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cubble: An R Package for Structuring Spatio-temporal Data

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Abstract

Spatio-temporal variables can be time invariant or not and this divides them into those can be identified only with the spatial identifier and those cross-identified by the spatial and temporal identifier. In this paper, a new data structure, **cubble**, is proposed for manipulating and visualising spatio-temporal data. The new data structure proposes two forms for manipulating the spatial and temporal dimension separately while providing a smooth switch between the two forms to link the two dimensions. Advanced considerations are given to illustrate data with hierarchical structure, data matching, and how **cubble** fits with interactive graphics pipeline. Examples are given to analysing Australia meteorology data, river level data, and climate reanalysis (ERA5).

Keywords: spatio temporal, R, climate weather station, data analysis.

1. Introduction

Spatio-temporal data concerns variables in the spatial coordinates across time. Some variables are invariant to time and can be solely identified by its spatial location while other time varying variables need both the spatial and temporal identifier to identify. Manipulating data in these two levels is usually done separately and the third tidy data principal ([Wickham 2014](#)) recommends each type of observational unit to form a table. Another feature for a spatio-temporal data structure to have is that variables created from subsequent operations can be automatically added to the existing table with the same level. This is better than an output that index the variables with the identifiers since otherwise analysts will need to manually join this output with existing variables in the same level.

Currently, available spatio-temporal data structure in R includes: **spacetime** ([Pebesma 2012](#)), which proposes four space-time layouts: Full grid (STF), sparse grid(STS), irregular (STI), and trajectory (STT). The data structure it uses is based on **sp** ([Pebesma and Bivand 2005](#)) and **xts** ([Ryan and Ulrich 2020](#)), both of which has been replaced by more recent implementations. **spatstat** ([Baddeley and Turner 2005](#)) implements a ppp class for point pattern data; and more recent, **stars** ([Pebesma 2021](#)) implements a spatio-temporal array with the dplyr's data cube structure **cubelyr** ([Wickham 2020](#)) as its backend. While these implementations either store spatial and temporal variables all in a single table, hence duplicate the spatial variables for each temporal unit; or split them into two separate tables that has the problem of manually joining, mentioned in the previously. This creates a gap in the software development. The requirement for such a tool is important given the ubiquity of spatio-temporal vector data in the wild: the Ireland wind data from **gstat** is an classic example data that splits variables into its spatial (`wind.loc`) and temporal (`wind`) dimension; Bureau of Meteorology (BoM) provides climate observations widely applied in agriculture and ecology study.

This paper describes the implementation of a new spatio-temporal data structure: **cubble**. **cubble** implements a relational data structure that uses two forms to manage the switch between spatial and temporal dimension. With this structure, users can manipulate the spatial or temporal dimension separately, while leaves the linking of two dimensions to **cubble**. The software is available from the Comprehensive R Archive Network (CRAN) at [CRAN link].

The rest of the paper will be divided as follows: Section 2 presents the workflow of data manipulation in cubble. Section 3 explains how cubble deals with some advanced considerations including data with hierarchical structure, data matching, and how cubble fits with existing static and interactive visualisation tools. Section 4 gives examples of the features introduced in the previous two sections with climate and hydrology data. An example on how cubble handle Netcdf data is also provided. Section 5 concludes the paper.

2. The cubble package

Spatio-temporal data usually come in various forms and Figure 1 shows four examples of this. These four examples show some common characters of the spatio-temporal data: 1) a spatial identifier, that uniquely identifies each site, 2) a temporal identifier, that prescribes the time stamp each site is recorded, 3) Coordinates, comprising of latitude and longitude, that locate each site on the map. These identifiers will be the building blocks for cubble. Spatio-temporal data can also be thought of as a data cube with three axes: id, time, and variable. Notice

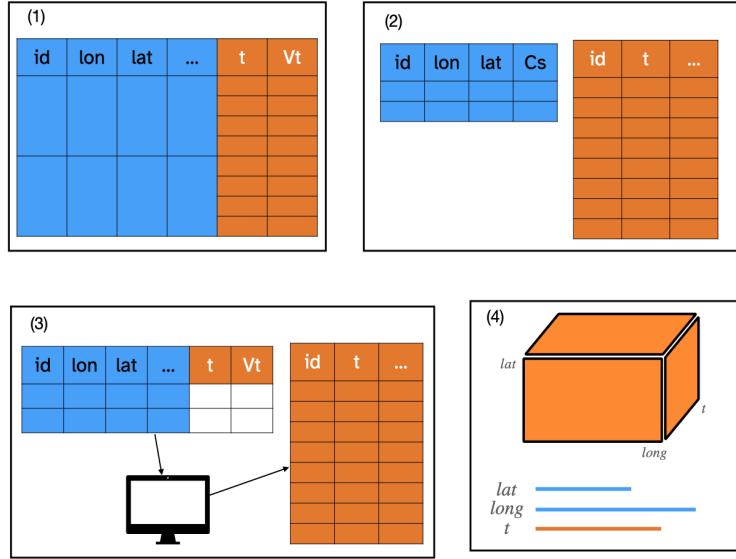


Figure 1: An illustration of different spatio-temporal data format: (1) a single table for all the variables; (2) separate tables for spatial and temporal variables; (3) a table of metadata used to query the database and a separate table for queried data; and (4) an array data structure of cube or hypercube.

that in the time-variable face, time invariant variables share the same value across all the time stamps while time varying variables have values varying across time. This heterogeneity will be used to split the data into two forms in cubble.

In a cubble, there are two forms: nested form and long form, and Figure 2 sketches the two forms along with the associated attributes. The decision on which form to use is output-oriented, meaning analysts need to first think about whether the output of a particular operation is identified only by the spatial identifier, or a combination of spatial and temporal identifier. The nested cubble is suitable for working with operations that are only identified by the site and this type of operation can be a pure manipulation of spatial variables, or a summary of temporal variables by site (i.e. the output of counting the number of raining day is only identified by sites and hence should be performed with the nested form). Underneath the nested form, a cubble is built from a row-wise dataframe (`rowwise_df`) where each site forms a separate group. This structure simplifies the calculation that involves temporal variables by avoiding the use of `map` syntax when working with list-column.

For those operations whose output involves both a spatial and temporal dimension, long form should be used. The long form is identified by both the spatial and temporal identifier and adopts a grouped dataframe (`grouped_df`) to forms each site as a group. Spatial variables are stored separately in a `tibble` as an special attribute of the long cubble. This design avoids repeating the spatial variables at each time stamp while not dropping information from spatial variables.

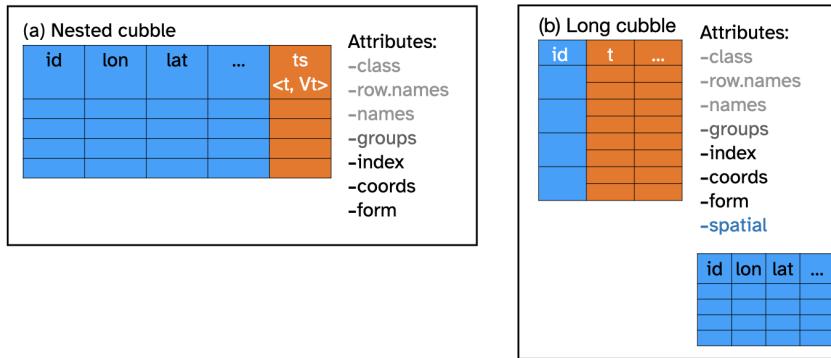


Figure 2: An illustration of the nested and long form in cubble. The nested form defines each site in a row and nests the time varying variables into a single column **ts**. The long form cubble uses **id** and **t** to identify each row and store the time invariant variables as an attribute, **spatial**.

2.1. Create a cubble in the nested form

`as_cubble()` creates a cubble by supplying the three key components: **key** as the spatial identifier; **index** as the temporal identifier; and a vector of **coords** in the order of longitude first and then latitude. The naming of **key** and **index** follows the convention in the **tsibble** package. The cubble created by default is in the nested form. Below is an example of creating a cubble:

```
R> cubble_nested <- cubble::climate_flat %>%
+   as_cubble(key = id, index = date, coords = c(long, lat))
R> cubble_nested

# cubble:  id [5]: nested form
# bbox:      [115.97, -32.94, 133.55, -12.42]- check gap on long and lat
# temporal: date [date], prcp [dbl], tmax [dbl], tmin [dbl]
#             id      lat    long elev name      wmo_id ts
#             <chr>   <dbl> <dbl> <dbl> <chr>   <dbl> <list>
1 ASN00009021 -31.9  116.  15.4 perth airport  94610 <tibble [366 x 4]>
2 ASN00010311 -31.9  117.  179   york       94623 <tibble [366 x 4]>
3 ASN00010614 -32.9  117.  338   narrogin   94627 <tibble [366 x 4]>
4 ASN00014015 -12.4  131.  30.4 darwin airport 94120 <tibble [366 x 4]>
5 ASN00015131 -17.6  134.  220   elliott    94236 <tibble [366 x 4]>
```

There are a few information in the cubble header: the name of the **key** variable (**id**) and its number (5), bounding box ([115.97, -32.94, 133.55, -12.42]), and also the name of variable nested in the **ts** column with its type: **date** [date], **prcp** [dbl], **tmax** [dbl], **tmin** [dbl].

2.2. Stretch a nested cubble into the long form

The long cubble is suitable to manipulate the time dimension of the data. The function `stretch()` switches the nested cubble into the long cubble by first extracts all the spatial variables into a separate tibble and store in the `spatial` attribute and then unnests the `ts` column:

```
R> cubble_long <- cubble_nested %>% stretch(ts)
R> cubble_long

# cubble:  date, id [5]: long form
# bbox:    [115.97, -32.94, 133.55, -12.42]- check gap on long and lat
# spatial: lat [dbl], long [dbl], elev [dbl], name [chr], wmo_id [dbl]
  id      date      prcp  tmax tmin
  <chr>    <date>    <dbl> <dbl> <dbl>
1 ASN00009021 2020-01-01     0  31.9 15.3
2 ASN00009021 2020-01-02     0  24.9 16.4
3 ASN00009021 2020-01-03     6  23.2 13
4 ASN00009021 2020-01-04     0  28.4 12.4
5 ASN00009021 2020-01-05     0  35.3 11.6
# ... with 1,825 more rows
```

Notice here that the third line in the header now shows the name and type of spatial variables: `lat [dbl]`, `long [dbl]`, `elev [dbl]`, `name [chr]`, `wmo_id [dbl]`.

2.3. Tamp a long cubble back to the nested form

Manipulation on the spatial and temporal dimension can be an iterative process. Many times, analysts will need to go back and forth between the nested and long cubble. `tamp()` inverses the `stretch()` that introduced in the previous section, to switch from a long cubble to the nested cubble:

```
R> cubble_back <- cubble_long %>% tamp()
R> cubble_back

# cubble:  id [5]: nested form
# bbox:    [115.97, -32.94, 133.55, -12.42]- check gap on long and lat
# temporal: date [date], prcp [dbl], tmax [dbl], tmin [dbl]
  id      lat  long  elev name      wmo_id ts
  <chr>    <dbl> <dbl> <dbl> <chr>    <dbl> <list>
1 ASN00009021 -31.9 116. 15.4 perth airport 94610 <tibble [366 x 4]>
2 ASN00010311 -31.9 117. 179   york       94623 <tibble [366 x 4]>
3 ASN00010614 -32.9 117. 338   narrogin  94627 <tibble [366 x 4]>
4 ASN00014015 -12.4 131. 30.4 darwin airport 94120 <tibble [366 x 4]>
5 ASN00015131 -17.6 134. 220   elliott    94236 <tibble [366 x 4]>
```

2.4. Migrate spatial variables to a long cubble

Some functions require time invariant variables to be in the same table as the time varying ones. In cubble, this can be done through `migrate()`, which moves the time invariant variables into the long cubble:

```
R> cubble_mig <- cubble_long %>% migrate(long, lat)
R> cubble_mig

# cubble: date, id [5]: long form
# bbox: [115.97, -32.94, 133.55, -12.42]- check gap on long and lat
# spatial: lat [dbl], long [dbl], elev [dbl], name [chr], wmo_id [dbl]
  id      date      prcp  tmax  tmin  long   lat
  <chr>    <date>    <dbl> <dbl> <dbl> <dbl>
1 ASN00009021 2020-01-01     0  31.9  15.3 116. -31.9
2 ASN00009021 2020-01-02     0  24.9  16.4 116. -31.9
3 ASN00009021 2020-01-03     6  23.2  13    116. -31.9
4 ASN00009021 2020-01-04     0  28.4  12.4 116. -31.9
5 ASN00009021 2020-01-05     0  35.3  11.6 116. -31.9
# ... with 1,825 more rows
```

Notice that these added time invariant variables will not be remembered the cubble and will disappear if switched to the nested form and then switched back. Hence they should most likely been used at the last step of the analysis:

```
R> cubble_mig %>% tamp() %>% stretch()

# cubble: date, id [5]: long form
# bbox: [115.97, -32.94, 133.55, -12.42]- check gap on long and lat
# spatial: long [dbl], lat [dbl], elev [dbl], name [chr], wmo_id [dbl]
  id      date      prcp  tmax  tmin
  <chr>    <date>    <dbl> <dbl> <dbl>
1 ASN00009021 2020-01-01     0  31.9  15.3
2 ASN00009021 2020-01-02     0  24.9  16.4
3 ASN00009021 2020-01-03     6  23.2  13
4 ASN00009021 2020-01-04     0  28.4  12.4
5 ASN00009021 2020-01-05     0  35.3  11.6
# ... with 1,825 more rows
```

2.5. Compatibility with existing packages

Building from an `tbl_df` class, cubble has implemented methods for `dplyr` generics, which includes:

- basic: `mutate`, `filter`, `summarise`, `select`, `arrange`, `rename`, `left_join`
- grouping: `group_by`, `ungroup`
- slice family: `slice_head`, `slice_tail`, `slice_sample`, `slice_min`, `slice_max`

cubble is also compatible with **tsibble**. When creating a cubble from a tsibble, Only the `coords` argument need to be specified:

```
R> # casting a tsibble into cubble
R> dt <- climate_flat %>%
+   tsibble::as_tsibble(key = id, index = date) %>%
+   cubble::as_cubble(coords = c(long, lat))
R> dt

# cubble: id [5]: nested form
# bbox: [115.97, -32.94, 133.55, -12.42] - check gap on long and lat
# temporal: date [date], prcp [dbl], tmax [dbl], tmin [dbl]
  id      lat  long elev name      wmo_id ts
  <chr>    <dbl> <dbl> <dbl> <chr>    <dbl> <list>
1 ASN00009021 -31.9 116. 15.4 perth airport 94610 <tbl_ts [366 x 4]>
2 ASN00010311 -31.9 117. 179  york        94623 <tbl_ts [366 x 4]>
3 ASN00010614 -32.9 117. 338 narrogin     94627 <tbl_ts [366 x 4]>
4 ASN00014015 -12.4 131. 30.4 darwin airport 94120 <tbl_ts [366 x 4]>
5 ASN00015131 -17.6 134. 220  elliott      94236 <tbl_ts [366 x 4]>
```

In the created nested form, each element of the list-column `ts` is of `tbl_ts` class so that existing operations on the tsibble class can still be applied:

```
R> # add station-based features in the nested form.
R> dt %>%
+   mutate(fabletools::features(ts, tmax, list(tmax_mean = mean, tmax_var = var)))

# cubble: id [5]: nested form
# bbox: [115.97, -32.94, 133.55, -12.42] - check gap on long and lat
# temporal: date [date], prcp [dbl], tmax [dbl], tmin [dbl]
  id      lat  long elev name      wmo_id ts      tmax_mean tmax_var
  <chr>    <dbl> <dbl> <dbl> <chr>    <dbl> <list>    <dbl>    <dbl>
1 ASN00009021 -31.9 116. 15.4 perth airport 94610 <tbl_t~      25.7    38.6
2 ASN00010311 -31.9 117. 179  york        94623 <tbl_t~      26.2    51.1
3 ASN00010614 -32.9 117. 338 narrogin     94627 <tbl_t~      23.7    45.4
4 ASN00014015 -12.4 131. 30.4 darwin airport 94120 <tbl_t~      33.1    3.02
5 ASN00015131 -17.6 134. 220  elliott      94236 <tbl_t~      34.6    24.7
```

3. Advanced features/ considerations

3.1. Hierarchical structure

Spatial locations can have grouping structure that is either inherent to the data (i.e. countries are nested in continents), or formed by clustering. Rather than analysing variables in the site level, summarised variables in the cluster level can give a crisper picture of local areas. In

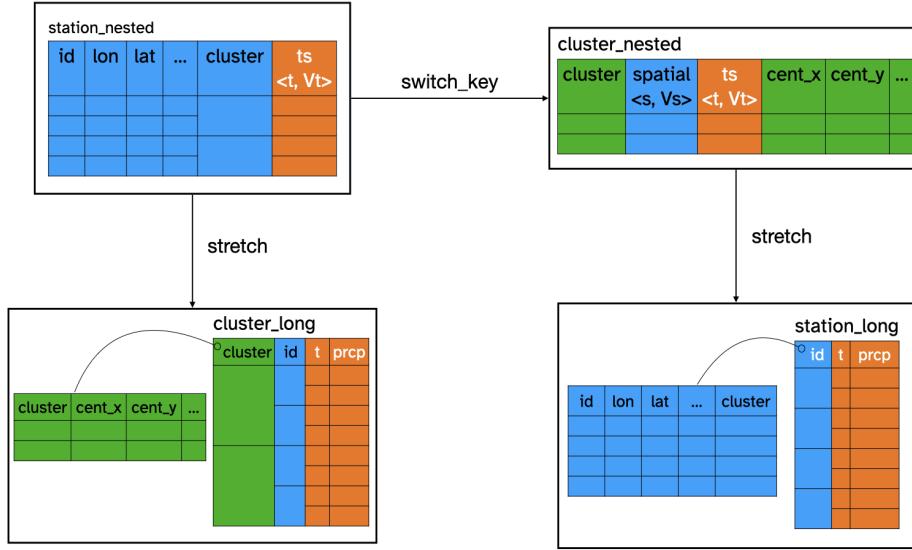


Figure 3: An illustration of the original and cluster level cubble in the nested form long form for hierarchical structure data. `switch_key()` changes the station level cubble into a cluster level cubble and both can be stretched into the long form.

cubble, `switch_key()` can be used to create a new level of grouping of spatial location by specifying a clustering variable. Figure 3 illustrates the relationship of cubbles at station and cluster level, in both the long and nested form. By specifying `cluster_nested <- station_nested %>% switch_key(key = cluster)`, the cubble re-defines the cubble key from `id` in `station_nested` to `cluster` in `cluster_nested`. All the spatial variables variant to `cluster` are now nested into a `.val` column and cluster level variables can be computed in the same fashion as station level variables in `station_nested`. Following the same principal of `stretch`. the long form cluster level cubble expands the time series variables with both indices: `cluster` and `id`. All the cluster level variables are stored separately for recovering the nested from from the long form.

3.2. Data fusion and matching

refine the beginning. To be a valid pair of matching, the matched pair from different data sources need to

- be spatially close to each other, and
- have similar temporal movement

`match_sites()` from **cubble** matches data based on these two criteria. It first matches the two data sources spatially through computing the pairwise distance based on latitude and longitude. Pairs that pass the spatial matching are then matched temporally through computing the number of matched peaks within a fixed length window. Figure 4 illustrate this

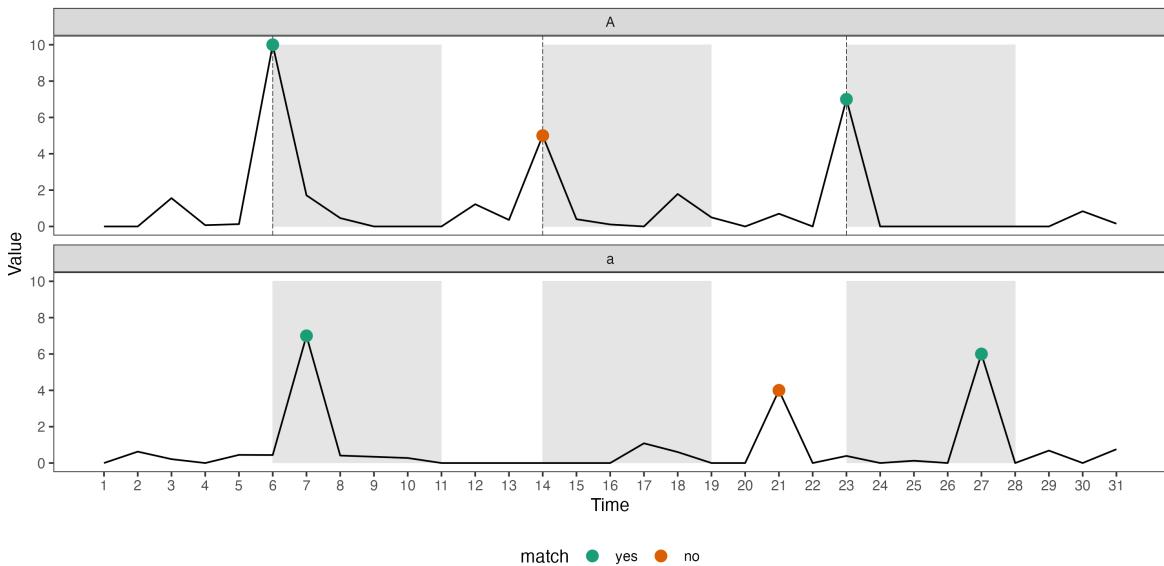


Figure 4: An illustration of temporal matching in cubble. Three highest peaks are identified in each series and intervals are constructed on series A. Two peaks in series a fall into the intervals and hence the two series are considered to have 2 matches.

temporal matching in more details. Given two series A and a. 3 peaks have been picked in each series. An interval, with default length of 5, is constructed for each peak in series A and the peaks in series a are tested against whether they fall into the any of the intervals. In this illustration, there are 2 matches for these two series. Several arguments are available in `match_sites()` to fine-tune the matching:

- `spatial_n_keep`. the number of spatial match for each site to keep
- `spatial_dist_max`. the maximum distance allowed for a matched pair
- `temporal_n_highest`. the number of peak used - 3 in the example above
- `temporal_window`. the length of the interval - 5 in the example above
- `temporal_min_match`. the minimum number of matched peak for a valid matched pair

This functionality can be seen as a matching (Stuart 2010; McIntosh, Jenkins, White, Barnard, Thomson, Dolby, Simpson, Streicher, Kleinman, Ragan *et al.* 2018) exercise in the spatio-temporal domain to pair up nearby observations. It can also be considered as a form of data fusion (Castanedo 2013; Cocchi 2019), where data from multiple sources are combined together.

3.3. Interactive graphics

Cubble fits in naturally with the interactive graphic pipeline discussed in the literature (Buja, Asimov, and Hurley 1988; Buja, Cook, and Swayne 1996; Sutherland, Rossini, Lumley, Lewin-Koh, Dickerson, Cox, and Cook 2000; Xie, Hofmann, and Cheng 2014; Cheng, Cook, and Hofmann 2016). Diagram 5 illustrates how linking works from the map to the time series with the two forms of a cubble. The map and time series plot is associated with the nested or long cubble respectively and when a user action is captured on the map, the site will be

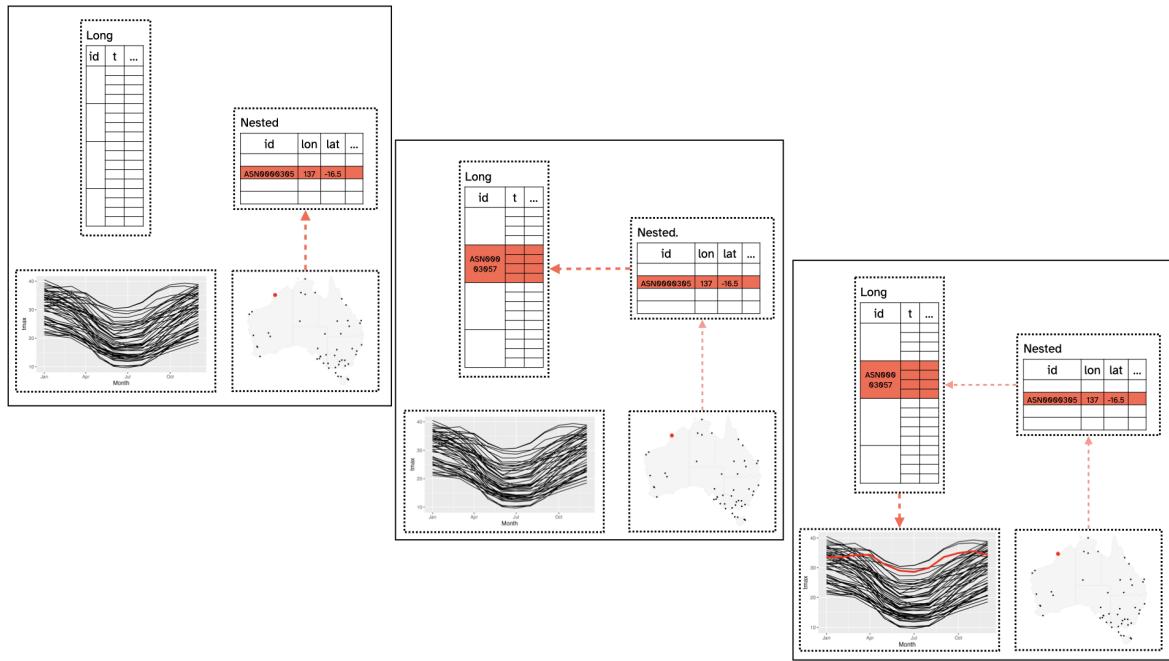


Figure 5: An illustration of the data model under interactive graphics with cubble. The line plot and the map is made separately with the long and nested cubble. When a station is selected on the map (left), the corresponding row in the nested cubble will be activated. This will link to all the rows with the same id in the long cubble (middle) and update the line plot (right).

activated in the nested cubble (left). The nested cubble will communicate to the long cubble to activate all the observations with the same `id` (middle). The long cubble will then highlight the activated series in the time series plot (right).

The linking is also available from the time series plot to the map. The selection(s) on the time series is through selecting the point(s) on the time series and once a point is selected, it will be activated in the long cubble. All the observations that share the same `id` are then activated and this includes other points in the same time series in the long cubble and the corresponding observation of site in the nested cubble. These activated observations will then be reflected in the updated plots and Diagram 13 in the Appendix illustrates this process.

3.4. Glyph map

Glyph map (Wickham, Hofmann, Wickham, and Cook 2012) plots the time series as single glyphs on the map and in R, **GGally** implements the glyph map through the `glyphs()` function. The function constructs a data frame with calculated position (`gx`, `gy`, `gid`) of each point on the time series using linear algebra (Equation 1 and 2 in Wickham *et al.* (2012)). The data can then be piped into `ggplot` to create the glyph map as:

```
R> library(ggplot2)
R> gly <- glyphs(data,
+   x_major = ..., x_minor = ...,
```

```

+           y_major = ..., y_minor = ..., ...)
R>
R> ggplot(gly, aes(gx, gy, group = gid)) +
+   geom_path()

```

A re-implementation of the glyph map as a ggproto `GeomGlyph` has been made in the `cubble` package so that the glyph map can be created with `geom_glyph()`:

```

R> ggplot(data = data) +
+   geom_glyph(aes(x_major = ..., x_minor = ...,
+                   y_major = ..., y_minor = ...))

```

Polar glyph map can be specify as a parameter, `polar = TRUE`. in the `geom_glyph()`. along with `width` and `height` in either absolute or relative value. Global and local scale can be controlled by the parameter `global_rescale`, which default to `TRUE` for global scaling. Reference box and line can be added with separate `geom_glyph_box()` and `geom_glyph_line()`.

4. Examples

4.1. Australia historical maximum temperature

Global Historical Climatology Network (GHCN) provides daily climate measures from stations across the world and the dataset `weatherdata::historical_tmax` extracts the maximum temperature for 236 Australian stations. All the stations start recording from year 1969 with the longest back to year 1859. The data `historical_tmax` is already presented as a cubble, with `id` as the key, `date` as the index, and `c(longitude, latitude)` as the coordinates. This example compares the maximum temperature in two periods: 1971 - 1975 and 2016 - 2020 for stations in Victoria and New South Wales.

Stations in the two states can be subsetted by the station number: Australia GHCN station number starts with “ASN00” and followed by the **Bureau of Meteorology (BOM) station number**, where the 2nd and 3rd digit (7th and 8th in the GHCN number) define the state of the station. New South Wales stations start from 46 to 75 and Victoria stations follow from 76 to 90. Filtering Victoria and New South Wales stations is an operation in the spatial dimension and hence uses the nested form:

```

R> tmax <- weatherdata::historical_tmax %>%
+   filter(between(stringr::str_sub(id, 7, 8), 46, 90))

```

Filtering for the period 1971 ~ 1975 and 2016 ~ 2020 is an operation on the time dimension and the nested cubble needs to be switched to the long cubble by `stretch()`:

```

R> tmax <- tmax %>%
+   stretch() %>%
+   filter(lubridate::year(date) %in% c(1971:1975, 2016:2020))

```

A monthly average is used for both periods to smooth the maximum temperature and it is again an operation on the time dimension:

```
R> tmax <- tmax %>%
+   group_by(month = lubridate::month(date),
+             group = as.factor(ifelse(lubridate::year(date) > 2015,
+                                         "2016 ~ 2020", "1971 ~ 1975"))) %>%
+   summarise(tmax = mean(tmax, na.rm = TRUE))
```

There are a few stations which don't have records during 1971 - 1975 and further investigation shows that while the first and last year of each series is recorded, the missing years in this period is not reported. These stations are filtered out by examining whether the summarised time series has a total of 24 months. The long cubble needs to be switched to the nested form for this spatial operation using `tamp()`:

```
R> tmax <- tmax %>% tamp() %>% filter(nrow(ts) == 24)
```

Lastly, to create a glyph map, both the major (`longitude`, `latitude`) and minor (`month`, `tmax`) coordinates need to be in the same table. Spatial variables can be moved to the long form with `migrate()`:

```
R> tmax <- tmax %>% stretch() %>% migrate(latitude, longitude)
```

`tmax` can then be supplied to `geom_glyph()` for the glyph map in Figure 6 with a station inset on the top left corner:

```
R> nsw_vic <- ozmaps::abs_stc %>%
+   filter(NAME %in% c("Victoria", "New South Wales"))
R>
R> ggplot() +
+   geom_sf(data = nsw_vic,
+           fill = "transparent", color = "grey", linetype = "dotted") +
+   geom_glyph(data = tmax,
+              aes(x_major = longitude, x_minor = month,
+                  y_major = latitude, y_minor = tmax,
+                  group = interaction(id, group), color = group),
+              width = 1, height = 0.5) +
+   ...
```

4.2. Australia precipitation pattern in 2020

In the previous example, there has already been some overlapping of the glyphs for a few stations near (151E, 34S) and (152E, 33S) and this will be a problem when mapping more stations in the national level. Aggregation can be helpful to group series into clusters before visualising the cluster with glyph map.

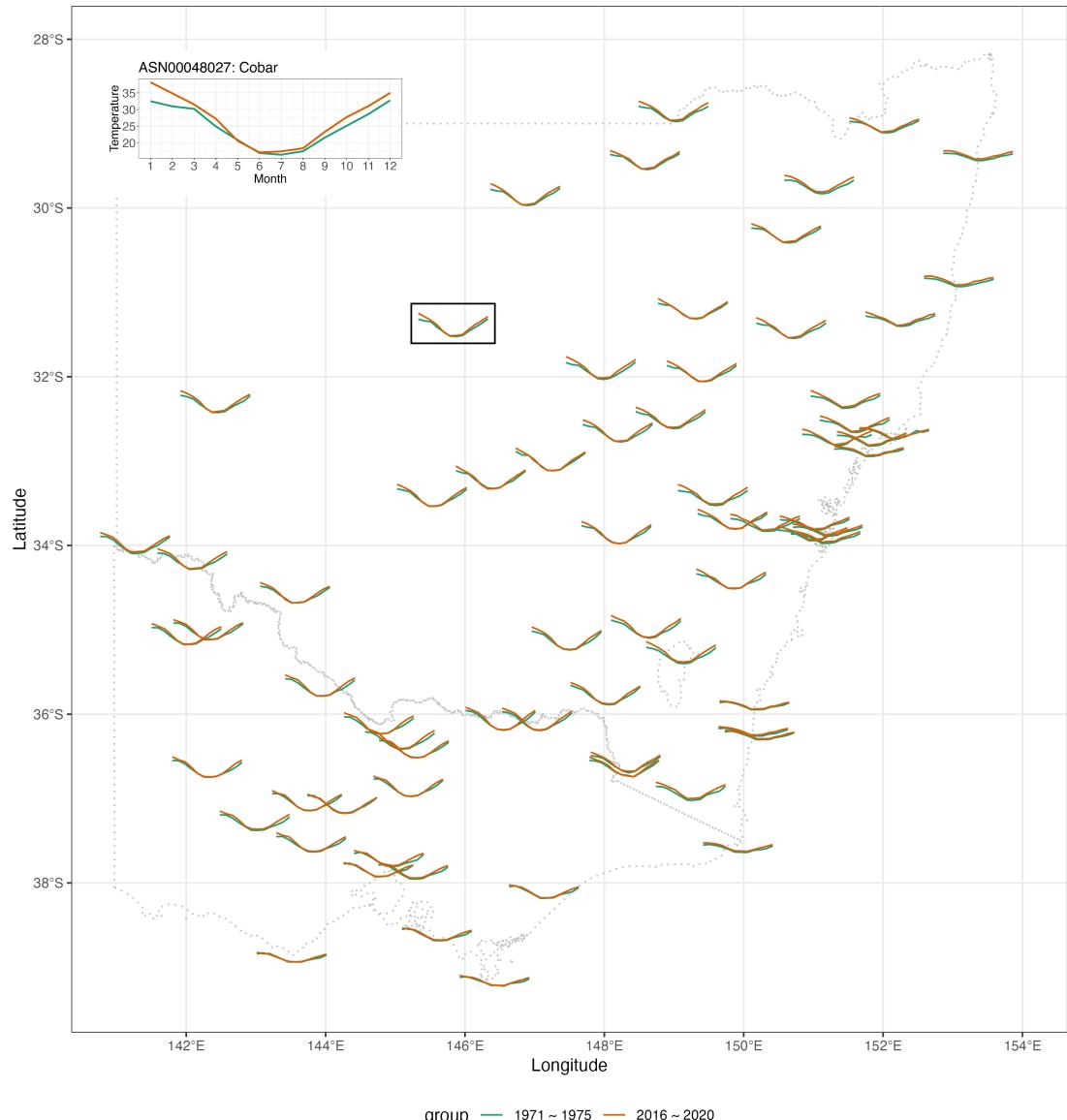


Figure 6: A glyph map of the average maximum temperature by month of Victoria and New South Wales weather stations in Australia. On the top left corner is an insetted plot of station Cobar highlighted in the black box.

This example shows how to organise data at both level with `switch_key()`. The dataset used is `weatherdata::climate_full`, which records daily precipitation and maximum/ minimum temperature for 639 stations in Australia from 2016 to 2020. A simple kmean algorithm based on the distance matrix is used here to create 20 clusters. This creates `station_nested` as a station level nested cubble with a cluster column indicating the group each station belongs to. More complex algorithms can be used for other problem, as long as there is a mapping from each station to a cluster.

```
R> station_nested <- weatherdata::climate_full %>%
+   mutate(cluster = ...)
```

To create a group level cubble, use `switch_key()` with the new key variable, `cluster`:

```
R> cluster_nested <- station_nested %>% switch_key(cluster)
```

With the group level cubble, `get_centroid()` is useful to compute the centroid of each cluster, which will be used as the major axis for the glyph map later:

```
R> cluster_nested <- cluster_nested %>% get_centroid()
```

Long form cubble at both levels can be access through stretching the nested form and operations applicable to long form cubble are still available. With access to both station and cluster level cubbles, various plots can be made to understand the cluster. Figure 7 shows two example plots that can be made with this data: subplot A makes a glyph map with cluster level cubble and subplot B inspects the station membership of each cluster using the nested station level cubble.

4.3. River level data in Victoria water gauges

Bureau of Meteorology also collects `water data` from river gauges, which includes electrical conductivity, turbidity, water course discharge, water course level, and water temperature. In particular, water level will interactive with precipitation from the climate data since rainfall will raise the water level in the river. Figure 8 gives the location of available weather station and water gauges in Victoria.

From the map, a few water gauges and weather stations are close to each other and there is the potential that fluctuation of the water level can reflect the precipitation measured by the climate station. As introduced in Section 3.2, `match_sites()` can be used to match one source of data with another source in a cubble. Here `prcp` in `climate` will be matched to `Water_course_level` in `river`, which is specified in the argument `temporal_var_to_match`. `temporal_independent` controls the dataset that will be used to construct the interval (see the illustration in section 3.2 for details on this). Here the goal is to see if precipitation will be reflected by the water level in the river and hence a lagged effect of water level on precipitation. This will put precipitation data, `climate`, as the independent. Given there is one year worth of data, the number of peak (`temporal_n_highest`) to consider is slightly raised from a default 20 to 30. `temporal_min_match` filters out pairs don't have enough match and to return all the pairs, set `temporal_min_match` to 0.



Figure 7: Profile of aggregated precipitation from 639 weather stations in Australia. Subplot A shows the glyph map of the weekly averaged precipitation of each cluster. The group number printed in the middle of y minor axis and can be used as a reference line to read the magnitude. Subplot B shows the station membership of each cluster.

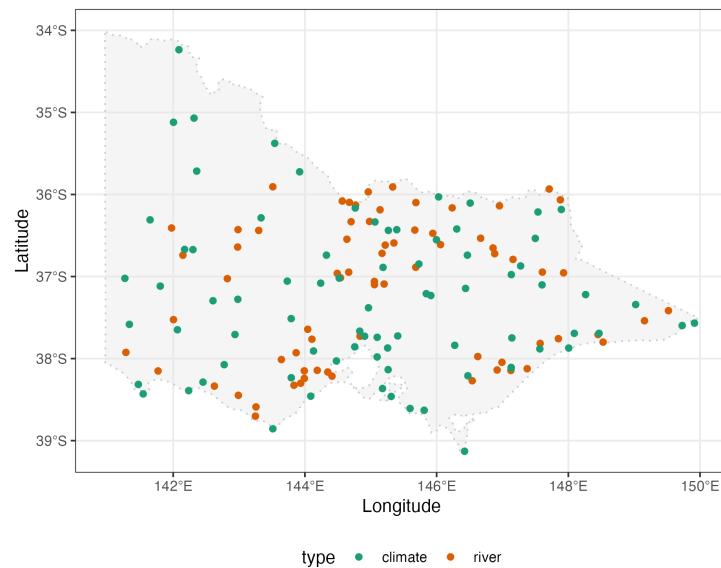


Figure 8: Location of weather stations and river gauges in Victoria, Australia.

```
R> res <- match_sites(
+   river, climate,
+   temporal_var_to_match = c("Water_course_level" = "prcp"),
+   temporal_independent = "prcp",
+   temporal_n_highest = 30,
+   temporal_min_match = 15
+ )
```

The output from matching is also a cubble, with additional column `dist` and `group` produced from spatial matching and `n_match` from the temporal matching.

```
# cubble: id [8]: nested form
# bbox: [144.52, -37.73, 146.06, -36.55]
# temporal: date [date], matched_var [dbl]
  id      name          lat  long type    dist group ts      n_match
  <chr>   <chr>        <dbl> <dbl> <chr>  <dbl> <int> <list>      <int>
1 405234 SEVEN CREEKS @ D~ -36.9 146. river  6.15     5 <tibble ~      21
2 404207 HOLLAND CREEK @ ~ -36.6 146. river  8.54    10 <tibble ~      21
3 ASN00082042 strathbogie -36.8 146. clima~  6.15     5 <tibble ~      21
4 ASN00082170 benalla airport -36.6 146. clima~  8.54    10 <tibble ~      21
5 230200 MARIBYRNONG RIVE~ -37.7 145. river  6.17     6 <tibble ~      19
6 ASN00086038 essendon airport -37.7 145. clima~  6.17     6 <tibble ~      19
7 406213 CAMPASPE RIVER @~ -37.0 145. river  1.84     1 <tibble ~      18
8 ASN00088051 redesdale     -37.0 145. clima~  1.84     1 <tibble ~      18
```

Figure 9 plots the matched pairs on the map or to view the matched series and with the chosen parameter, there are four pairs of matches, which all locates in the middle Victoria and the concurrent increase of precipitation and water level can be observed.

4.4. ERA5: climate reanalysis data

NetCDF (Network Common Data Form) is a data format commonly used in climatology community to deliver global mapping of atmosphere, ocean, and land. It has two major components: dimension to define the spatio-temporal grid (longitude, latitude, and time) and variable which populates the defined grid. Attributes are usually associated with dimension and variable in the NetCDF format data and a [metadata convention for climate and forecast](#) has been designed to standardise this data format. Current packages on manipulating NetCDF data in R include a high-level R interface: **ncdf4** (Pierce 2019), a low-level interface that calls C-interface: **RNetCDF** (Michna and Woods 2021, 2013), and a tidyverse implementation: **tidync** (Sumner 2020).

Cubble provides an `as_cubble()` method to coerce the `ncdf4` class from the **ncdf4** package into a **cubble**. It maps each combination of longitude and latitude into an `id` (the `key`) and nests time and variables in the nested form:

```
R> # read in the .nc file as a ncdf4 class
R> raw <- ncdf4::nc_open(here::here("data/era5-pressure.nc"))
R>
```

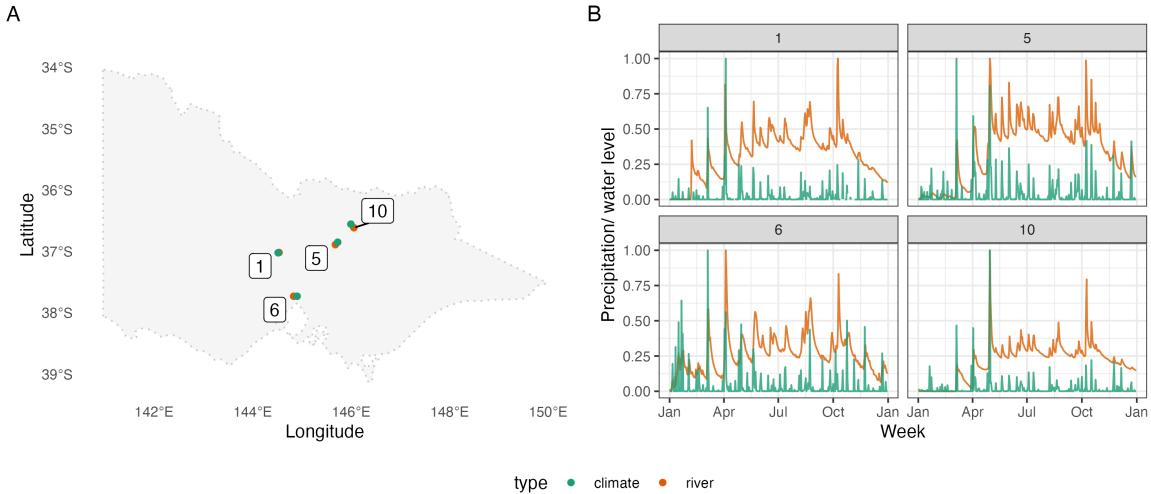


Figure 9: Matched weather stations and river gauges on the map (A) and across time (B). Precipitation and water level have been standardised between 0 and 1 to be displayed on the same scale. The increases in the precipitation is reflected by the water level.

```
R> # convert the variable q and z in the ncdf4 into a cubble
R> dt <- as_cubicle(raw, vars = c("q", "z"))
```

Memory limit with Netcdf data in cubble depends on longitude grid point x latitude grid point x time grid point x number of variable. Cubble can handle slightly more than 300 x 300 (longitude x longitude) grid points for 3 variables in one year and spatial grid can be reduced to trade for longer time period and more variables. A 300 by 300 spatial grid can be a bounding box of [100, -80, 180, 0] at 0.25 degree resolution or global bounding box [-180, -90, 180, -90] at 1 degree resolution. Subsetting longitude and latitude grid is available through `long_range` and `lat_range` if the Netcdf file has finer resolution than needed.

```
R> # Assume my_ncdf has bounding box of [-180, -90, 180, -90]
R> # at 0.25 degree resolution and subset it to have
R> # 1 degree resolution:
R> dt <- as_cubicle(my_ncdf, vars = c("q", "z"),
+                     long_range = seq(-180, 180, 1),
+                     lat_range = seq(-90, 90, 1))
```

Figure 10 gives an example of reproducing Figure 19 in Hersbach, Bell, Berrisford, Hirahara, Horányi, Muñoz-Sabater, Nicolas, Peubey, Radu, Schepers *et al.* (2020) using ERA5 data. ERA5 data (Hersbach *et al.* 2020) is the latest reanalysis of global atmosphere, land surface, and ocean waves from 1950 onwards and is available in the NetCDF format. It can be directly downloaded from the [Copernicus Climate Data Store \(CDS\)](#) website or programmatically via R package `ecmwfr` (Hufkens, Stauffer, and Campitelli 2019). Variable Specific humidity and geopotential are queried on the 10 hPa pressure level for four dates: 2002-09-22, 2002-09-26,

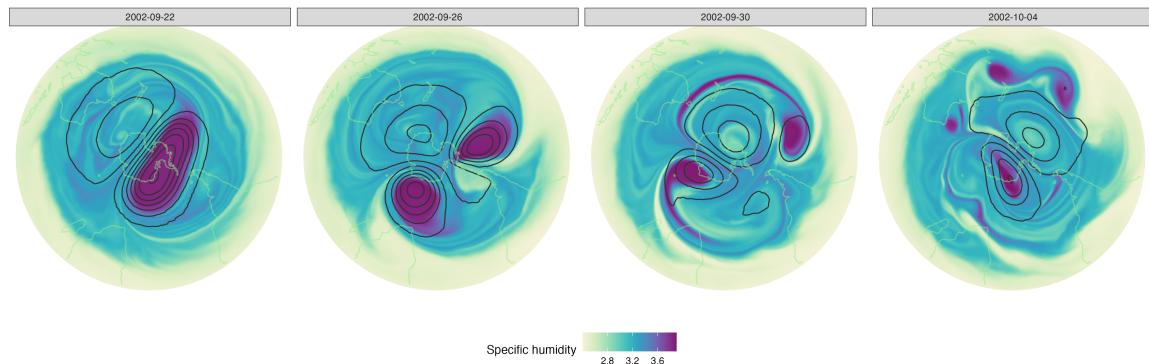


Figure 10: A reproduction of the second row (ERA5 data) of Figure 19 in Hersbach et al (2020).

2002-09-30, and 2002-10-04 and once downloaded, the data can be read into a cubble using the code above. Readers who are interested in the details of can refer to [Simmons, Soci, Nicolas, Bell, Berrisford, Dragani, Flemming, Haimberger, Healy, Hersbach et al. \(2020\)](#) and [Simmons, Hortal, Kelly, McNally, Untch, and Uppala \(2005\)](#).

4.5. Interative graphic with cubble

With spatio-temporal data, users may wish to make plots to learn the spatial distribution of a variable or to find patterns such as trend or seasonality in the time series. Combining this two types of plot with interactivity let users to link between points on the map and their corresponding time series and explore the spatial and temporal dimension of the data simultaneously. Below is an example that describes the process of building an interactive graphic with **cubble** and **crosstalk**.

Starting with the original data, some pre-processing may be required to summarise the data before the visualisation. This example explores the variation of monthly temperature range across 639 weather stations in Australia and with `weatherdata::climate_full`, daily temperature range is first calculated as the difference between `tmax` and `tmin`. The three daily variables are then averaged into month over 2016 - 2020 in the long form. Variance of the temperature difference is then calculated for each station in the nested form. Then, a `SharedData` object is constructed for each form of the cubble and the same `group` argument ensures the cross-linking of the two forms via the common `id` column. The spatial map and time series plot are then made with each `SharedData` objects separately. In this example, stations on the Australia map, made from the nested form, are coloured by the calculated variance and a ribbon band is constructed using the long form cubble to show the maximum and minimum temperature of each station across month. With a different dataset, users are free to calculate any per station measure in the nested form or to make any time-wise summary of the data in the long form to customise the spatial or temporal view. And the cross-linking is always safeguarded by the shared `id` column embedded in the cubble structure. Below is the pseudo code that outlines the process to construct an interactive graphic described above:

```
R> # data pre-processing
R> clean <- weatherdata::climate_full %>% ...
```

```
R>
R> # created SharedData instance for crosstalk
R> nested <- clean %>% SharedData$new(~id, group = "cubicle")
R> long <- stretch(clean) %>% SharedData$new(~id, group = "cubicle")
R>
R> # create the spatial and temporal view each with a ShareData instance
R> p1 <- nested %>% ...
R> p2 <- long %>% ...
R>
R> # Combine p1 and p2
R> crosstalk::bscols(plotly::ggplotly(p1), plotly::ggplotly(p2), ...)
```

In Figure 11, the first row shows the initial view of the interactive graphic. Overall, most regions in Australia have low variance of temperature range across different months while the north-west coastline, bottom of South Australia, and Victoria stands out with larger monthly changes. In the second row, Mount Elizabeth is selected on the map given its dark colour and this links to the ribbon on the right where there is a larger temperature range is presented in Australian winter (June to August). The third row selects the Grampian station in Victoria and the linked ribbon shows an opposite wider range in Australian summer period (December to February). The last row selects point with the lowest minimum temperature in August in the ribbon plot and surprisingly, this links to the Thredbo Airport in the Victoria and New South Wales border, rather than somewhere in the Tasmania island!

With leaflet popup, the temperature range can be displayed as a small subplot upon clicking on the map. This would require first creating the popup plots from the long form cubble as a vector and then add these plots to a leaflet map, created from the nested cubble, with `leafpop::addPopupGraphs()`:

```
R> # data pre-processing
R> clean <- weatherdata::climate_full %>% ...
R>
R> # use the long form to create subplots for each station
R> df_id <- unique(clean$id)
R> p <- map(1:length(df_id), function(i){
+   dt <- clean %>% filter(id == df_id[i])
+   ggplot(dt) %>% ...
+ })
R>
R> # create nested form leaflet map with temperature band as subplots
R> nested <- tamp(clean)
R> leaflet(nested) %>%
+   addTiles() %>%
+   addCircleMarkers(group = "a", ...) %>%
+   leafpop::addPopupGraphs(graph = p, ...)
```

Figure 12 shows the same content as Figure 11 but made with leaflet and popups.

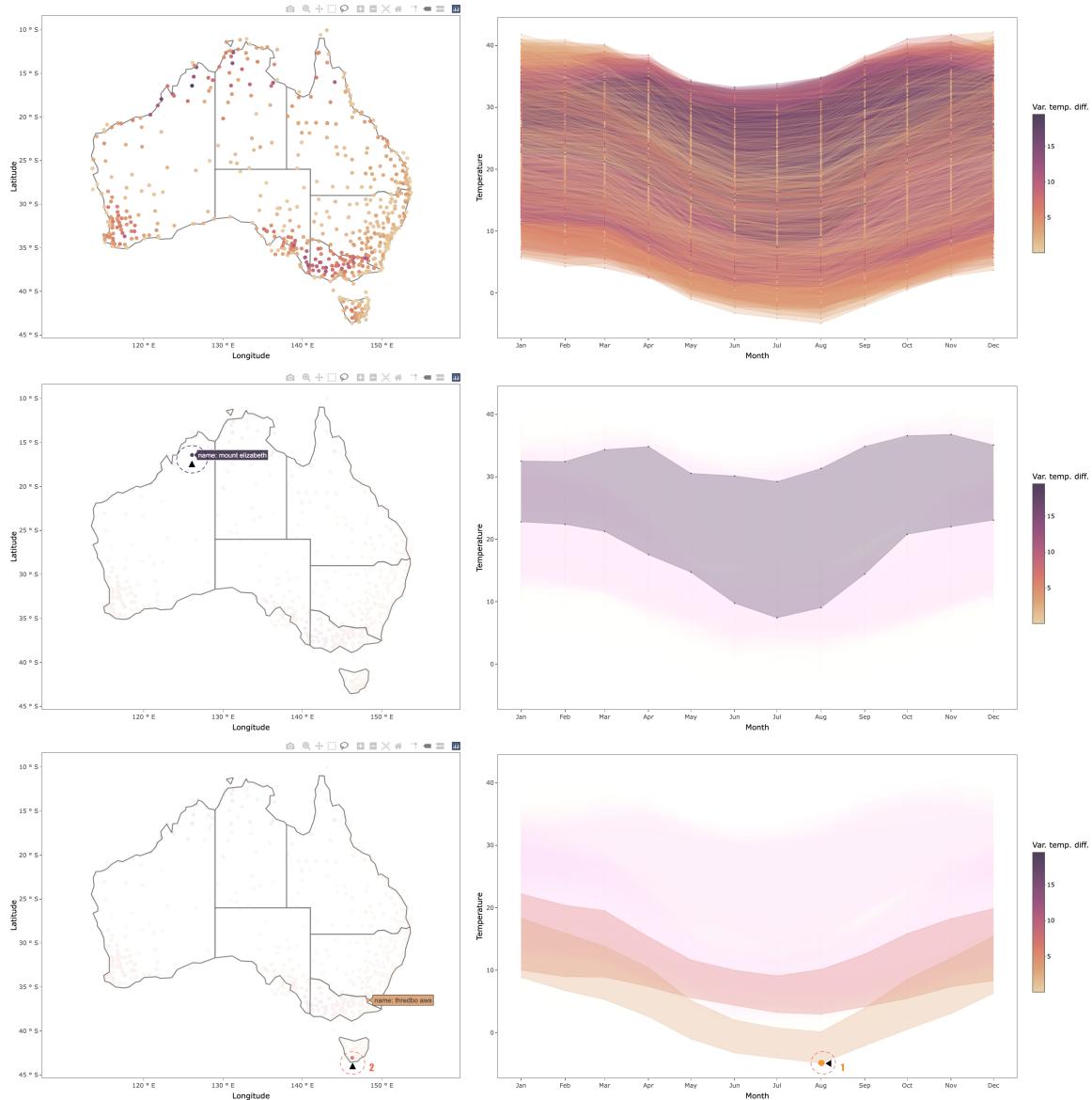


Figure 11: Exploring temperature variation using linking of a map and seasonal display. Each row is a screen dump of the process. The top row shows all locations and all temperature profiles. Selecting a location with high variance on the map produces the plot in the second row. The maximum nad minimum temperature is shown using a ribbon. The bottom row first selects the lowest temperature in August in the seasonal display. A location in the Tasmania Island is then selected to compare the temperature variation with Thredbo AWS.

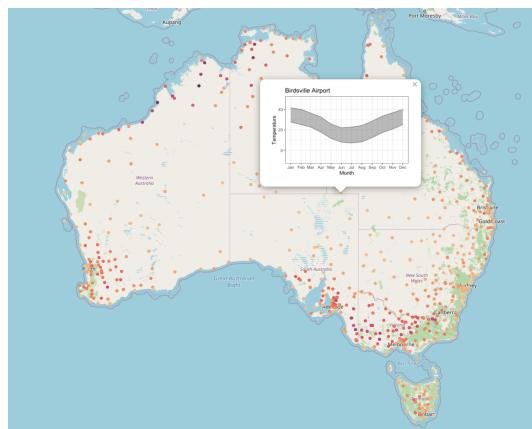


Figure 12: Same as Figure 11 with the temperature variation shown as a popup in the leaflet map.

5. Conclusion

This paper describes the R package **cubble** for manipulating and visualising spatio-temporal data. A new data structure, that builds from the `rowwise_df` and `grouped_df` class in the tidyverse ecosystem, is proposed to connect the spatial and temporal variables in the spatio-temporal data. This design frees the data analysts from spending time on organising variables of different observational units. The data structure is also flexible to the techniques and packages analysts use to analyse the data, for example, in the matching example in section 4.3, users are free to use algorithms from another pacakge to cluster stations. Further development and maintenance of the package involves responding to changes in the tidyverse packages that **cubble** imports, in particular, `tibble`, `tidyr`, and `dplyr`. Another area for further development is to extend **cubble** to other spatial objects other than points.

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7. Appendix

References

- Baddeley A, Turner R (2005). “Spatstat: An R Package for Analyzing Spatial Point Patterns.” *Journal of Statistical Software*, **12**(6), 1–42. URL <https://doi.org/10.18637/jss.v012.i06>.

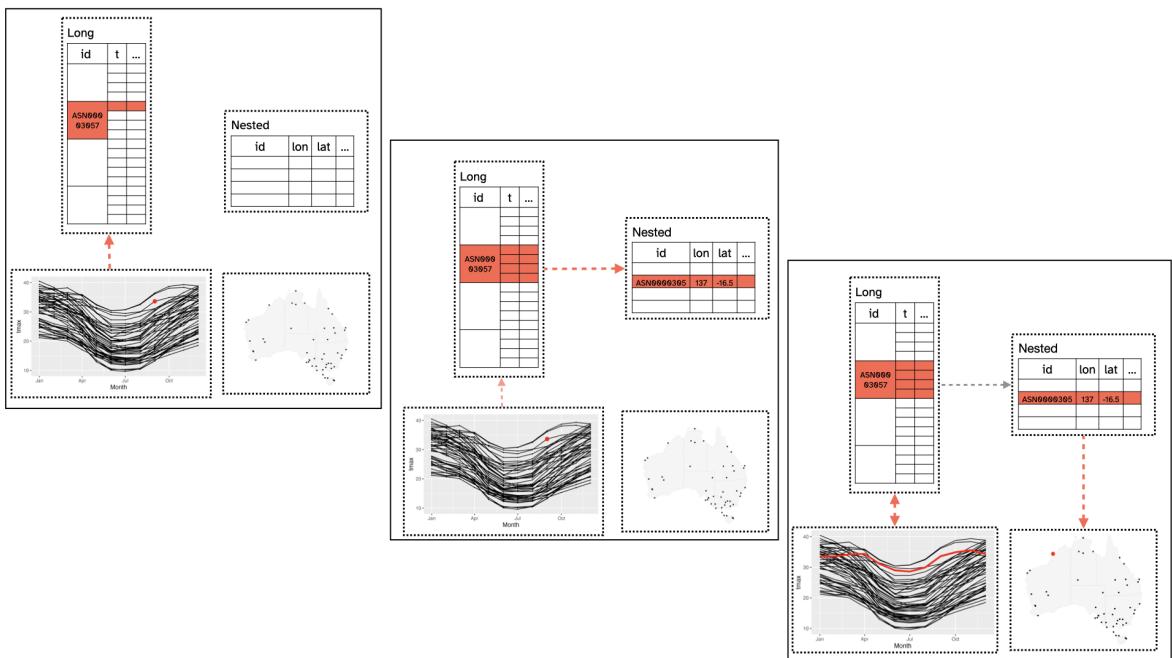


Figure 13: An illustration of the data model under interactive graphics with cubble. When a point on the time series is selected, the corresponding row in the long cubble will be activated. This will link to all the rows with the same id in the long cubble and the row in the nested cubble with the same id (middle). Both plots will be updated with the full line selected and the point highlighted on the map (right).

- Buja A, Asimov D, Hurley C (1988). “Elements of a viewing pipeline.” *Dynamic Graphics Statistics*, p. 277.
- Buja A, Cook D, Swayne DF (1996). “Interactive high-dimensional data visualization.” *Journal of computational and graphical statistics*, **5**(1), 78–99. URL <https://doi.org/10.2307/1390754>.
- Castanedo F (2013). “A review of data fusion techniques.” *The scientific world journal*, **2013**.
- Cheng X, Cook D, Hofmann H (2016). “Enabling interactivity on displays of multivariate time series and longitudinal data.” *Journal of Computational and Graphical Statistics*, **25**(4), 1057–1076. URL <https://doi.org/10.1080/10618600.2015.1105749>.
- Cocchi M (2019). *Data fusion methodology and applications*. Elsevier.
- Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J, Nicolas J, Peubey C, Radu R, Schepers D, et al. (2020). “The ERA5 global reanalysis.” *Quarterly Journal of the Royal Meteorological Society*, **146**(730), 1999–2049.
- Hufkens K, Stauffer R, Campitelli E (2019). “The ecmwfr package: an interface to ECMWF API endpoints.” doi:10.5281/zenodo.2647541. URL <https://bluegreen-labs.github.io/ecmwfr/>.
- McIntosh AI, Jenkins HE, White LF, Barnard M, Thomson DR, Dolby T, Simpson J, Streicher EM, Kleinman MB, Ragan EJ, et al. (2018). “Using routinely collected laboratory data to identify high rifampicin-resistant tuberculosis burden communities in the Western Cape Province, South Africa: A retrospective spatiotemporal analysis.” *PLoS medicine*, **15**(8), e1002638.
- Michna P, Woods M (2013). “RNetCDF—A package for reading and writing NetCDF datasets.” *The R Journal*, **5**(2), 29–36.
- Michna P, Woods M (2021). *RNetCDF: Interface to 'NetCDF' Datasets*. R package version 2.5-2, URL <https://CRAN.R-project.org/package=RNetCDF>.
- Pebesma E (2012). “spacetime: Spatio-Temporal Data in R.” *Journal of Statistical Software*, **51**(7), 1–30. URL <https://doi.org/10.18637/jss.v051.i07>.
- Pebesma E (2021). *stars: Spatiotemporal Arrays, Raster and Vector Data Cubes*. R package version 0.5-2, URL <https://CRAN.R-project.org/package=stars>.
- Pebesma E, Bivand RS (2005). “S classes and methods for spatial data: the sp package.” *R news*, **5**(2), 9–13.
- Pierce D (2019). *ncdf4: Interface to Unidata netCDF (Version 4 or Earlier) Format Data Files*. R package version 1.17, URL <https://CRAN.R-project.org/package=ncdf4>.
- Ryan JA, Ulrich JM (2020). *xts: eXtensible Time Series*. R package version 0.12.1, URL <https://CRAN.R-project.org/package=xts>.
- Simmons A, Hortal M, Kelly G, McNally A, Untch A, Uppala S (2005). “ECMWF analyses and forecasts of stratospheric winter polar vortex breakup: September 2002 in the Southern Hemisphere and related events.” *Journal of the atmospheric sciences*, **62**(3), 668–689.

- Simmons A, Soci C, Nicolas J, Bell B, Berrisford P, Dragani R, Flemming J, Haimberger L, Healy S, Hersbach H, et al. (2020). *Global stratospheric temperature bias and other stratospheric aspects of ERA5 and ERA5. 1.* European Centre for Medium Range Weather Forecasts.
- Stuart EA (2010). “Matching methods for causal inference: A review and a look forward.” *Statistical science*, **25**(1), 1.
- Sumner M (2020). *tidync: A Tidy Approach to 'NetCDF' Data Exploration and Extraction.* R package version 0.2.4, URL <https://CRAN.R-project.org/package=tidync>.
- Sutherland P, Rossini A, Lumley T, Lewin-Koh N, Dickerson J, Cox Z, Cook D (2000). “Orca: A visualization toolkit for high-dimensional data.” *Journal of Computational and Graphical Statistics*, **9**(3), 509–529. URL <https://www.tandfonline.com/doi/abs/10.1080/10618600.2000.10474896>.
- Wickham H (2014). “Tidy Data.” *Journal of Statistical Software*, **59**(10), 1–23. URL <https://doi.org/10.18637/jss.v059.i10>.
- Wickham H (2020). *cubelyr: A Data Cube 'dplyr' Backend.* R package version 1.0.1, URL <https://CRAN.R-project.org/package=cubelyr>.
- Wickham H, Hofmann H, Wickham C, Cook D (2012). “Glyph-maps for visually exploring temporal patterns in climate data and models.” *Environmetrics*, **23**(5), 382–393.
- Xie Y (2015). *Dynamic Documents with R and knitr.* 2nd edition. Chapman and Hall/CRC, Boca Raton, Florida. ISBN 978-1498716963, URL <https://yihui.name/knitr/>.
- Xie Y, Allaire J, Grolemund G (2018). *R Markdown: The Definitive Guide.* Chapman and Hall/CRC, Boca Raton, Florida. ISBN 978-1138359338, URL <https://bookdown.org/yihui/rmarkdown/>.
- Xie Y, Hofmann H, Cheng X (2014). “Reactive programming for interactive graphics.” *Statistical Science*, pp. 201–213. URL <https://doi.org/10.1214/14-STS477>.

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