



Journal of Statistical Software

MMMMMM YYYY, Volume VV, Issue II.

doi: 10.18637/jss.v000.i00

cubble: An R Package for Organizing and Wrangling Multivariate Spatio-temporal Data

H. Sherry Zhang
Monash University

Dianne Cook
Monash University

Ursula Laa
University of Natural Resources and Life Sciences

Nicolas Langrené
BNU-HKBU United International College

Patricia Menéndez
Monash University

Abstract

Multivariate spatio-temporal data refers to multiple measurements taken across space and time. For many analyses, spatial and time components can be separately studied: for example, to explore the temporal trend of one variable for a single spatial location, or to model the spatial distribution of one variable at a given time. However for some studies, it is important to analyze different aspects of the spatio-temporal data simultaneously, like for instance, temporal trends of multiple variables across locations. In order to facilitate the study of different portions or combinations of spatio-temporal data, we introduce a new data structure, **cubble**, with a suite of functions enabling easy slicing and dicing on the different components spatio-temporal components. The proposed **cubble** structure ensures that all the components of the data are easy to access and manipulate while providing flexibility for data analysis. In addition, **cubble** facilitates visual and numerical explorations of the data while easing data wrangling and modelling. The **cubble** structure and the functions provided in the **cubble** R package equip users with the capability to handle hierarchical spatial and temporal structures. The **cubble** structure and the tools implemented in the package are illustrated with different examples of Australian climate data.

Keywords: spatial, temporal, spatio temporal, R, environmental data, exploratory data analysis.

2 **cubble**: An R Package for Organizing and Wrangling Multivariate Spatio-temporal Data

The `rticles::jss_article` template used during preparation (<https://github.com/rstudio/rticles/tree/c085e125d874c11bb474ec53f4b754e179f8a4e9>) has the behavior that a reference prints out all the author names when it is used for the first time. See a standalone example [here](#).

Here a hack is used to overcome this temporarily

Here I reference Pebesma and Bivand (2022), Bach, Dragicevic, Archambault, Hurter, and Carpendale (2014), Lu, Appel, and Pebesma (2018), Wickham, Averick, Bryan, Chang, McGowan, François, Grolemund, Hayes, Henry, Hester, Kuhn, Pedersen, Miller, Bache, Müller, Ooms, Robinson, Seidel, Spinu, Takahashi, Vaughan, Wilke, Woo, and Yutani (2019), Müller and Wickham (2021), Pebesma (2018), Pebesma (2021), Pebesma (2012), Wickham, François, Henry, and Müller (2022), Wickham (2016), Wang, Cook, and Hyndman (2020b), Hassell, Gregory, Blower, Lawrence, and Taylor (2017), Wickham (2014), Cheng, Karambelkar, and Xie (2021), Cheng and Sievert (2021), Cheng, Cook, and Hofmann (2016), Buja, Cook, and Swayne (1996), Xie, Hofmann, and Cheng (2014), Sutherland, Rossini, Lumley, Lewin-Koh, Dickerson, Cox, and Cook (2000), Buja, Asimov, and Hurley (1988), Wickham, Hofmann, Wickham, and Cook (2012), Hersbach, Bell, Berrisford, Hirahara, Horányi, Muñoz-Sabater, Nicolas, Peubey, Radu, Schepers *et al.* (2020), Sumner (2020), Michna and Woods (2021), Pierce (2019), Hufkens, Stauffer, and Campitelli (2019), Simmons, Soci, Nicolas, Bell, Berrisford, Dragani, Flemming, Haimberger, Healy, Hersbach, Horányi, Inness, Munoz-Sabater, Radu, and Schepers (2020), Simmons, Hortal, Kelly, McNally, Untch, and Uppala (2005), McIntosh, Jenkins, White, Barnard, Thomson, Dolby, Simpson, Streicher, Kleinman, Ragan *et al.* (2018), Stuart (2010), Castanedo (2013), Cocchi (2019), Xie (2015), Xie, Allaire, and Grolemund (2018), Wang, Cook, and Hyndman (2020a), Wickham (2019), ?=“Cook, D. and Swayne, D.”, Commonwealth of Australia (2022), NOAA (2022), Copernicus Climate Change Service (2022), Wickham, Cook, Hofmann, and Buja (2011)

1. Introduction

Spatio-temporal data has a spatial component referring to the location of each observation and a temporal component that is recorded at regular or irregular time intervals. It may also include multiple variables measured at each spatial and temporal values. With spatio-temporal data, one can fix the time to explore the spatial features of the data, fix the spatial location/s to explore temporal aspects, or dynamically explore the space and time simultaneously.

In order to computationally explore the spatial, temporal and spatio-temporal faces of such data, the data needs to be stored and represented under a specific data object that allows the user to query, group and dissect all the data faces.

The SpatioTemporal CRAN task view ([Pebesma and Bivand 2022](#)) gathers information about R packages designed for spatio-temporal data and it has a section on *Representing data* that lists existing spatio-temporal data representations used in R. Among them, [Pebesma \(2012\)](#) summarises spatio-temporal data into three forms: time-wide, space-wide, and long formats. The associated package **spacetime** ([Pebesma 2012](#)) implements four spatio-temporal layouts (full grid, sparse grid, irregular, and trajectory) to handle different space and time combinations. The **stars** ([Pebesma 2021](#)) package has a new implementation to use dense arrays to represent spatio-temporal cubes. It also interfaces with **sf** ([Pebesma 2018](#)), a package commonly used for wrangling spatial data, and the **tidyverse** ([Wickham et al. 2019](#)) suite for general data wrangling and visualization in R.

Still, the data representation for spatio-temporal data can be further extended and there are two reasons for this. Firstly, the raw data sourced in the wild is less often presented in any one of the layouts above, and fitting the raw data into a data object can sometimes be difficult. More often, spatio-temporal data are collected in separate 2D tables and analysts need to assemble them into a whole piece before exploring the data. Examples of components of spatio-temporal data can be 1) areal data recording the shape of a collection of areas of interest; 2) geostatistical data storing the longitude and latitude coordinates of locations, typically also with other metadata related to the location, and; 3) temporal data of each location across time.

The other reason is about tidy data concepts ([Wickham 2014](#)) and how they should be applied to spatio-temporal data. According to the tidy data principles, data should be structured into 1) one row per observation, 2) one column per variable, and 3) one type of data per table. The long form data is preferred over wide data form given the downstream software such as **dplyr** ([Wickham et al. 2022](#)) and **ggplot2** ([Wickham 2016](#)) for data wrangling and visualization. However, the long form can be inefficient to store feature geometries, especially for large multipolygons for hourly, daily or sub-daily periods over years, which are extensively collected and handled, for example in time series analysis. This poses the question of how to arrange spatial and temporal variables in a way that would make data wrangling, visualizing and analyzing spatio-temporal data easier.

This paper presents a new R package, **cubble**, which addresses the two issues mentioned above. In the package, a new data structure, also called cubble, is proposed to organize spatial and temporal variables as two forms of a single data object so that they can be wrangled separately or combined while being kept synchronized. Among the four spacetime layouts in [Pebesma \(2012\)](#), cubble can be applied to full grid, sparse grid, or irregular, but not trajectory, which is outside the scope of this work. The software is available from the Comprehensive R Archive Network (CRAN) at <https://CRAN.R-project.org/package=cubble>.

The rest of the paper is organized as follows: Section 2 introduces the proposed cube structure as a way to conceptualize multivariate spatio-temporal data. Section 3 presents the main design and functionality of the **cubble** package. Section 4 explains how the **cubble** package deals with more advanced considerations, including data with hierarchical structure, data matching and how it fits with existing static and interactive visualization tools. Moreover we also illustrate how the **cubble** package deals with spatio-temporal data transformations. Section 5 uses Australian weather station data and river level data as examples to demonstrate the use of the **cubble** package. An example of how cubble handles NetCDF data is also provided. Section 6 discuss the paper contributions and future directions.

2. Conceptual framework: spatio-temporal cube

Spatio-temporal data can be conceptualized using a cubical data model with three axes which typically are, time, latitude and longitude. This abstraction can be useful for generalizing operations and visualization purposes: [Lu et al. \(2018\)](#) shows how array operations (select, scale, reduce, rearrange, and compute) can be mapped onto the cube; [Bach et al. \(2014\)](#) reviews the temporal data visualization based on space-time cube operations. Notice that the term space-time cube in their article “does not need to involve spatial data”, but refers to “an abstract 2D substrate that is used to visualize data at a specific time”. Despite its main focus being on temporal data, the mindset of abstracting out data representation to construct visualizations, still applies to our spatio-temporal data manipulation and visualization approaches.

The most common space-time cube uses the three axes, time, latitude, longitude, and can be considered stacking space across time. Ours is a multivariate spatio-temporal cube with the three axes defined to be time, site and variables, as illustrated in the leftmost column of Figure 1. The time axis is the same in both versions, while the site axis now captures both latitude and longitude. Finally, variables are stacked on this space-time canvas, with one observation per site and time point. This notion is adopted to avoid using hyper-cubes when describing multivariate spatio-temporal data and is the conceptual framework behind the **cubble** objects. With this conceptual model, operations on spatio-temporal data can be mapped to operations on the cube and the rest of Figure 1 show examples of slicing on site, time, and variable.

While the data cube model is conceptually convenient for spatio-temporal data, a 3D data array is not sufficiently rich for data wrangling, for several reasons. Although arrays can be efficient for the computation on numerical values, spatio-temporal data typically includes various types of variables. For example, character strings and specific datetime classes are common. In addition, it will be generally useful to be able to create new variables which is trickier to manage in an array. Thus for convenient wrangling, we have opted to create a special **cubble** class.

3. The **cubble** package

A **cubble** object is an S3 class ([Wickham 2019](#)) built on the **tibble** class, specifically to organize spatio-temporal data. The **cubble** class uses an attribute “form”, to arrange the spatial or temporal data components tidily. The form attribute can take a value of either

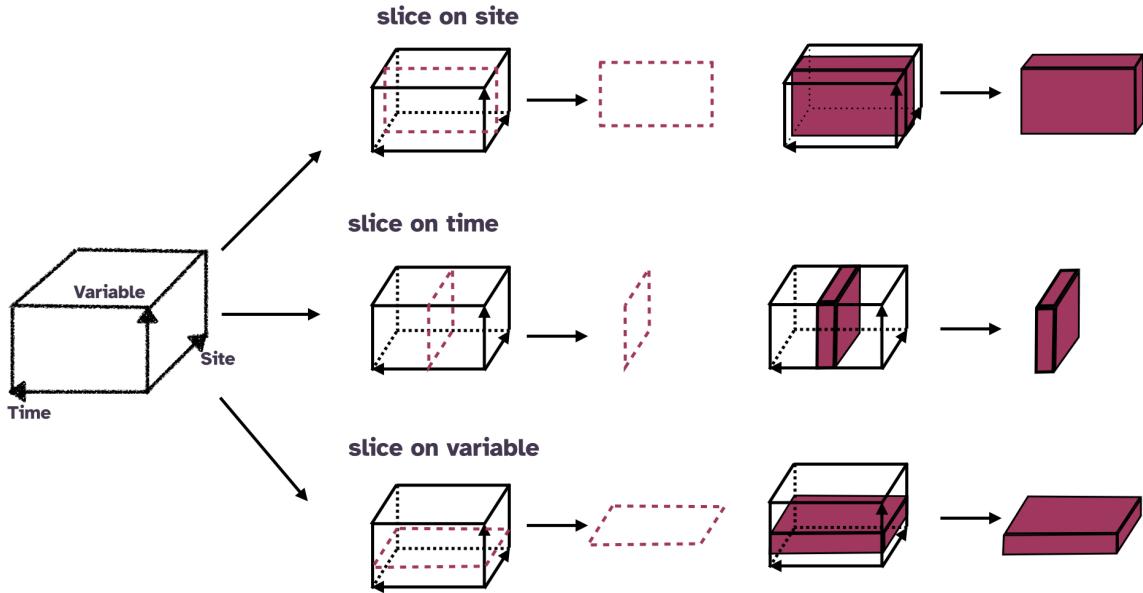


Figure 1: An illustration of the conceptual spatio-temporal cube with different slicing on time, site, and variable. For each axis, the slicing can be on a single value or a set of values.

“nested” or “long”. The nested cubble is a subclass of rowwise tibble (`rowwise_df`). It arranges each spatial site in a row, and uses list columns to store the feature geometry and the temporal information. The long cubble is a subclass of grouped tibble (`grouped_df`), which expands the temporal information into the long form and stores the spatial information in a “spatial” attribute.

The main functions in the package are `as_cubble()`, `face_spatial()`, `face_temporal()`, and `unfold()`. The following sections explain their roles, why the new cubble structure is needed and how the package relates to existing packages for spatial and temporal data analysis.

The data `climate_flat` is used to illustrate **cubble** functionality. This is a subset from National Oceanic and Atmospheric Administration (NOAA) Global Historical Climatology Network Daily (GHCND) data. It contains spatial variables, station ID, latitude, longitude, elevation, station name, World Meteorology Organisation ID, in addition to daily temporal information, maximum and minimum temperature values and precipitation records for year 2020. The first five rows of `climate_flat` are shown below:

# A tibble: 1,830 x 10										
	id	lat	long	elev	name	wmo_id	date	prcp	tmax	tmin
1	ASN0000~	-31.9	116.	15.4	pert~	94610	2020-01-01	0	31.9	15.3
2	ASN0000~	-31.9	116.	15.4	pert~	94610	2020-01-02	0	24.9	16.4
3	ASN0000~	-31.9	116.	15.4	pert~	94610	2020-01-03	6	23.2	13
4	ASN0000~	-31.9	116.	15.4	pert~	94610	2020-01-04	0	28.4	12.4
5	ASN0000~	-31.9	116.	15.4	pert~	94610	2020-01-05	0	35.3	11.6

```
# ... with 1,825 more rows
```

3.1. Create a cubble

The function `as_cubble()` is used to create a cubble with three arguments: `key` as the spatial identifier; `index` as the temporal identifier; and a vector of `coords` in the order (longitude, latitude). The arguments `key` and `index` follow the wording in the `tsibble` package to describe the temporal order and multiple series while `coords` specifies the spatial location of each site. The code below creates a cubble out of `climate_flat` (a single tibble) with `id` as the key, `date` as the index, and `c(long, lat)` as the coordinates:

```
R> cubble_nested <- 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]
# 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>
2 ASN00010311 -31.9  117. 179   york        94623 <tibble>
3 ASN00010614 -32.9  117. 338 narrogin     94627 <tibble>
4 ASN00014015 -12.4  131. 30.4 darwin airport 94120 <tibble>
5 ASN00015131 -17.6  134. 220  elliott      94236 <tibble>
```

Printing a cubble provides some information about the data. Here `id` is the variable name to identify each location and there are five unique locations. The bounding box is `[115.97, -32.94, 133.55, -12.42]` and provides information about the coordinates in the data. The third row shows the name and type of all variables nested in the `ts` column. In this example, it includes `date` [date], `prcp` [dbl], `tmax` [dbl], `tmin` [dbl].

A `cubble` object is a subclass of the `rowwise_df` class where each row forms a group. All the temporal variables are nested in a list column, hence it is also called the nested cubble. The rowwise structure makes it simpler to operate on the list using the `mutate()` syntax, which is simpler than the `purr::map()` when working with a list column. For example, calculating the number of rainy days can be done by:

```
R> cubble_nested |>
+   mutate(rain_day = sum(ts$prcp != 0))

# cubble:  id [5]: nested form
# bbox:      [115.97, -32.94, 133.55, -12.42]
# temporal: date [date], prcp [dbl], tmax [dbl], tmin [dbl]
#             id      lat  long elev name          wmo_id ts      rain_day
#             <chr>    <dbl> <dbl> <dbl> <chr>        <dbl> <list>      <int>
1 ASN00009021 -31.9  116. 15.4 perth airport  94610 <tibble>      104
```

```

2 ASN00010311 -31.9 117. 179 york      94623 <tibble>     89
3 ASN00010614 -32.9 117. 338 narrogin 94627 <tibble>     90
4 ASN00014015 -12.4 131. 30.4 darwin airpo~ 94120 <tibble>    106
5 ASN00015131 -17.6 134. 220 elliott   94236 <tibble>     63

```

A cubble can be created from various common spatio-temporal data formats, including basic R objects like `tibble`, `tsibble`, and `sf`. Section 5.1 describes converting multiple tables into a `cubble` object and Section 3.6.4 illustrates how to convert a netCDF object.

3.2. Change focus by facing the time-variables

The nested form can be used for those operations where the output is only indexed by the spatial identifier (`key`), but becomes inadequate when outputs need both a spatial and a temporal identifier (`key` and `index`). The `cubble` class also provides a long form, which expands the `ts` column and temporarily “hides” the spatial variables. The function `face_temporal()` is used to switch from the nested cubble into the long one. The first row in Figure 2 illustrates this operation where the focus of the cube now changes from the site-variable face to the time-variable face. This code switches the cubble just created into its long form:

```

R> cubble_long <- cubble_nested |> face_temporal()
R> cubble_long

# cubble: date, id [5]: long form
# bbox: [115.97, -32.94, 133.55, -12.42]
# 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  13.0
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

```

The first line in the printed cubble now shows it in the long form and the third line has been changed to display the name and type of spatial variables: `lat` [dbl], `long` [dbl], `elev` [dbl], `name` [chr], `wmo_id` [dbl]. Unlike the nested form, the long cubble is built from a `grouped_df` class where all the observations from the same site form a group.

3.3. Change focus back to the site-variable face

Wrangling spatio-temporal data can be seen as an iterative process in the spatial and temporal dimensions. Switching the focus back to the site-variable face can be accomplished by the function `face_spatial()`, which is the inverse of `face_temporal()`. The second row of Figure 2 illustrates the function, which is used as follows:

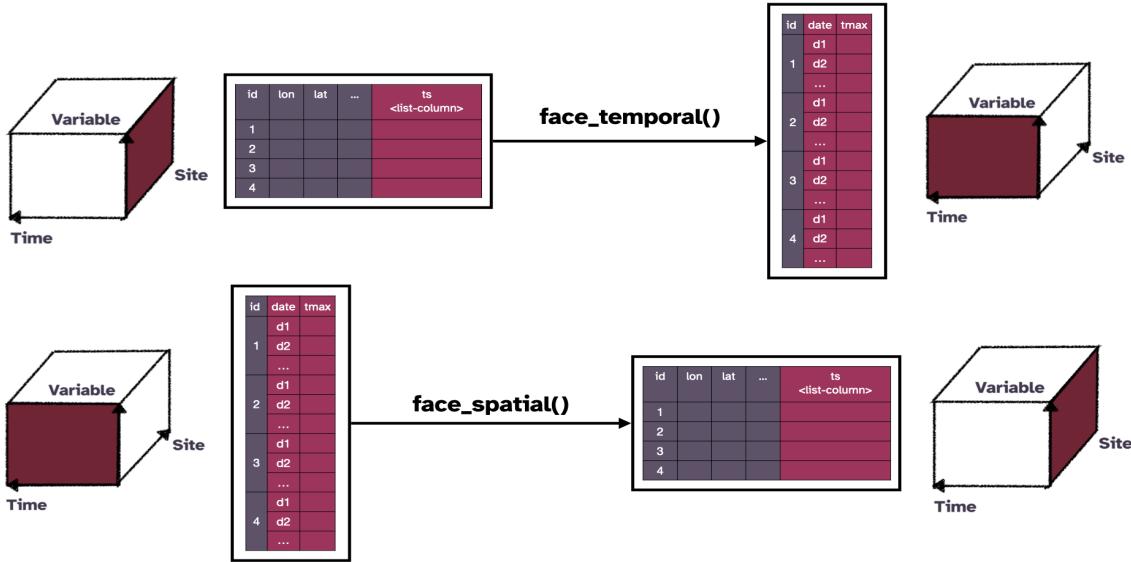


Figure 2: An illustration of function `face_temporal` and `face_spatial` in `cubble`. In the first row, `face_temporal` switches a cubble from the nested form into the long form and the focus has switched from the spatial aspect (the side face) to the temporal aspect (the front face). In the second row, `face_spatial` switches a cubble back to the nested form from the long form and shifts focus back to the spatial aspect.

```
R> cubble_back <- cubble_long |> face_spatial()
R> cubble_back

# cubble:  id [5]: nested form
# bbox:      [115.97, -32.94, 133.55, -12.42]
# 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>
# 2 ASN00010311 -31.9  117.  179   york         94623 <tibble>
# 3 ASN00010614 -32.9  117.  338  narrogin     94627 <tibble>
# 4 ASN00014015 -12.4  131.  30.4 darwin airport  94120 <tibble>
# 5 ASN00015131 -17.6  134.  220  elliott       94236 <tibble>

R> identical(cubble_nested, cubble_back)

[1] TRUE
```

3.4. Unfold spatial variables into the long cubble

Sometimes, analysts may need to apply some variable transformation that involves both the spatial and temporal variables. An example of this is the transformation of temporal variables

into the spatial dimension in glyph maps (Wickham *et al.* 2012). (How to make glyph maps will be explained in Section 4.4, and are illustrated in the second example.) This type of operation can be seen as flattening, or *unfolding*, the cube into a 2D data frame. Here the function `unfold()` moves the spatial variables `long` and `lat` into the long cubble:

```
R> cubble_unfold <- cubble_long |> unfold(long, lat)
R> cubble_unfold

# cubble: date, id [5]: long form
# bbox: [115.97, -32.94, 133.55, -12.42]
# 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> <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
```

3.5. Why not just use the existing tidyverse functions

Some readers may question why a new data structure is needed rather than directly creating a list-column on the combined data using `dplyr::nest_by()`. The reason is that **cubble** is specifically designed to utilize the spatio-temporal structure when arranging observations in a single object. Moreover, it enables easy pivoting between purely spatial, purely temporal, or unfolded into a combined form.

3.6. Compatibility with existing packages

The **cubble** package leverages tools available in existing packages used for spatial and temporal analysis, specifically, **dplyr**, **tsibble**, **sf (s2)**, and **netcdf4**, as explained here.

dplyr

The **dplyr** package has many tools for wrangling tidy data, many of which are useful in the spatio-temporal analysis. The **cubble** package provides `methods` that support the use of the following **dplyr** operations on both the nested and long forms: `mutate`, `filter`, `summarise`, `select`, `arrange`, `rename`, `left_join`, and the slice family (`slice_*`).

tsibble

A **tsibble** object is a tibble where the `index` and `key` components are used to store temporal and strata information, that makes working with temporal data cognitively efficient. A **cubble** object can use a **tsibble** for storing the temporal information, and effectively utilize the specialist time series operations in the **tsibble** package. It is easy to cast an existing **tsibble** object into a **cubble** simply by supplying the `coords`:

```
R> climate_flat_ts <- climate_flat |>
+   tsibble::as_tsibble(key = id, index = date)
R> climate_flat_cb <- climate_flat_ts |>
+   cubble::as_cubble(coords = c(long, lat))
R> climate_flat_cb

# cubble: id [5]: nested form
# bbox: [115.97, -32.94, 133.55, -12.42]
# 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>
2 ASN00010311 -31.9 117. 179  york        94623 <tbl_ts>
3 ASN00010614 -32.9 117. 338  narrogin    94627 <tbl_ts>
4 ASN00014015 -12.4 131. 30.4 darwin airport 94120 <tbl_ts>
5 ASN00015131 -17.6 134. 220  elliott     94236 <tbl_ts>
```

When a nested cubble is created, each element in the list-column `ts` has a `tsibble` class (labelled `tbl_ts`) and operations available to the `tsibble` class are still valid on this element. For example, the code below calculates two time series features (mean and variance) of maximum temperature, utilizing the `tsibble` structure in the cubble:

```
R> climate_flat_cb |>
+   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]
# 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 ASN00009~ -31.9 116. 15.4 pert~ 94610 <tbl_ts>    25.7    38.6
2 ASN00010~ -31.9 117. 179  york   94623 <tbl_ts>    26.2    51.1
3 ASN00010~ -32.9 117. 338  narr~ 94627 <tbl_ts>    23.7    45.4
4 ASN00014~ -12.4 131. 30.4 darw~ 94120 <tbl_ts>    33.1    3.02
5 ASN00015~ -17.6 134. 220  elli~ 94236 <tbl_ts>    34.6    24.7
```

sf and s2

An `sf` object is a spatial data object, containing a feature geometry list-column (`sfc`) in the form of various geometry types (POINT, LINESTRING, POLYGON, MULTIPOLYGON). The `sf` package provides functions that operate efficiently on this spatial information. A cubble can store the spatial information as an `sf` object. Methods for the `sfc` class can be applied in the

nested form of the cubble object. An illustration is in Section 5.1. The spatial information can also be stored as an `s2` in a cubble object.

netCDF

NetCDF data is another format commonly used for storing spatio-temporal data. It has two main components: *dimension* for defining the spatio-temporal grid (longitude, latitude, and time) and *variable* that populates the defined grid. Attributes can be associated with dimensions or variables. Because there can be many different styles of representing this information there is a metadata convention (Hassell *et al.* 2017) to standardize the format of the attributes. A few packages in R exist for manipulating NetCDF data and these include a high-level R interface: **ncdf4** (Pierce 2019), a low-level interface that calls a C-interface: **RNetCDF** (Michna and Woods 2021), and a tidyverse implementation: **tidync** (Sumner 2020).

Cubble provides an `as_cibble()` method to coerce the `ncdf4` class from the **ncdf4** package into a `cibble` object. It maps each combination of longitude and latitude into an `id` as the `key`:

```
R> raw <- ncdf4::nc_open(here::here("data/era5-pressure.nc"))
R> dt <- as_cibble(raw, vars = c("q", "z"))
```

NetCDF data can be quite large, and it is sometimes best to subset the data when converting to a cubble. We would recommend reducing to about 300×300 grid points for three daily variables in one year. A 300 by 300 spatial grid can be a bounding box of [100, -80, 180, 0] at 0.25 degree resolution or a global bounding box [-180, -90, 180, -90] at 1 degree resolution. The size of spatial grid can be reduced if longer time periods or more variables are needed, through `long_range` and `lat_range`:

```
R> dt <- as_cibble(
+   my_ncdf, vars = c("q", "z"),
+   long_range = seq(-180, 180, 1), lat_range = seq(-90, 90, 1)
+ )
```

4. Other features and considerations

4.1. Hierarchical structure

Spatial locations can have grouping structures either inherent to the data e.g., state within country or obtained during the analysis e.g., cluster id. In this case, it can be useful to summarize variables at various levels of the hierarchy. The function `switch_key()` can be used to change the grouping level of spatial locations. The diagram in Figure 3 shows how this function can be used to switch the grouping from station ids to cluster ids. The result can also be stretched into long form. By specifying

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

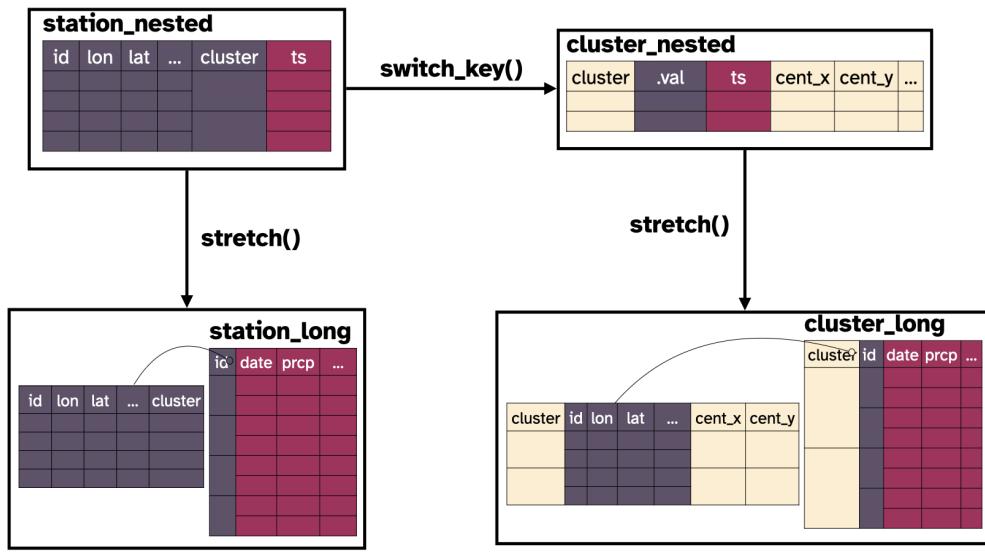


Figure 3: Hierarchical spatial structure can be handled using `switch_key()`, to create summaries based on any level. Here the switch is between the station id and a cluster id. Once the change is made the data can be stretched into the long form.

the cubble redefines the cubble key from the `id` column in `station_nested` to the `cluster` column in `cluster_nested`. All the spatial variables belonging to the `cluster` column are now nested into a `.val` column which allows for summarizing based on cluster.

4.2. Data fusion and matching

One task that may interest spatio-temporal analysts is combining data collected at nearby but not exactly the same sites, for example, weather station measured rainfall and river levels. This can be considered to be a matching problem (Stuart 2010; McIntosh *et al.* 2018) to pair similar time series from nearby locations, or even a data fusion exercise that merges data collected from different sources (Cocchi 2019). The function `match_sites()` in the `cubble` package provides a simple algorithm for this task. The algorithm first matches spatially by computing the pairwise distance on latitude and longitude. Then it matches temporally by computing the number of matched peaks within a fixed length moving window. Figure 4 illustrates this temporal matching. In the two series, A and a, three peaks have been identified in each. An interval, of fixed length, is constructed for each peak in series A, while the peaks in series a are tested against whether they fall into any of the intervals. Here two out of three peaks match. Options for `match_sites()` are:

- `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 peaks used - 3 in the example above;
- `temporal_window`: the length of the interval - 5 in the example above; and



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 two matches.

- `temporal_min_match`: the minimum number of matched peaks for a valid matched pair.

4.3. Interactive graphics

The cubble workflow fits well with an interactive graphics pipeline (e.g., Buja *et al.* (1988), Buja *et al.* (1996), Sutherland *et al.* (2000), Xie *et al.* (2014), Cheng *et al.* (2016)) that is available in R with the package `crosstalk` (Cheng and Sievert 2021). Figure 5 illustrates how linking can be achieved between a map and multiple time series using a cubble. The map (produced from the nested form) and time series (produced from the long form) are both shared `crosstalk` objects. When a user makes a selection on the map, the site is highlighted (a). This activates a row in the nested `cubble` object, which is then communicated to the long cubble – all the observations with the same id (b) will be selected. The long cubble will then highlight the corresponding series in the time series plot (c).

Linking is also available starting from the time series plot, by selecting points. This will activate rows having the same id in the long cubble. The corresponding rows in the nested cubble are activated, and highlighted the map. (An illustration can be found in the appendix.) Note that this type of linking, both from the map or the time series, is what Cook and Swayne (2007) would call categorical variable linking, where station id is the categorical variable.

4.4. Spatio-temporal transformations

Spatio-temporal data lends itself to a range of transformations. Glyph maps (Section 3.4) transform the measured variable and time coordinates into microplots at the spatial locations. Calendar plots (Wang *et al.* 2020a) deconstruct time to produce plots of variables in a calendar format. Summarizing multiple variables is commonly done using projections, or linear

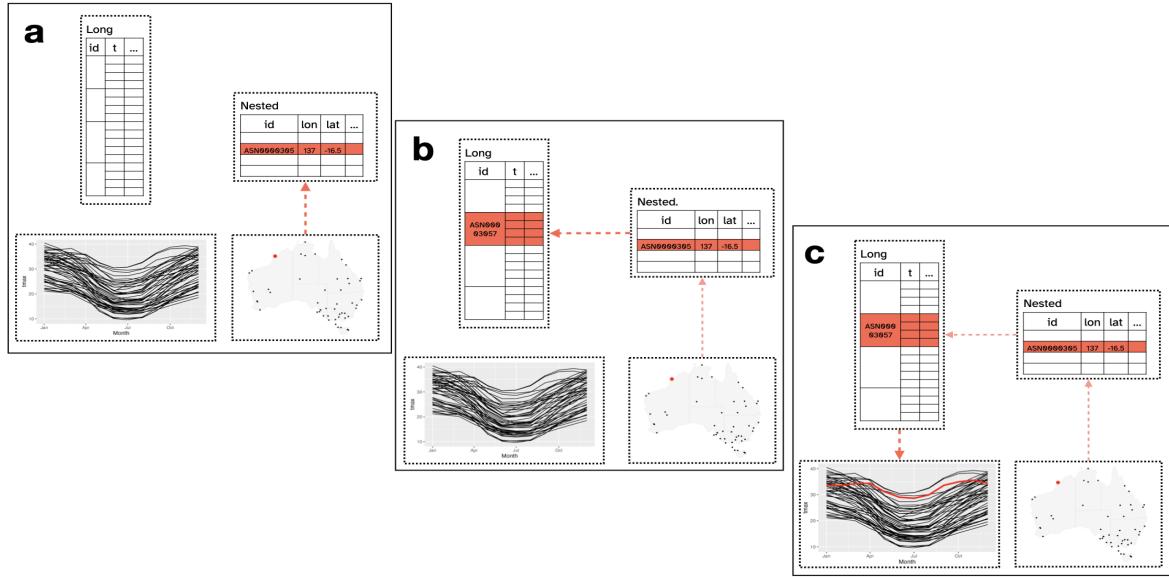


Figure 5: Linking between multiple plots. The line plots and the map are constructed from shared `crosstalk` objects (long and nested cubbles). When a station is selected on the map (a), the corresponding row in the nested cubble will be activated. This will link to all the rows with the same id in the long cubble (b) and update the line plot (c).

combinations. Here we elaborate on the transformations made to produce a glyph map.

The package **GGally** (Schloerke, Cook, Larmarange, Briatte, Marbach, Thoen, Elberg, and Crowley 2021) has implemented glyph maps 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 (Equations 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 new implementation of the glyph map as a ggproto, `GeomGlyph`, has been made in the **cubble** package so that a glyph map can be created with `geom_glyph()`:

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

An example using a glyph map is shown in Section 5.2.

Some useful controls over the glyph map are also available in the `geom_glyph()` implementation. Polar coordinate glyph maps are specified using `polar = TRUE`, and parameters `width` and `height` can be specified in either absolute or relative value. Global and local scale is specified with `global_rescale`, which defaults to `TRUE`. Reference boxes and lines can be added with separate `geom_glyph_box()` and `geom_glyph_line()` lines.

5. Examples

The five examples here are chosen to illustrate these aspects of using `cubble`: creating a `cubble` object from two COVID data tables with the complication of differing location names, using spatial transformations to make a glyph map of seasonal temperature changes over years, aggregating information spatially to explore precipitation patterns, matching river level data and weather station records for analysis of water supply, reading netCDF format data to reproduce a climate reanalysis plot, and the workflow to create complex interactive linked plots. (There is an additional example and figures in the Appendix, and more examples in the package vignettes.)

5.1. Victoria COVID spatio-temporal incidence and spread

Since the start of the pandemic, the Victoria State Government in Australia has provided daily COVID counts by local government area (LGA). This data can be used to visualize COVID incidence and spread spatially, when combined with map polygon data available from the Australian Bureau of Statistics. These different sources need to be combined for the analysis, by matching the LGA names. Here is how to do this with the `cubble` package, including how to handle mismatches arising from different names of the same LGAs in the two tables. The COVID data is stored in a csv file and looks like:

```
R> covid |> head(5)

# A tsibble: 5 x 5 [1D]
# Key:     lga [1]
# Groups:   lga, source [1]
  date      lga      source          n roll_mean
  <date>    <chr>    <chr>      <int>     <dbl>
1 2022-01-01 Alpine (S) Contact with a confirmed case  1       NA
2 2022-01-02 Alpine (S) Contact with a confirmed case  2       NA
3 2022-01-03 Alpine (S) Contact with a confirmed case  4       NA
4 2022-01-04 Alpine (S) Contact with a confirmed case  4       NA
5 2022-01-05 Alpine (S) Contact with a confirmed case  2       NA
```

and the spatial polygons are an ESRI shapefile as follows:

```
R> lga |> head(5)

Simple feature collection with 5 features and 7 fields
Geometry type: MULTIPOLYGON
```

```

Dimension:      XY
Bounding box:  xmin: 142.3535 ymin: -38.67876 xmax: 147.3909 ymax: -36.39269
Geodetic CRS:  WGS 84

  lga_code_2018          lga state_code_2016 state_name_2016
132        20110    Alpine (S)                 2       Victoria
133        20260   Ararat (RC)                 2       Victoria
134        20570  Ballarat (C)                 2       Victoria
135        20660   Banyule (C)                 2       Victoria
136        20740 Bass Coast (S)                2       Victoria
  areasqkm_2018 cent_long cent_lat           geometry
132     4788.1568    146.9742 -36.85357 MULTIPOLYGON (((146.7258 -3...
133     4211.1171    142.8432 -37.47271 MULTIPOLYGON (((143.1807 -3...
134     739.0321     143.7815 -37.49286 MULTIPOLYGON (((143.6622 -3...
135     62.5402      145.0851 -37.73043 MULTIPOLYGON (((145.1357 -3...
136     865.8095    145.5581 -38.50730 MULTIPOLYGON (((145.5207 -3...

```

The function `as_cubicle()` is used to create a `cubicle` object from the two spatial and temporal tables, and requires specifying the arguments `key`, `index`, and `coords` (as described in Section 3.1). It will automatically try to match the sites in both tables using the location names and will show a warning message when there are mismatches, as shown below:

```

R> cb <- as_cubicle(
+   list(spatial = lga, temporal = covid),
+   key = lga, index = date, coords = c(cent_long, cent_lat)
+ )

! Some sites in the temporal table don't have corresponding spatial information

! Some sites in the spatial table don't have corresponding temporal information

! Use argument `output = "unmatch"` to check on the unmatched key

```

It can be seen that there are two-way mismatches – LGAs in the COVID data that do not match with LGAs names in the spatial polygon data, and vice versa. The mismatches can be identified by using the `output = "unmatch"` argument in the `as_cubicle()` function:

```

R> pair <- as_cubicle(
+   list(spatial = lga, temporal = covid),
+   key = lga, index = date, coords = c(cent_long, cent_lat),
+   output = "unmatch"
+ )
R>
R> pair

$paired
# A tibble: 2 x 2

```

```

  spatial          temporal
  <chr>           <chr>
1 Kingston (C) (Vic.) Kingston (C)
2 Latrobe (C) (Vic.) Latrobe (C)

$others
$others$temporal
[1] "Interstate" "Overseas"   "Unknown"

$others$spatial
[1] "No usual address (Vic.)"
[2] "Migratory - Offshore - Shipping (Vic.)"

```

With this information both tables can be fixed, to create the desired `cubble` object, as follows:

```

R> lga <- lga />
+   mutate(lga = ifelse(lga == "Kingston (C) (Vic.)", "Kingston (C)", lga),
+         lga = ifelse(lga == "Latrobe (C) (Vic.)", "Latrobe (C)", lga)) />
+   filter(!lga %in% pair$others$spatial)
R>
R> covid <- covid /> filter(!lga %in% pair$others$temporal)
R>
R> cb <- as_cubble(data = list(spatial = lga, temporal = covid),
+                     key = lga, index = date, coords = c(cent_long, cent_lat))

```

5.2. Australian historical maximum temperature

The Global Historical Climatology Network (GHCN) provides daily climate measures from stations across the world. The data used here (`historical_tmax`) is a subset extracted using the package `rnoaa` (Chamberlain 2021), containing the records of maximum temperature for 236 Australian stations from 1859 through 1969 and provides information also on the latitude, longitude and elevation of each of the stations. The goal of this example is to compare the monthly average maximum temperature between two periods, 1971-1975 and 2016-2020, for stations in Victoria and New South Wales, using a *glyph map*.

First, the stations need to be filtered to those in NSW and Victoria by using the station identifiers, stored within the 11 digits of the `id` variable entries. The country code is in the first 5 digits (Australia is represented by “ASN00”) and the next 6 digits encode the station following the Australian Bureau of Meteorology (BOM) (Commonwealth of Australia 2022) coding protocols. New South Wales stations correspond to entries in the range 46-75 and the Victorian stations to 76-90. Filtering Victoria and New South Wales stations is a *spatial operation* and hence uses the `cubble` object in the nested form:

```

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

```

Next, the monthly maximum average temperature is calculated for both periods. This is a *temporal operation* requiring a switch into the long cubble form using the `face_temporal()`

function. In addition, a new indicator for the two time periods of interest is created before the calculation of monthly averages:

```
R> tmax <- tmax |>
+   face_temporal() |>
+   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))
```

A quick check on the number of observations for each location is made, revealing that there are several with less than 24 observations – these stations lack temperature values for some months. In this example, those stations are removed by switching to a long **cubicle** to operate on the spatial component over time, and then, move back into the nested **cubicle** (to make the glyph map):

```
R> tmax |>
+   face_spatial() |>
+   mutate(n = nrow(ts)) |>
+   arrange(n) |>
+   pull(n) |>
+   head(10)
```

```
[1] 12 12 12 13 19 19 20 24 24 24
```

```
R> tmax <- tmax |>
+   face_spatial() |>
+   filter(nrow(ts) == 24) |>
+   face_temporal()
```

In order to create a glyph map displaying the monthly series (Figure 6), the spatial variables need to be unfolded with the temporal variables. The reason being that the major (**long**, **lat**) and minor (**month**, **tmax**) coordinates need to be on the same table to create the glyph map. The **geom_glyph()** function does both the transformation and the plotting.

```
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 = long, x_minor = month,
+                  y_major = lat, y_minor = tmax,
```

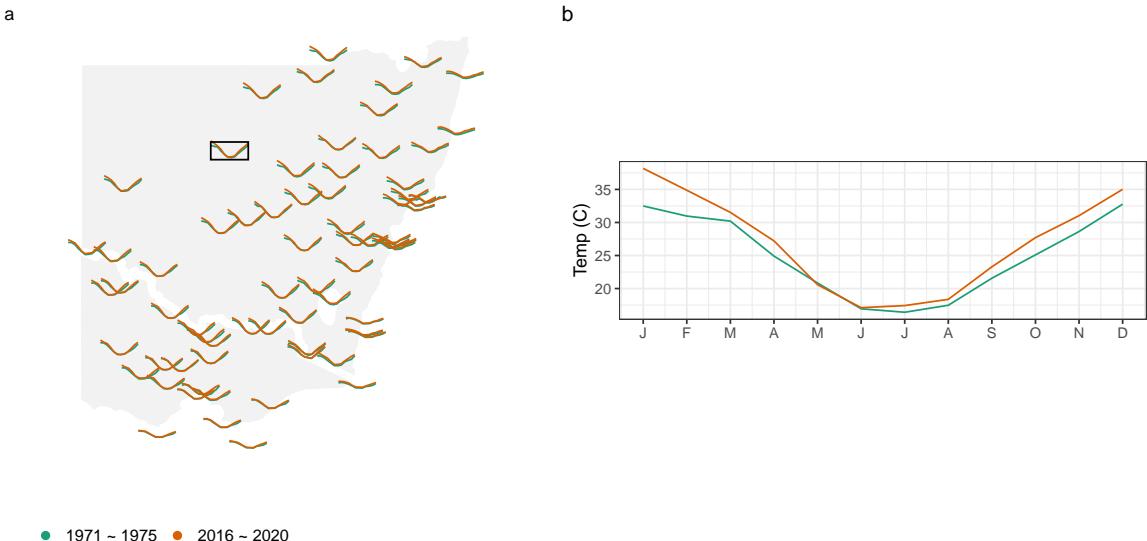


Figure 6: A glyph map of the monthly maximum average temperature for weather stations in Victoria and New South Wales for the periods (1971-1975, 2016-2020). The corresponding average time series for the Cobar station are display on the top left corner. From the glyph map we can observe that the monthly trend is similar for all locations (low in the winter, high in the summer), and small increased temperatures, particularly in late summer can be seen at most stations in New South Wales.

```
+         group = interaction(id, group), color = group),
+         width = 1, height = 0.5) +
+   ...
```

Glyph maps work well to explore temporal patterns across spatial locations, particularly when the spatial locations are gridded. In this example, they are irregularly spaced, which can result in overlapping glyphs obscuring each other. To fix this, one could aggregate data from nearby stations. An example of this using is included in the Appendix.

5.3. River levels and rainfall in Victoria

River level and rainfall data for the same areas should have some similarity. Here we examine the river gauge data (`Water_course_level`) from the Bureau of Meteorology (Commonwealth of Australia 2022) in relation to weather station rainfall from NOAA's climate data (NOAA 2022) (`climate`). The goal is to match water gauges with nearby weather stations, spatially and temporally, using 2020 measurements using `match_sites()` function.

This function requires passing the major and minor data sets used for matching, in this case those are `river` and `climate`. The variables used for the temporal matching are `Water_course_level` from the `river` data set and `prcp` in the `climate` data set. The rest of the arguments, as explained in Section 4.2, correspond to the maximum and minimum number of peaks in the time series to be matched. In this example those are set to be a maximum of 30 and a minimum of 15 (approximately 2 and 1 per month).

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

This function returns a **cubble** object, with additional columns: **dist** storing the distance between matched stations, **group** summarizing spatial matching, and **n_match** showing 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 CR~ -36.9  146. river  6.15     5 <tibble>    21
2 404207 HOLLAND ~ -36.6  146. river  8.54    10 <tibble>    21
3 ASN00082042 strathbo~ -36.8  146. clim~  6.15     5 <tibble>    21
4 ASN00082170 benalla ~ -36.6  146. clim~  8.54    10 <tibble>    21
5 230200 MARIBYRN~ -37.7  145. river  6.17     6 <tibble>    19
# ... with 3 more rows
```

Figure 7 shows four matched pairs on the map (a) and standardized data as time series (b). The expected concurrent increase in precipitation and water level can be seen clearly.

5.4. ERA5: climate reanalysis data

Figure 8 reproduces the ERA5 data (Hersbach *et al.* 2020) row of Figure 19 in (Hersbach *et al.* 2020). Here we explain how this would be done using **cubble**. The plots show that the southern polar vortex splits into two on 2002-09-26 and further splits into four on 2002-10-04. Further explanation of why this is interesting can be found in the figure source, and also (Simmons *et al.* 2020), (Simmons *et al.* 2005).

The ERA5 data (Hersbach *et al.* 2020) provides hourly estimates across the Earth for atmospheric, land and oceanic climate variables. The data is available in the NetCDF format from the European Centre for Medium-Range Weather Forecasts (ECMWF). It can be directly downloaded from Copernicus Climate Data Store (CDS) (Copernicus Climate Change Service 2022) website or via the package **ecmwfr** (Hufkens *et al.* 2019).

For the reproduction, we focus on the **era5-pressure** data, hourly pressure levels from 1970 to present, with the *specific humidity* and *geopotential*.

The downloaded netCDF data is read into R using the **ncdf4** package, and converted to a **cubble** object:

```
R> raw <- ncdf4::nc_open(here::here("data/era5-pressure.nc"))
R> dt <- as_cubble(
```

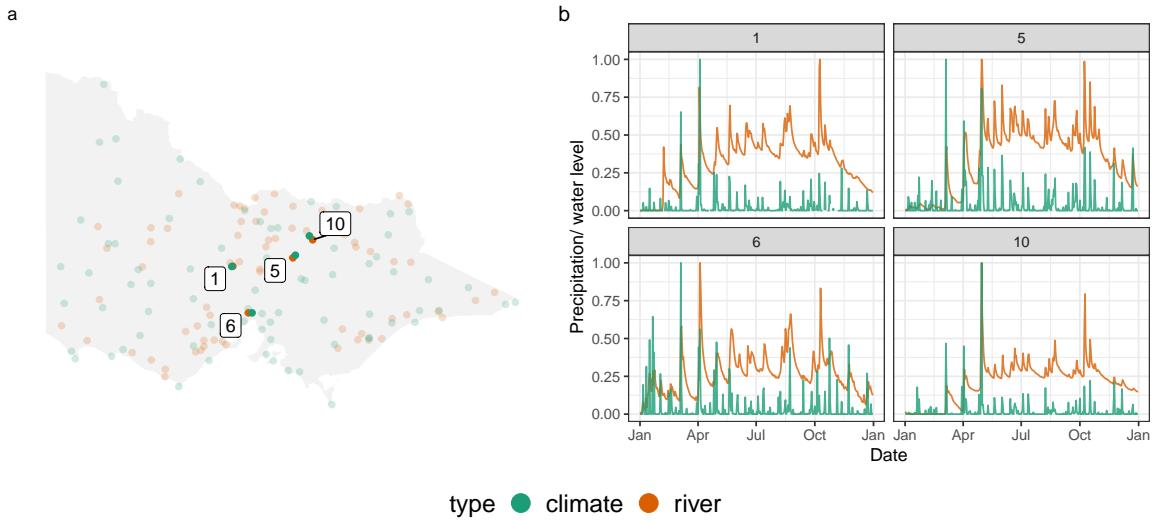


Figure 7: Weather stations and river gauges with matched pairs labelled on the map (a) and plotted across time (b). Precipitation and water level have been standardised between 0 and 1 to be displayed on the same scale. The water level reflects the increase in precipitation. The numbers (1, 5, 6, 10) indicate the group index derived from spatial matching, only those that were selected by temporal matching are shown here.

```
+   raw, vars = c("q", "z"),
+   long_range = seq(-180, 180, 1), lat_range = seq(-88, 88, 1))
```

Creating the plot requires making transformations on time, unfolding the data for computing the statistic of interest, which is plotted directly as a contour plot with `ggplot`. Code is provided to accomplish this in the supplementary material.

5.5. Interactive graphics

Interactive graphics can be useful because they make it possible to look at the data in a multiple of ways on-the-fly. This is especially important for spatio-temporal data, where we would like to interactively connect spatial and temporal displays. This example describes the process of using `cubicle` with `crosstalk` to build an interactive display connecting a map of Australia, with ribbon plots of temperature range observed at the stations. The purpose is to explore the variation of monthly temperature range over the country. Figure 9 shows three snapshots of the interactivity.

The key steps are to convert both the nested and long forms of the data into shared `crosstalk` objects, and to plot these side-by-side. The two are linked by the station identifier.

```
clean <- climate_full |> ...
nested <- clean |> SharedData$new(~id, group = "cubicle")
long <- face_temporal(clean) |> SharedData$new(~id, group = "cubicle")
```

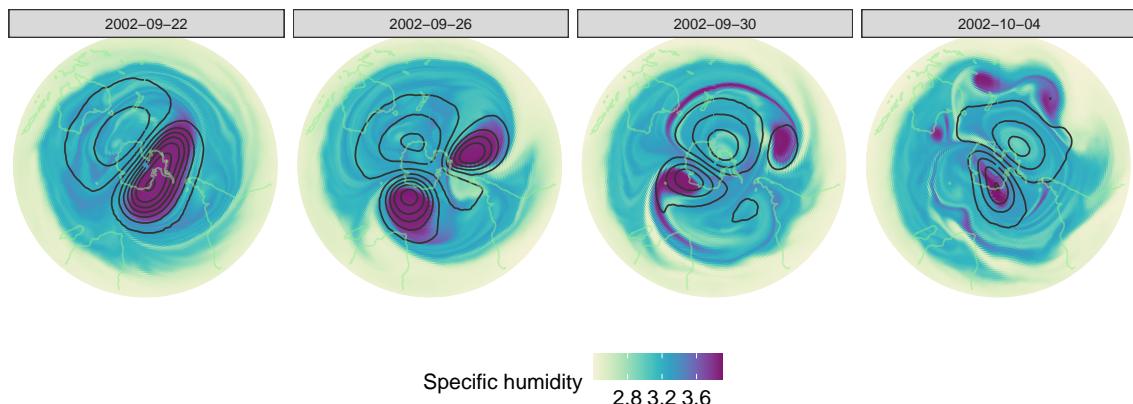


Figure 8: A reproduction of the second row (ERA5 data) of Figure 19 in Hersbach et al (2020) to illustrate the break-up of southern polar vortex in late September and early October 2002. The polar vortex, signalled by the high specific humidity, splits into two on 2002-09-26 and furthers split into four on 2002-10-04.

```
p1 <- nested |> ...
p2 <- long |> ...

crosstalk::bscols(plotly::ggplotly(p1), plotly::ggplotly(p2), ...)
```

Plot (a) shows the initial state of the interactive display: all locations are shown as dots on the map, coloured by temperature range, and the right plot shows the ribbons representing maximum to minimum for all stations. In plot (b) the “Mount Elizabeth” station, which shows a high variance colour on the initial map, is selected on the map and this produces the ribbon on the right. In plot (c) the lowest temperature in August is selected, which is “Thredbo” station on the left map. It was surprising to us that this was not a station in Tasmania, so for comparison a station in Tasmania is selected on the map to show in relation to Thredbo. We can see that Thredbo has a bigger winter dip in temperature, and although Tasmania is cold generally, its temperatures are more consistent.

6. Conclusion

This paper presents an R package **cubble** for organizing, manipulating and visualizing spatio-temporal data. The package introduces a new data structure for spatio-temporal data, **cubble**, that connects the time invariant and varying variables and that allows the user to work with a nested and long form of the data. This work adds capabilities into the spatio-temporal practitioners toolbox to integrate it with a tidy data framework. The data structure and functions introduced in this package can be used and combined with existing spatial data analysis packages such as **sf**, data wrangling packages such as **dplyr**, and visualization packages such as **ggplot2**, **plotly** and **leaflet**.

Numerous examples are provided in the main text, appendix and package vignettes. These in-

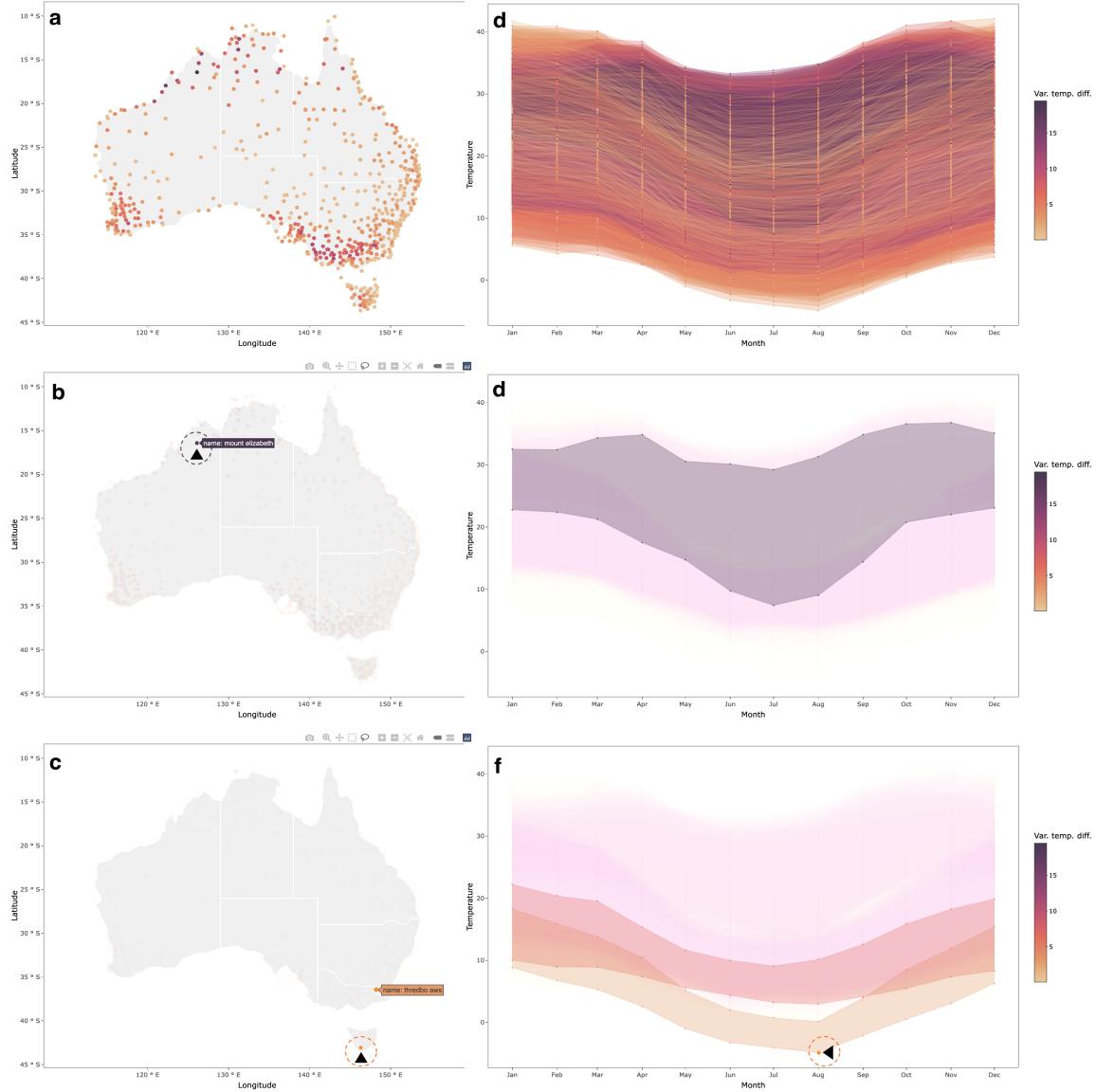


Figure 9: Exploring temperature variation using linking of a map and seasonal display. Each row is a screen dump of the process. The top row shows all locations and all temperature profiles. Selecting a particular location on the map (here Mount Elizabeth) produces the plot in the second row. The maximum and minimum temperatures are shown using a ribbon. The bottom row first selects the lowest temperature in August in the seasonal display, which highlights the corresponding station on the map (Thredbo AWS). Another station, located in the Tasmania Island, is then selected to compare its temperature variation with Thredbo AWS.

clude creating and coercing data with mismatched names, handling hierarchical data, matching time series spatially and temporally, reproducing ERA5 plots from netCDF data. Visualization of the **cubble** objects can be done with interactive graphic pipelines using **crosstalk**, **plotly** and **leaflet**.

There are several possible future directions for the work. The data structure only described fixed spatial sites, and it could be useful to provide tools to accommodate moving coordinates as might be encountered in animal movement data. That could be achieved with a list-column for the location coordinates, and an additional form that these locations can be pivoted into, like the long form for temporal variables. For multiple measured variables, the **cubble** package could be integrated with dimension reduction methods, and dynamic graphics for multiple dimensions such as a tour (Wickham *et al.* 2011).

7. Acknowledgement

This work is funded by a Commonwealth Scientific and Industrial Research Organisation (CSIRO) Data61 Scholarship and started while Nicolas Langrené was affiliated with CSIRO’s Data61. The article is created using the package **knitr** (Xie 2015) and **rmarkdown** (Xie *et al.* 2018) in R with the **rticles::jss_article** template. The source code for reproducing this paper can be found at: <https://github.com/huizehang-sherry/paper-cubble>.

References

- Bach B, Dragicevic P, Archambault D, Hurter C, Carpendale S (2014). “A Review of Temporal Data Visualizations Based on Space-Time Cube Operations.” *Eurographics conference on visualization*, p. 19. URL <https://hal.inria.fr/hal-01006140/>.
- 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**.
- Chamberlain S (2021). **rnoaa**: ‘NOAA’ Weather Data from R. R package version 1.3.8, URL <https://CRAN.R-project.org/package=rnoaa>.
- Cheng J, Karambelkar B, Xie Y (2021). **leaflet**: Create Interactive Web Maps with the JavaScript **leaflet** Library. R package version 2.0.4.1, URL <https://CRAN.R-project.org/package=leaflet>.
- Cheng J, Sievert C (2021). **crosstalk**: Inter-Widget Interactivity for HTML Widgets. R package version 1.1.1, URL <https://CRAN.R-project.org/package=crosstalk>.

- 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.
- Commonwealth of Australia (2022). “Australia’s Official Weather Forecasts & Weather Radar - Bureau of Meteorology.” Online; accessed 24 June 2022, URL <http://www.bom.gov.au/>.
- Cook D, Swayne D (2007). *Interactive and Dynamic Graphics for Data Analysis with examples using R and GGobi*. Springer-Verlag New York, New York. With contributions from Buja, A., Temple Lang, D., Hofmann, H., Wickham, H. and Lawrence, M. and additional data, R code and demo movies at <http://www.ggobi.org>.
- Copernicus Climate Change Service (2022). “Climate Data Store.” Online; accessed 24 June 2022, URL <https://cds.climate.copernicus.eu/#!/home>.
- Hassell D, Gregory J, Blower J, Lawrence BN, Taylor KE (2017). “A data model of the Climate and Forecast metadata conventions (CF-1.6) with a software implementation (cf-python v2.1).” *Geoscientific Model Development*, **10**(12), 4619–4646. ISSN 1991-959X. doi: [10.5194/gmd-10-4619-2017](https://doi.org/10.5194/gmd-10-4619-2017). URL <https://gmd.copernicus.org/articles/10/4619/2017/>.
- 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 **ecwmfr** Package: An Interface to ECMWF API Endpoints.” URL <https://bluegreen-labs.github.io/ecmwfr/>.
- Lu M, Appel M, Pebesma E (2018). “Multidimensional Arrays for Analysing Geoscientific Data.” *ISPRS International Journal of Geo-Information*, **7**(8), 313. ISSN 2220-9964. doi: [10.3390/ijgi7080313](https://doi.org/10.3390/ijgi7080313). URL <http://www.mdpi.com/2220-9964/7/8/313>.
- 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).
- Michna P, Woods M (2021). **RNetCDF**: Interface to ‘NetCDF’ Datasets. R package version 2.5-2, URL <https://CRAN.R-project.org/package=RNetCDF>.
- Müller K, Wickham H (2021). **tibble**: Simple Data Frames. R package version 3.1.6, URL <https://CRAN.R-project.org/package=tibble>.
- NOAA (2022). “National Centers for Environmental Information (NCEI).” Online; accessed 24 June 2022, URL <https://www.ncei.noaa.gov/>.
- 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 (2018). “Simple Features for R: Standardized Support for Spatial Vector Data.” *R Journal*, **10**(1), 439.
- 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 R (2022). “CRAN Task View: Handling and Analyzing Spatio-Temporal Data.” Version 2022-03-07, URL <https://CRAN.R-project.org/view=SpatioTemporal>.
- 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>.
- Schloerke B, Cook D, Larmarange J, Briatte F, Marbach M, Thoen E, Elberg A, Crowley J (2021). **GGally**: *Extension to ggplot2*. R package version 2.1.2, URL <https://CRAN.R-project.org/package=GGally>.
- 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. doi:[10.1175/JAS-3322.1](https://doi.org/10.1175/JAS-3322.1). URL <https://journals.ametsoc.org/view/journals/atsc/62/3/jas-3322.1.xml>.
- Simmons A, Soci C, Nicolas J, Bell B, Berrisford P, Dragani R, Flemming J, Haimberger L, Healy S, Hersbach H, Horányi A, Inness A, Muñoz-Sabater J, Radu R, Schepers D (2020). “Global Stratospheric Temperature Bias and Other Stratospheric Aspects of ERA5 and ERA5.1.” (859). doi:[10.21957/rcxqfmg0](https://doi.org/10.21957/rcxqfmg0). URL <https://www.ecmwf.int/node/19362>.
- 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>.
- Wang E, Cook D, Hyndman RJ (2020a). “Calendar-based Graphics for Visualizing People’s Daily Schedules.” *Journal of Computational and Graphical Statistics*, **29**(3), 490–502.
- Wang E, Cook D, Hyndman RJ (2020b). “A New Tidy Data Structure to Support Exploration and Modeling of Temporal Data.” *Journal of Computational and Graphical Statistics*, **29**(3), 466–478. URL <https://doi.org/10.1080/10618600.2019.1695624>.
- Wickham H (2014). “Tidy Data.” *Journal of Statistical Software*, **59**(10), 1–23. URL <https://doi.org/10.18637/jss.v059.i10>.
- Wickham H (2016). **ggplot2**: *Elegant Graphics for Data Analysis*. Springer-Verlag New York. ISBN 978-3-319-24277-4. URL <https://ggplot2.tidyverse.org>.

- Wickham H (2019). *Advanced R*. CRC press. ISBN 978-0815384571. URL <https://adv-r.hadley.nz/rcpp.html>.
- Wickham H, Averick M, Bryan J, Chang W, McGowan LD, François R, Grolemund G, Hayes A, Henry L, Hester J, Kuhn M, Pedersen TL, Miller E, Bache SM, Müller K, Ooms J, Robinson D, Seidel DP, Spinu V, Takahashi K, Vaughan D, Wilke C, Woo K, Yutani H (2019). “Welcome to the **tidyverse**.” *Journal of Open Source Software*, **4**(43), 1686. doi: [10.21105/joss.01686](https://doi.org/10.21105/joss.01686).
- Wickham H, Cook D, Hofmann H, Buja A (2011). “**tourr**: An R Package for Exploring Multivariate Data with Projections.” *Journal of Statistical Software*, **40**(2). ISSN 1548-7660. URL <http://www.jstatsoft.org/v40/i02/>.
- Wickham H, François R, Henry L, Müller K (2022). **dplyr**: *A Grammar of Data Manipulation*. R package version 1.0.8, URL <https://CRAN.R-project.org/package=dplyr>.
- 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. doi: [10.1002/env.2152](https://doi.org/10.1002/env.2152).
- 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*, **29**(2), 201 – 213. URL <https://doi.org/10.1214/14-STS477>.

Affiliation:

H. Sherry Zhang
 Monash University
 21 Chancellors Walk, Clayton VIC 3800 Australia
 E-mail: huize.zhang@monash.edu

Dianne Cook
 Monash University
 21 Chancellors Walk, Clayton VIC 3800 Australia
 E-mail: dcook@monash.edu

Ursula Laa
 University of Natural Resources and Life Sciences
 Gregor-Mendel-Straße 33, 1180 Wien, Austria
 E-mail: ursula.laa@boku.ac.at

Nicolas Langrené
BNU-HKBU United International College
2000 Jintong Road, Tangjiawan, Zhuhai, Guangdong Province, China
E-mail: nicolaslangrene@uic.edu.cn

Patricia Menéndez
Monash University
21 Chancellors Walk, Clayton VIC 3800 Australia
E-mail: patricia.menendez@monash.edu