends are in °C/decade, from Table 5.

	SSP1-2.6		SSP2-4.5		SSP3-7.0	
Climate Zone	**ΔT**	**ΔT_d**	**ΔT**	**ΔT_d**	**ΔT**	**ΔT_d**
Auckland	0.16	0.16	0.22	0.22	0.29	0.28
Hamilton	0.16	0.15	0.23	0.22	0.31	0.28
Tauranga	0.17	0.15	0.22	0.22	0.29	0.28
Wellington	0.13	0.13	0.20	0.20	0.27	0.26
Christchurch	0.17	0.11	0.23	0.19	0.31	0.24
Dunedin	0.13	0.11	0.18	0.17	0.26	0.24

Expressed in this way, the trends for SSP3-7.0 are not dissimilar to those found from observations, as shown in Table 3. As noted in Section 2.2.2, we interpreted the function τ_x of Equation (5) as quadratic, increasing from zero over six decades to its present value. In contrast, the trends we use in morphing are linear, both in the interpretation of past data and in the shifts applied to estimate future values.

We initially treated the morphed datasets in the same way as historical, allowing the standard procedure to choose representative years independently for each SSP-RCP. The resultant selections for the morphed TMY3s are shown in Table 12, analogous to Table 8 but for just the six climate zones containing the country’s largest cities.

Table 12. Month-years for morphed TMY3s initially selected for six zones and three SSP-RCPs.

Zone	SSP	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AK	1	2007	2008	2021	2001	2015	2018	2014	2008	2018	2004	2006	2002
AK	2	2007	2003	2012	2001	2015	2018	2009	1995	2018	2004	1995	2002
AK	3	2003	2003	2012	2009	1996	2018	2009	1995	2015	2008	1995	2002
HN	1	2010	2015	2020	2001	2010	2007	2021	2016	2022	2004	2015	2002
HN	2	2010	2015	2006	2001	2010	2007	2021	2016	2022	2004	2015	2002
HN	3	2010	2015	2006	2001	2010	2018	2021	2016	2021	2004	2015	2016
BP	1	2010	1997	2021	2011	2006	2018	1996	1998	2012	2004	2009	2000
BP	2	2010	1997	2021	2009	2006	2018	1996	1998	2012	1995	2009	2014
BP	3	1995	1997	2020	2009	2006	2018	1996	1998	2012	1995	2009	2014
WN	1	2016	2009	2020	2002	2004	2015	2002	2003	2021	2022	2009	2020
WN	2	2016	2009	2020	2002	2004	2015	2015	2003	2021	2022	2009	2020
WN	3	2017	2009	2020	2002	2004	2015	2015	2015	2021	2022	2009	2020
CC	1	1995	1996	2020	2000	2000	1998	2002	2015	2000	2019	2005	2008
CC	2	1995	1996	2020	2011	2000	1998	2002	2015	2015	1994	2002	2009
CC	3	1995	1996	2020	2011	2000	1998	2002	2015	2015	1994	2002	2009
DN	1	2021	2007	2014	2000	2013	2001	2016	2007	2009	2000	2011	2014
DN	2	2010	2017	2014	2020	2013	2017	2016	2007	2013	2000	2011	2016
DN	3	2010	2017	2009	2018	2013	1998	2016	2007	2013	2012	2011	2009

3.5.2 Revised TMY3 procedure

This approach, while conceptually sound, produced results that were counterintuitive. Simulations with the morphed data did not show the effects of rising temperatures – reduced demand for heating and greater need for cooling – as consistently as expected. This results from a weakness of the TMY selection procedure.

The weights in Table 2 give temperature and dew point each 20% of the total, with the other 60% coming from solar radiation and wind. Moreover the other selection criteria, implemented via our Equations (3) and (4), can make the selection of year for each month sensitive to very small changes in individual parameter values. While the intention is that two such years for a given month would give close results in simulations, there is no guarantee of this. Changing the choice of ‘best among equals’ can produce different results for a specific building and location, even if such differences might average out over many settings and simulations.

From discussion with both the Client and reviewers of the data at the Building Research Association of New Zealand (BRANZ), we determined that it would be better to avoid the changes in month-year selections illustrated in Table 12 for six of the zones. Instead, we simply maintain the same month-year selections from the 2024 TMYs into the morphed future TMYs. Tests by BRANZ with the resulting files show expected and consistent decreases in heating and decreases in cooling demand in warming climates.

For each of the morphed TMY3s, the Design Conditions are updated in accordance with ASHRAE definitions as though the entire time series were shifted. The Typical/Extreme Periods are of course calculated for the morphed TMY3. Ground temperatures are increased by the monthly shifts plotted in Figure 4. The respective details in Table 5 appear in the second line of 'Comments' in the files.

3.5.3 Morphed DSY1s

Reconstructing the DSY1s with morphed data resulted in the selection of years shown in Table 13.

Table 13. Threshold temperatures and initially selected DSY1 years for historical and morphed DSY1s.

Zone	City	SSP-RCP	Mean ΔT °C	Threshold °C	DSY1
AK	Auckland	-	-	24.5	2018
		1	0.56	25.4	2018
		2	0.99	25.9	2018
		3	1.91	27.1	2022
HN	Hamilton	-	-	25.6	2020
		1	0.57	26.3	2019
		2	1.03	26.7	2022
		3	1.99	27.9	2022
BP	Tauranga	-	-	25.0	2019
		1	0.58	25.6	2019
		2	1.00	26.0	2019
		3	1.90	27.0	2019
WN	Wellington	-	-	21.8	2018
		1	0.46	22.3	2018
		2	0.90	22.7	2018
		3	1.75	23.7	2018
CC	Christchurch	-	-	24.5	2020
		1	0.61	25.5	1998
		2	1.02	25.9	1998
		3	2.00	27.1	1998
DN	Dunedin	-	-	21.2	2019
		1	0.44	21.6	2019
		2	0.82	22.0	2019
		3	1.70	22.8	2015

Because of the shift in dry bulb temperatures, the threshold temperatures for each region used to calculate *SWCDH* in Equation (7) are changed, and again small changes in the time series result in different year selections. This is highlighted in Table 13, which also includes for comparison the corresponding threshold and year from the same sites in unshifted historical data. The shift in threshold does not match the mean temperature change because thresholds refer to higher temperatures and shifts differ between months.

In four of the six major city climate zones, the selected year for the morphed DSY1 is the same as for the original DSY1, at least for the lower-emission SSP-RCP scenarios, but they change for others and for the higher-emission scenarios. A change in selection means that the trend implicit in the morphing since the 20 years around 2005 has differentially affected the $SWCDH$ values and changed their relative ranking. Though expected and algebraically correct, this change is again undesirable.

3.5.4 Revised DSY1 procedure

Again, strict adherence to the definitions, now for DSY1s, results in climate files that do not show proportionate change in risk of overheating as climate warms. As with the month-year selection of TMYs, we concluded that it is better to use the same representative year for both the historical and projected future temperatures, but this time it was not suitable to just use the historical choice.

In practice, for each site we examined plots of *SWCDH* calculated from Equation (7), for both historical data and morphed data, including fitted Generalised Extreme Value distributions for each. With some necessary subjectivity, we selected years that were near to optimal for all four versions of the time series. The selected years are those shown in Table 10, but for several sites they are not the original choice for historical data. Note that Auckland (2018 to 1998), Hamilton (2020 to 2022), and Christchurch (2020 to 1998) all changed from the first choice in Table 13 to the final in Table 10.

We set out the detail here just for completeness, but note that the selections in both Table 12 and Table 13 are not present in the supplied data files. Instead the selections, should they be needed, are as shown in Table 8 and Table 10. Consistent with the TMY3 format used for both the TMYs and the DSYs, the respective year is also shown in the files.

Just as for the morphed TMY3s, the morphed DSY1s include Design Conditions, Typical/Extreme Periods, and Earth Temperatures derived from the morphed data or adjusted in accord with them.

3.6 RSWYs

These are incomplete at the time of this report and will be described in a separate report.

4 Products

The products of this work have been supplied to MBIE, and to BRANZ as reviewers. They are 18 files – one for each climate zone – with the file names, types, and purpose shown in Table 14 below. In the file names, ‘xx’ denotes each zone’s two-letter code as shown in Figure 6 and in the first column of Table 6 to Table 10.

Table 14. Files developed in this work, and their intended purpose. There are 18 of each type, one for each of the climate zones shown in Figure 6.

File Name	Description	Purpose
TMY3_NZ_xx.epw	Synthetic year of months selected to best represent 2024 when allowing for trends, in EnergyPlus format	General simulations of building performance in present climates
MDRY_NZ_xx.WAC	Continuous year of historical data selected for high occurrence of driving rain, in WAC format for WUFI	Simulating moisture ingress, mould and damp, in present climates
DSY1_NZ_xx.epw	Continuous year of historical data representing a moderately warm summer, in EnergyPlus format	Testing risk of overheating to CIBSE TM52/TM59 criteria, in recent climates
TMY3_NZ_M1_xx.epw	Synthetic year of months morphed from 2005 to 2040 in SSP1-2.6, in EnergyPlus format	Simulating buildings at ~0.5 °C above present, or ~1.5 °C above pre-industrial
TMY3_NZ_M2_xx.epw	Synthetic year of months morphed from 2005 to 2050 in SSP2-4.5, in EnergyPlus format	Simulating buildings at ~1.0 °C above present, or ~2.0 °C above pre-industrial
TMY3_NZ_M3_xx.epw	Synthetic year of months morphed from 2005 to 2070 in SSP3-8.0, in EnergyPlus format	Simulating buildings at ~2.0 °C above present, or ~3.0 °C above pre-industrial
DSY1_NZ_M1_xx.epw	Continuous year for a warm summer morphed from 2005 to 2040 in SSP1-2.6, in EnergyPlus format	Assessing overheating at ~0.5 °C above present, or ~1.5 °C above pre-industrial
DSY1_NZ_M2_xx.epw	Continuous year for a warm summer morphed from 2005 to 2050 in SSP2-4.5, in EnergyPlus format	Assessing overheating at ~1.0 °C above present, or ~2.0 °C above pre-industrial
DSY1_NZ_M3_xx.epw	Continuous year for a warm summer morphed from 2005 to 2070 in SSP3-7.0, in EnergyPlus format	Assessing overheating at ~2.0 °C above present, or ~3.0 °C above pre-industrial

The other product of the work is this report, for reference by those using the above files.

Copies of the data files, and this report, are secured on NIWA’s Project Drive.

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Glossary of abbreviations and terms

ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
BRANZ	Building Research Association of New Zealand
CIBSE	Chartered Institution of Building Services Engineers (London)
CMIP6	Coupled Model Intercomparison Project – Phase 6
DF	Distribution Function
DSY	Design Summer Year (DSY1 follows 2016 specification)
EECA	Energy Efficiency and Conservation Authority
F-S	Finkelstein-Schafer (statistic used in TMY selection)
GCM	General Circulation Model
HERS	Home Energy Rating Scheme (New Zealand)
MDRY	Moisture Design Reference Year (ANSI/ASHRAE 160-2021)
NatHERS	Nationwide House Energy Rating Scheme (Australia)
RCP	Representative Concentration Pathway (IPCC AR5)
RSWY	Reference Summer Weather Year (Laouadi et al. 2020)
SET	Standard Effective Temperature (Laouadi et al. 2020)
SSP	Shared Socioeconomic Pathway (IPCC AR6)
SWCDH	Static Weighted Cooling Degree Hour (Virk and Eames 2016)
TLA	Territorial Local Authority
TMY	Typical Meteorological Year (synthetic year of 12 typical months)
TRY	Test Reference Year (complete year of hourly data)
WCDH	Weighted Cooling Degree Hour (Virk and Eames 2016)
WUFI	Wärme Und Feuchte Instationär (heat and moisture transiency software)

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