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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 class, **cubble**, with a suite of functions enabling easy slicing and dicing on different spatio-temporal components. The proposed **cubble** class ensures that all the components of the data are easy to access and manipulate while providing flexibility for data analysis. In addition, the **cubble** package facilitates visual and numerical explorations of the data while easing data wrangling and modelling. The **cubble** class and the functions provided in the **cubble** R package equip users with the capability to handle hierarchical spatial and temporal structures. The **cubble** class 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.

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 Comprehensive R Archive Network (CRAN) task view SpatioTemporal (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 package **stars** (Pebesma 2021) has a new implementation to use dense arrays to represent spatio-temporal cubes. It also interfaces with the package **sf** (Pebesma 2018), 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 packages 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 class, 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), the **cubble** class 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 presents the main design and functionality of the **cubble** package. Section 3 explains how the **cubble** package deals with more advanced considerations, including data with hierarchical structure, data matching and how the package fits with existing static and interactive visualization tools. Moreover we also illustrate how the **cubble** package deals with spatio-temporal data transformations. Section 4 uses Australian weather station data and river level data as examples to demonstrate the use of the package. An example of how the **cubble** package handles Network Common Data Form (NetCDF) data is also provided. Section 5 discuss the paper contributions and future directions.

2. The cubble package

2.1. The cubble object

[conceptual framework] Spatio-temporal data comes various spatial and temporal characteristics and requires different data structures to wrangle: climate weather stations are recorded at fixed point location but with potential temporal data quality issue (missingness on the day); GPS data tracks unique point locations at different timestamps; satellite imageries captures snapshots of landscape at selected time. The type of spatio-temporal data cubble tackles are those collected at unique fixed locations while allowed for irregularity in the temporal dimension, like the weather station data. In the four layouts presented by the spacetime paper (Pebesma 2012), cubble handles full space-time and sparse space-time layouts.

The cubble class is an S3 class, built on tibble, to pivot spatio-temporal data into a nested (spatial) form and a long (temporal) form. It has two subclasses:

- a nested/ spatial cubble has class c("spatial_cubble_df", "cubble_df")
- a long/ temporal cubble has class c("temporal_cubble_df", "cubble_df")

A nested cubble arranges spatial variables in columns and nests temporal variables in a specialised `ts` column. Below prints an nested cubble object using the weather station data collected in three airports (the creation of a cubble object will be explained in Section 2.2). This toy data is a subset of a larger data `climate_aus` collected from Global Historical Climatology Network Daily (GHCND). The three airport stations in Melbourne are recorded with station metadata: station ID, longitude, latitude, elevation, station name, world meteorology organisation ID. The temporal variables are precipitation, maximum and minimum temperature, which can be read from the cubble header:

```
R> cb_nested

# cubble: key: id [3], index: date, nested form
# spatial: [144.8321, -37.98, 145.0964, -37.6655], Missing CRS!
# temporal: date [date], prcp [dbl], tmax [dbl], tmin [dbl]
  id      long   lat elev name          wmo_id ts
  <chr>    <dbl> <dbl> <dbl> <chr>        <dbl> <list>
1 ASN00086038 145. -37.7 78.4 essendon airport  95866 <tibble [10 x 4]>
```

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```
2 ASN00086077 145. -38.0 12.1 moorabbin airport 94870 <tibble [10 x 4]>
3 ASN00086282 145. -37.7 113. melbourne airport 94866 <tibble [10 x 4]>
```

A long cubble expands the temporal variables into the long form and stores the spatial variables as a data attribute. In the header of a long cubble object, the extent now prints the temporal range, the interval, and whether there is gaps in the data. It also prints the available spatial variables, as oppose to the temporal variables in the nested cubble.

```
R> cb_long
```

```
# cubble: key: id [3], index: date, long form
# temporal: 2020-01-01 -- 2020-01-10 [1D], no gaps
# spatial: long [dbl], lat [dbl], elev [dbl], name [chr], wmo_id [dbl]
#           id      date      prcp    tmax   tmin
#           <chr>    <date>    <dbl>    <dbl>   <dbl>
1 ASN00086038 2020-01-01      0  26.8   11
2 ASN00086038 2020-01-02      0  26.3  12.2
3 ASN00086038 2020-01-03      0  34.5  12.7
4 ASN00086038 2020-01-04      0  29.3  18.8
5 ASN00086038 2020-01-05     18  16.1  12.5
# i 25 more rows
```

The cubble attributes

A cubble object inherits the attributes from tibble (and its subclasses): `class`, `row.names`, and `names`, in addition to three specialised attributes:

- `key`: the spatial identifier
- `index`: the temporal identifier
- `coords`: a pair of ordered coordinates associated with the location

Readers known the `key` and `index` attributes from the `tsibble` package would already be familiar the two arguments. In cubble, the `key` attribute identifies the row in the nested cubble, and together with the `index` argument, identifies the row in the long cubble. Currently, cubble only supports one variable as the key and the accepted temporal class for index includes the base R class `Date`, `POSIXlt`, `POSIXct` and `tsibble`'s `yearmonth`, `yearweek`, and `yearquarter` class.

The `coords` attribute takes an ordered pair of coordinate. It can be a unprojected pair of longitude and latitude, or a projected easting and northing values. Under the hood, the `sf` package is used to calculate the bounding box, shown in the header of a nested cubble, and other spatial operations.

The long cubble has a special attribute `spatial` to store the spatial variables: all the variables in the nested cubble, except for the `ts` column. The shortcut function are available to extract components in the attributes, for example, `spatial()` for extracting the tibble object for the spatial variables:

```
R> spatial(cb_long)

# A tibble: 3 x 6
  id      long   lat   elev name          wmo_id
  <chr>    <dbl> <dbl> <dbl> <chr>        <dbl>
1 ASN00086038 145. -37.7  78.4 essendon airport  95866
2 ASN00086077 145. -38.0  12.1 moorabbin airport  94870
3 ASN00086282 145. -37.7 113. melbourne airport  94866
```

2.2. Creation and coercion

Creating from separate spatial and temporal tables

Spatio-temporal data may arrive in separate tables for analysts. For example, in climate data, analysts may initially receive station data containing geographic location information, variables recorded and their recording periods. They can then query the temporal variables using the stations of interest to obtain the corresponding temporal data. Alternatively, analyses may begin as purely spatial or temporal, and analysts may obtain additional temporal or spatial data to expand the result to spatio-temporal.

The function `make_cubble()` composes a `cubble` object from a spatial table (`spatial`) and a temporal table (`temporal`) with the three attributes introduced in the subsection 2.1: `key`, `index`, and `coords`. The following code creates the nested `cubble` object shown previously:

```
R> make_cubble(spatial = stations, temporal = meteo,
+                 key = id, index = date, coords = c(long, lat))
```

Coercing from foreign objects

Spatio-temporal data in other foreign objects can be coerced into a `cubble` object with the function `as_cubble()`. This includes casting from a `tibble` or `data.frame` with both spatial and temporal information, a NetCDF object, a `stars` object (Pebesma 2021), and a `sftime` object (Teickner *et al.* 2022). The two examples below show the casting from a tibble and a NetCDF object to a `cubble` object.

The dataset `climate_flat` joins the spatial data, `stations`, with the temporal data, `meteo`, into a single tibble object and it can be coerced into a `cubble` using:

```
R> climate_flat |> as_cubble(key = id, index = date, coords = c(long, lat))
```

The NetCDF data is another format commonly used for storing spatio-temporal data. In R, packages for wrangling NetCDF data 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). The code below casts a NetCDF object in the `ncdf4` class into a `cubble` object:

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```
R> path <- system.file("ncdf/era5-pressure.nc", package = "cubble")
R> raw <- ncdf4::nc_open(path)
R> as_cubble(raw)

# cubble: key: id [26565], index: time, nested form
# spatial: [113, -53, 153, -12], Missing CRS!
# temporal: time [dttm], q [dbl], z [dbl]
  id long lat ts
  <int> <dbl> <dbl> <list>
1     1 113    -12 <tibble [6 x 3]>
2     2 113.   -12 <tibble [6 x 3]>
3     3 114.   -12 <tibble [6 x 3]>
4     4 114.   -12 <tibble [6 x 3]>
5     5 114    -12 <tibble [6 x 3]>
# i 26,560 more rows
```

Sometimes, one may want to read in a subset of the NetCDF data and the argument `vars`, `long_range` and `lat_range` can be used to subset on the variable and the grid resolution:

```
R> as_cubble(raw, vars = "q",
+             long_range = seq(-180, 180, 1), lat_range = seq(-90, 90, 1))
```

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.

2.3. Functions and methods

Table 1 summarises functions implemented in the **cubble** package and Table 2 details the methods implemented for each of the three cubble classes: `cubble_df`, `spatial_cubble_df`, and `temporal_cubble_df`.

Table 1: Functions implemented in the **cubble** package

Category	Functions
base R	[, [[<- , names<-
tidyverse	dplyr_row_slice, dplyr_col_modify, dplyr_reconstruct, select, mutate, arrange, filter, group_by, ungroup, summarise, select, slice, rowwise, rename, bind_rows, bind_cols, relocate, type_sum, the slice family (slice_head, slice_tail, slice_max, slice_min, slice_sample) and the join family (left_join, right_join, inner_join, full_join, anti_join, semi_join)

Category	Functions
cubble	as_cubble, cubble, make_cubble, check_key, face_temporal, face_spatial, unfold, key, key_vars, key_data, index, index_var, coords, spatial, match_sites, match_spatial, match_temporal, geom_glyph, geom_glyph_box, geom_glyph_line, make_spatial_sf, make_temporal_tsibble, fill_gaps, scan_gaps

Table 2: Methods implemented for the three `cubble` classes:
`cubble_df`, `spatial_cubble_df`, and `temporal_cubble_df`

Class	Methods
<code>cubble_df</code>	[[<code><-</code> , <code>dplyr_col_modify</code> , <code>key_data</code> , <code>key_vars</code> , <code>key</code> , <code>print</code> [, <code>names<-</code> , <code>tbl_sum</code> , <code>dplyr_reconstruct</code> , <code>dplyr_row_slice</code> , <code>face_spatial</code> , <code>face_temporal</code> , <code>unfold</code> , <code>arrange</code> , <code>rename</code> , <code>rowwise</code> , <code>group_by</code> , <code>ungroup</code> , <code>select</code> , <code>spatial</code> , <code>summarise</code> , <code>unfold</code> , <code>update_cubble</code> [, <code>names<-</code> , <code>tbl_sum</code> , <code>arrange</code> , <code>dplyr_reconstruct</code> , <code>dplyr_row_slice</code> , <code>face_spatial</code> , <code>face_temporal</code> , <code>unfold</code> , <code>fill_gaps</code> , <code>group_by</code> , <code>ungroup</code> , <code>rename</code> , <code>rowwise</code> , <code>scan_gaps</code> , <code>select</code> , <code>spatial</code> , <code>summarise</code> , <code>tbl_sum</code> , <code>bind_rows</code> , <code>bind_cols</code> , <code>update_cubble</code>
<code>spatial_cubble_df</code>	
<code>temporal_cubble_df</code>	

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 operations in the **dplyr** package on both the nested and long forms: `mutate`, `filter`, `summarise`, `select`, `arrange`, `rename`, `left_join`, and the slice family (`slice_*`).

The toy example below demonstrates the using of a collection of dplyr functions (`mutate`, `select`, `filter`, and `arrange`) on a nested cubble object `cb_nested`:

```
R> cb_nested %>%
+   mutate(avg_temp = mean(ts$tmax, na.rm = TRUE)) %>%
+   select(-elev) %>%
+   filter(avg_temp > 26) %>%
+   arrange(-avg_temp)
```

cubble

The three basic cubble functions, `face_temporal()`, `face_spatial()`, and `unfold()`, are introduced in this section before more advanced functionalities in Section 3.

The pair of verbs, `face_temporal()` and `face_spatial()`, pivot the cubble object between the spatial and temporal face of the multivariate spatio-temporal cube, as illustrated in Figure

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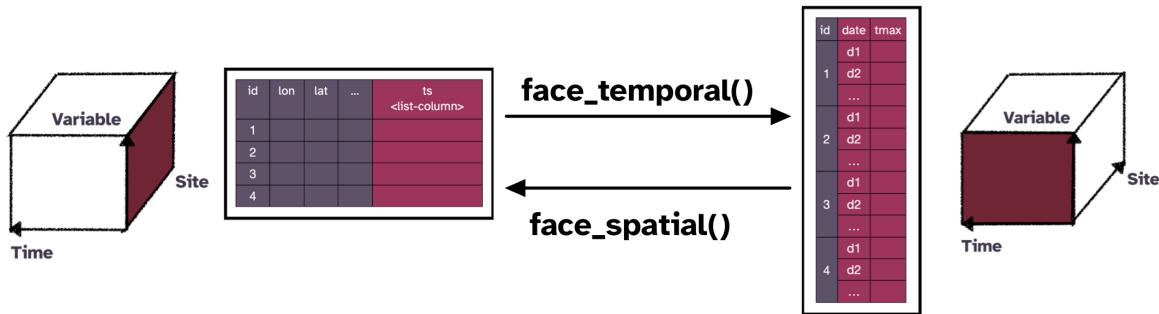


Figure 1: An illustration of the function `face_temporal()` and `face_spatial()`: `face_temporal()` converts a spatial cubble (nested form) into a temporal cubble (long form) to focus on the temporal variables. Conversely, `face_spatial()` transforms a temporal cubble into a spatial one to emphasize spatial variables.

1. The code below uses the function `face_temporal()` and `face_spatial()` to transform between a nested cubble (`cb_nested`) and a long one (`cb_long`), introduced earlier in subsection 2.1:

```
R> identical(face_temporal(cb_nested), cb_long)
```

```
[1] TRUE
```

```
R> identical(face_spatial(cb_long), cb_nested)
```

```
[1] TRUE
```

The pair of verbs are exact inverse and apply both functions on a cubble object will result in the object itself:

```
R> identical(face_spatial(face_temporal(cb_nested)), cb_nested)
```

```
[1] TRUE
```

```
R> identical(face_temporal(face_spatial(cb_long)), cb_long)
```

```
[1] TRUE
```

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 3.3, 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 `lon` and `lat` into the long cubble:

```
R> cb_long |> unfold(lon, lat)
```

```
# cubble: key: id [3], index: date, long form
# temporal: 2020-01-01 -- 2020-01-10 [1D], no gaps
# spatial: long [dbl], lat [dbl], elev [dbl], name [chr], wmo_id [dbl]
  id      date      prcp  tmax  tmin  long   lat
  <chr>    <date>    <dbl> <dbl> <dbl> <dbl>
1 ASN00086038 2020-01-01     0  26.8  11  145. -37.7
2 ASN00086038 2020-01-02     0  26.3  12.2 145. -37.7
3 ASN00086038 2020-01-03     0  34.5  12.7 145. -37.7
4 ASN00086038 2020-01-04     0  29.3  18.8 145. -37.7
5 ASN00086038 2020-01-05    18  16.1  12.5 145. -37.7
# i 25 more rows
```

2.4. Compatibility with other packages

Analysts often have their own preferred spatial or temporal data structure, which they may wish to keep for spatio-temporal analysis. For example, the `tbl_ts` class from the `tsibble` package (Wang *et al.* 2020b) is commonly used in time series forecasting and similarly, the `sf` class (Pebesma 2018) is often used in spatial data science. In `cubble`, analysts can combine these two structures together by allowing the spatial component to also be an `sf` object and the temporal component to also be a `tsibble` object.

tsibble

The `key` and `index` arguments in a `cubble` object corresponds to the `tsibble` counterparts and they can be safely omitted, if the temporal component is a `tsibble` object, i.e. `meteo_ts` in the example below. The `tsibble` class from the input will be carried over to the `cubble` object:

```
R> ts_nested <- make_cubble(
+   spatial = stations, temporal = meteo_ts, coords = c(long, lat))
R> (ts_long <- face_temporal(ts_nested))

# cubble: key: id [3], index: date, long form, [tsibble]
# temporal: 2020-01-01 -- 2020-01-10 [1D], no gaps
# spatial: long [dbl], lat [dbl], elev [dbl], name [chr], wmo_id [dbl]
  id      date      prcp  tmax  tmin
  <chr>    <date>    <dbl> <dbl> <dbl>
1 ASN00086038 2020-01-01     0  26.8  11
2 ASN00086038 2020-01-02     0  26.3  12.2
3 ASN00086038 2020-01-03     0  34.5  12.7
4 ASN00086038 2020-01-04     0  29.3  18.8
5 ASN00086038 2020-01-05    18  16.1  12.5
# i 25 more rows

R> class(ts_long)

[1] "temporal_cubble_df" "cubble_df"                  "tbl_ts"
[4] "tbl_df"              "tbl"                      "data.frame"
```

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The long cubble shows `[tsibble]` in the header to indicate the object also being in a `tbl_ts` class (`tsibble`). Methods applies to the `tbl_ts` class can also be applied to the temporal cubble objects, for example, checking whether the data contain temporal gaps:

```
R> ts_long %>% has_gaps()
```

```
# A tibble: 3 x 2
  id      .gaps
  <chr>   <lgl>
1 ASN00086038 FALSE
2 ASN00086077 FALSE
3 ASN00086282 FALSE
```

An existing `cubble` object can promote its temporal component to a `tsibble` object by applying `make_temporal_tsibble()`. The following code illustrates this with the object `cb_long` created in section 2.2 and the promoted cubble object is equal to the cubble object originally created from a `tsibble` object:

```
R> ts_long2 <- cb_long %>% make_temporal_tsibble()
R> identical(ts_long2, ts_long)
```

```
[1] TRUE
```

`sf`

Similarly, an `sf` object can be supplied as the spatial component to create a `cubble` object, with the `coords` argument being omitted. This opens up the possibility to represent fixed area with polygons or multipolygons (see Applications 4.1) and the `coords` argument will be calculated as the centroids of the (multi)polygons. The `[sf]` print in the cubble header suggest an spatial component being also a `sf` object:

```
R> (sf_nested <- make_cubble(
+   spatial = stations_sf, temporal = meteo,
+   key = id, index = date))

# cubble:  key: id [3], index: date, nested form, [sf]
# spatial:  [144.8321, -37.98, 145.0964, -37.6655], WGS 84
# temporal: date [date], prcp [dbl], tmax [dbl], tmin [dbl]
  id      elev name  wmo_id  long     lat      geometry ts
  <chr>   <dbl> <chr> <dbl> <dbl> <dbl>      <POINT [°]> <list>
1 ASN00086038  78.4 essen~  95866  145. -37.7 (144.9066 -37.7276) <tibble>
2 ASN00086077  12.1 moora~  94870  145. -38.0  (145.0964 -37.98)  <tibble>
3 ASN00086282 113. melbo~  94866  145. -37.7 (144.8321 -37.6655) <tibble>

R> class(sf_nested)
```

```
[1] "spatial_cubble_df" "cubble_df"           "sf"
[4] "tbl_df"            "tbl"                 "data.frame"
```

The `sf` functions applicable to a `cubble` object have been listed in Table 1 and the following code shows how to perform coordinate transformation with `st_transform` on a cubble object:

```
R> sf_nested %>% sf::st_transform(crs = "EPSG:3857")

# cubble: key: id [3], index: date, nested form, [sf]
# spatial: [16122635.6225205, -4576600.8687746, 16152057.3639371,
#   -4532279.35567565], WGS 84
# temporal: date [date], prcp [dbl], tmax [dbl], tmin [dbl]
#           id      elev name    wmo_id long   lat      geometry ts
# <chr>     <dbl> <chr> <dbl> <dbl> <dbl> <POINT [°]> <list>
1 ASN00086038 78.4 essen~ 95866 145. -37.7 (16130929 -4541016) <tibble>
2 ASN00086077 12.1 moora~ 94870 145. -38.0 (16152057 -4576601) <tibble>
3 ASN00086282 113. melbo~ 94866 145. -37.7 (16122636 -4532279) <tibble>
```

The counterpart to promote the spatial component in an existing `cubble` to be an `sf` object is `make_spatial_sf()`:

```
R> sf_nested <- cb_nested %>% make_spatial_sf()
R> all.equal(sf_nested, sf_nested)

[1] TRUE
```

2.5. Comparison to other spatio-temporal classes

Given the vast spatio-temporal data structure available in R to represent spatio-temporal data, this section compares and contrast the `cubble` with other existing alternative, namely `stars` and `sftime`.

The `stars` package (Pebesma 2021) uses an array structure, as oppose to tibble in the `cubble` package, to represent multivariate spatio-temporal data. While both packages support vector and raster data, it is a matter of choice on which structure to use given the application. Analysts working on satellite imageries may prefer the array structure while others originally working with spatio-temporal data in the 2D data frames may find `cubble` easier to adopt from their existing computing workflow.

The `sftime` package (Teickner *et al.* 2022) also builds from a tibble object, with a main focus to handle irregular spatio-temporal data. While `sftime` can also handle full space-time grids and sparse space-time layouts, `cubble` can be thought of as simplifying the repetition in spatial variables with two linked tibbles. This simplification gives memory efficiency when data is observed frequent, i.e. daily or subdaily, or the spatial geometry is expensive to repeat, i.e. polygons or multipolygons. Consider the `climate_aus` data in the `cubble` package with 639 stations observed daily in a single year 2020. The created `sftime` object is approximately 14 times larger than the corresponding `cubble` object (118.24 MB vs. 8.52 MB).

3. Other features and considerations

3.1. 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).

In **cubble**, data can be matched spatially or temporally with `match_spatial()` and `match_temporal()`. The function `match_spatial()` calculates the spatial distance between observations in two cubbles. Different distances are available with projected or unprojected coordinate reference system. Analysts can subset the number of matched group to output with argument `spatial_n_group` (by default 4 groups) and the number of match per group with argument `spatial_n_group` (by default 1, that is, one-to-one matching). The syntax to use `match_spatial()` is:

```
match_spatial(<cubble_obj1>, <cubble_obj2>, ...)
```

The function `match_temporal()` calculates the time series similarity between spatially matched groups. Two identifiers needs to be specified on the variable separates the each matched group (`match_id`) and the variable separates the two sources (`data_id`). The argument `temporal_by` uses the `by` syntax from `dplyr *_join` to specify the temporal matching variable.

The similarity score between two time series in the spatially matched group is calculated by a matching function, which analysts can customise. The matching function should take two time series in a list and output a single numerical score, which allows for interfacing with existing time series distance calculation implementation. By default, **cubble** implements a simple peak matching algorithm (`match_peak`) that counts the number of peaks in two time series that fall within a specified temporal window. The syntax to use `match_temporal()` is:

```
match_temporal(
  <cubble_obj_from_match_spatial>,
  data_id = ... , match_id = ... ,
  temporal_by = c("..." = "...")
)
```

3.2. Interactive graphics

The workflow with the **cubble** class works 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 2 illustrates how linking can be achieved between a map and multiple time series in a **cubble** object. 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

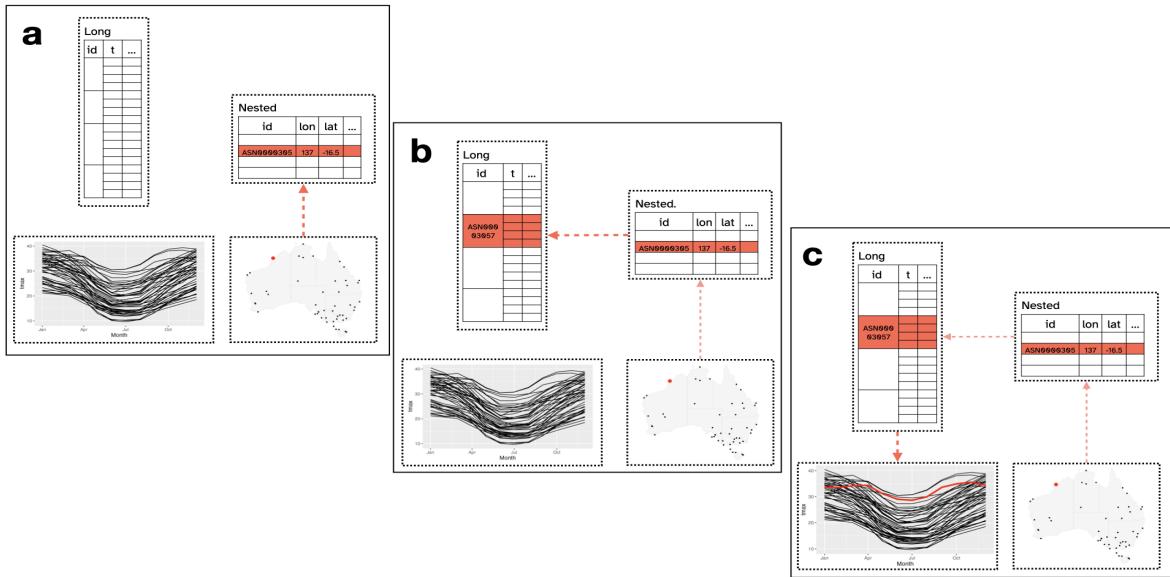


Figure 2: Linking between multiple plots. The line plots and the map are constructed from shared `crosstalk` objects (long and nested `cubicle`). When a station is selected on the map (a), the corresponding row in the nested `cubicle` will be activated. This will link to all the rows with the same id in the long `cubicle` (b) and update the line plot (c).

is highlighted (a). This activates a row in the nested `cubicle`, which is then communicated to the long `cubicle` – all the observations with the same id (b) will be selected. The long `cubicle` 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 `cubicle`. The corresponding rows in the nested `cubicle` are activated, and highlighted on 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.

3.3. Spatio-temporal transformations

Spatio-temporal data lends itself to a range of transformations. Glyph maps (Wickham *et al.* 2012) 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 combinations. Here we elaborate on the transformations made to produce a glyph map. The package **GGally** (Schloerke *et al.* 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)). A new implementation of the glyph map as a ggproto, `GeomGlyph`, has been made in the `cubicle` package so that a glyph map can be created with `geom_glyph()`:

```
R> data />
```

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

Some useful controls over the glyph map are also available in the `geom_glyph()` implementation

- polar coordinate glyph maps are specified using `polar = TRUE`,
- arguments `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`, and
 *reference boxes and lines can be added with geoms: `geom_glyph_box()` and `geom_glyph_line()`.

4. Applications

The five examples here are chosen to illustrate these aspects of the **cubble** package: creating a **cubble** object from two Coronavirus (COVID) data tables with the complication of differing location names, using spatial transformations to make a glyph map of seasonal temperature changes over years, 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. (The Appendix provides another example on aggregating information spatially to explore precipitation patterns.)

4.1. 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. Both the COVID count data (`covid`) and the LGA information (`lga`) are available in the **cubble** package with the `covid` data stored as a `tsibble` object, the `lga` data as an `sf` object.

The `make_cubble()` function is used to create a **cubble** object from the two spatial and temporal tables as described in Section 2.2. The `by` argument allows for mismatch of key names from the two tables in the `*_join()` by syntax:

```
R> cb <- make_cubble(lga, covid, by = c("lga_name_2018" = "lga"))

Warning: st_centroid assumes attributes are constant over geometries

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

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

! Use `check_key()` to check on the unmatched key
The cubble is created only with sites having both spatial and temporal information
```

The warning message reports on the mismatches of location from both sides: there are LGAs in the COVID data that do not match with LGAs names in the spatial polygon data, and vice versa. The `make_cubble()` function prompts the use of `check_key()` to identify the mismatches:

```
R> (check_res <- check_key(
+   spatial = lga, temporal = covid,
+   by = c("lga_name_2018" = "lga")
+ ))
```

\$paired

```
# A tibble: 78 x 2
  spatial      temporal
  <chr>        <chr>
  1 Alpine (S)  Alpine (S)
  2 Ararat (RC) Ararat (RC)
  3 Ballarat (C) Ballarat (C)
  4 Banyule (C) Banyule (C)
  5 Bass Coast (S) Bass Coast (S)
# i 73 more rows
```

\$potential_pairs

```
# A tibble: 2 x 2
  spatial      temporal
  <chr>        <chr>
  1 Kingston (C) (Vic.) Kingston (C)
  2 Latrobe (C) (Vic.) Latrobe (C)
```

\$others

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

\$others\$temporal

```
[1] "Interstate" "Overseas"    "Unknown"
```

The check result is a list with three elements: 1) matched pairs from both tables, 2) those pairs that can be potentially paired, and 3) others. Here the main mismatch comes from different encodings of two LGAs: Kingston and Latrobe. Analysts can then modify the input spatial and temporal data accordingly and create the bubble again:

```
R> lga2 <- lga />
+   rename(lga = lga_name_2018) />
+   mutate(lga = ifelse(lga == "Kingston (C) (Vic.)", "Kingston (C)", lga),
+         lga = ifelse(lga == "Latrobe (C) (Vic.)", "Latrobe (C)", lga)) />
+   filter(!lga %in% check_res$others$spatial)
R>
```

```
R> covid2 <- covid |> filter(!lga %in% check_res$others$temporal)
R>
R> (cb <- make_cubble(spatial = lga2, temporal = covid2))

# cubble:   key: lga [80], index: date, nested form, [sf]
# spatial:  [140.961682, -39.1591895, 149.976291, -33.9804256], WGS 84
# temporal: date [date], n [dbl], avg_7day [dbl]
# i 75 more rows
```

lga	long	lat	geometry	ts
1 Alpine (S)	147.	-36.9	<MULTIPOLYGON [°]>	<list>
2 Ararat (RC)	143.	-37.5	<MULTIPOLYGON [°]>	<list>
3 Ballarat (C)	144.	-37.5	<MULTIPOLYGON [°]>	<list>
4 Banyule (C)	145.	-37.7	<MULTIPOLYGON [°]>	<list>
5 Bass Coast (S)	146.	-38.5	<MULTIPOLYGON [°]>	<list>

4.2. Australian historical maximum temperature

The 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 237 Australian stations from ∞ through $-\infty$ 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 (NSW), using a glyph map.

First, the stations need to be filtered to those in Victoria and NSW 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. The NSW stations correspond to entries in the range 46-75 and the Victorian stations to 76-90. Filtering Victoria and NSW stations is a *spatial operation* and hence uses the nested `cubbble`:

```
R> tmax <- historical_tmax %>  
+   filter(between(as.numeric(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` 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(
+     yearmonth = tsibble::make_yearmonth(
+       year = ifelse(lubridate::year(date) > 2015, 2016, 1971),
```

```
+     month = lubridate::month(date))
+   )/|
+   summarise(tmax = mean(tmax, na.rm = TRUE)) %>%
+   mutate(group = as.factor(lubridate::year(yearmonth)),
+         month = lubridate::month(yearmonth))
```

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 the nested `cubicle` to operate on the spatial component over time, and then, move back into the long `cubicle` (to make the glyph map):

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

In order to create a glyph map displaying the monthly series (Figure 3), 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> ggplot() +
+   geom_sf(data = MAP_DATA, ...) +
+   geom_glyph(data = tmax,
+             aes(x_major = long, x_minor = month,
+                  y_major = lat, y_minor = tmax,
+                  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 use is included in the Appendix.

4.3. River levels and rainfall in Victoria

Bureau of Meteorology collects water data from river gauges and this includes variables: 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. Both `climate_vic` and `river` are cubicle objects and we can get a summary of the 10 closest pairs:

```
R> res_sp <- match_spatial(climate_vic, river, spatial_n_group = 10)
R> print(res_sp, n = 20)
```

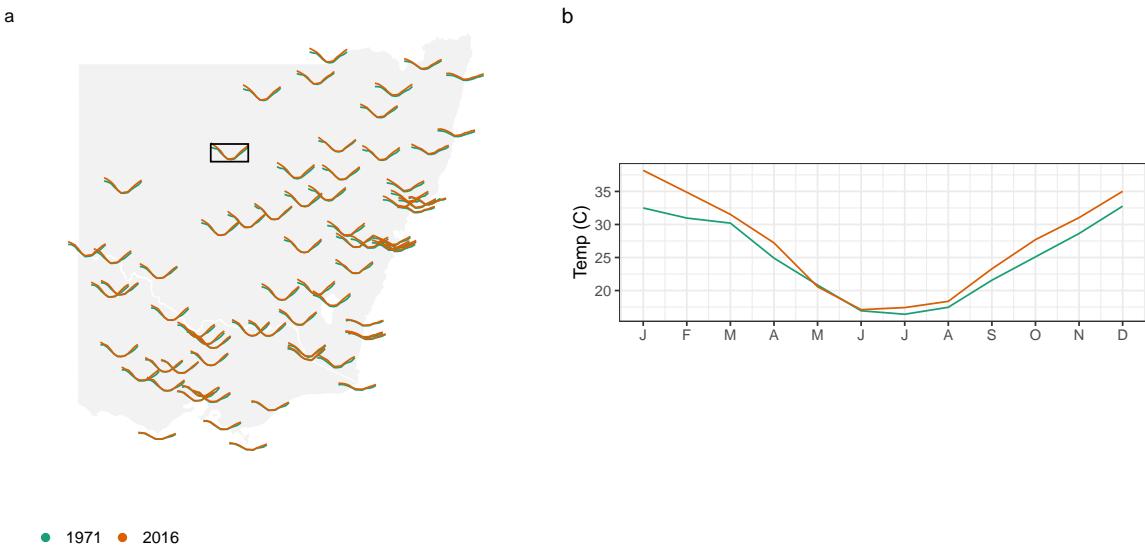


Figure 3: A glyph map of the monthly maximum average temperature for weather stations in Victoria and New South Wales (NSW) for the periods (1971-1975, 2016-2020). The corresponding average time series for the cobar station are display on the top left corner. From the glyph map we can observe that the 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 NSW.

```
# A tibble: 10 x 4
  from      to    dist group
  <chr>     <chr>   [m] <int>
1 ASN00088051 406213 1838.     1
2 ASN00084145 222201 2185.     2
3 ASN00085072 226027 3282.     3
4 ASN00080015 406704 4034.     4
5 ASN00085298 226027 4207.     5
6 ASN00082042 405234 6153.     6
7 ASN00086038 230200 6167.     7
8 ASN00086282 230200 6928.     8
9 ASN00085279 224217 7431.     9
10 ASN00080091 406756 7460.    10
```

The result can also be returned as cubble objects with argument `return_cubble = TRUE`. The output is a list where each element is a paired cubble object and you may consider combining all the results into a single cubble with `bind_rows()`. Care needs to be taken on in the case when a site is close to two stations since by construction, cubble require unique rows in the nested form. From the summary table above, river station 226027 is matched to more than one weather station: ASN00085072 (group 3) and ASN00085298 (group 5). (Similarly river station 230200 is matched in group 7 and 8). One can either deselect one pair before binding the results, or take the list and work with the `purrr::map` syntax:

```
R> res_sp <- match_spatial(
+   climate_vic, river,
+   spatial_n_group = 10, return_cubble = TRUE)
R> str(res_sp, max.level = 0)

List of 10

R> (res_sp <- res_sp[-c(5, 8)] %>% bind_rows())

# cubble: key: id [16], index: date, nested form, [sf]
# spatial: [144.5203, -38.144913, 148.4667, -36.128657], WGS 84
# temporal: date [date], prcp [dbl], tmax [dbl], tmin [dbl]
  id      long    lat elev name wmo_id ts      type           geometry
  <chr>  <dbl> <dbl> <dbl> <chr> <dbl> <list> <chr>           <POINT [°]>
1 ASN00~  145. -37.0 290  rede~  94859 <tibble> clim~ (144.5203 -37.0194)
2 406213  145. -37.0 NA    CAMP~   NA <tibble> river (144.5403 -37.01512)
3 ASN00~  148. -37.7 62.7 orbo~  95918 <tibble> clim~ (148.4667 -37.6922)
4 222201  148. -37.7 NA    SNOW~   NA <tibble> river (148.451 -37.70739)
5 ASN00~  147. -38.1  4.6 east~  94907 <tibble> clim~ (147.1322 -38.1156)
# i 11 more rows
# i 2 more variables: group <int>, dist [m]
```

For temporal matching, the variable water level (`Water_course_level`) from the river data will be matched to precipitation (`prcp`) in the weather station data. The variable identifying each matched group is `group` and the variable identifying the two datasets is `type`, and similarly, the cubble output can be returned with the argument `return_cubble = TRUE`. Here we select the four pairs with the highest number of matching peaks:

```
R> res_tm <- res_sp %>%
+   match_temporal(
+     data_id = type, match_id = group,
+     temporal_by = c("prcp" = "Water_course_level"),
+     return_cubble = TRUE)
R> (res_tm <- res_tm %>% bind_rows() %>% filter(group %in% c(1, 7, 6, 9)))

# cubble: key: id [8], index: date, nested form, [sf]
# spatial: [144.5203, -37.8817, 147.572223, -36.8472], WGS 84
# temporal: date [date], matched [dbl]
  id      long    lat elev name wmo_id type           geometry group
  <chr>  <dbl> <dbl> <dbl> <chr> <dbl> <chr>           <POINT [°]> <int>
1 ASN00088~  145. -37.0 290  rede~  94859 clim~ (144.5203 -37.0194)  1
2 406213    145. -37.0 NA    CAMP~   NA river (144.5403 -37.01512)  1
3 ASN00082~  146. -36.8 502  stra~  95843 clim~ (145.7308 -36.8472)  6
4 405234    146. -36.9 NA    SEVE~   NA river (145.6828 -36.88701)  6
5 ASN00086~  145. -37.7 78.4 esse~  95866 clim~ (144.9066 -37.7276)  7
# i 3 more rows
# i 3 more variables: dist [m], ts <list>, match_res <dbl>
```

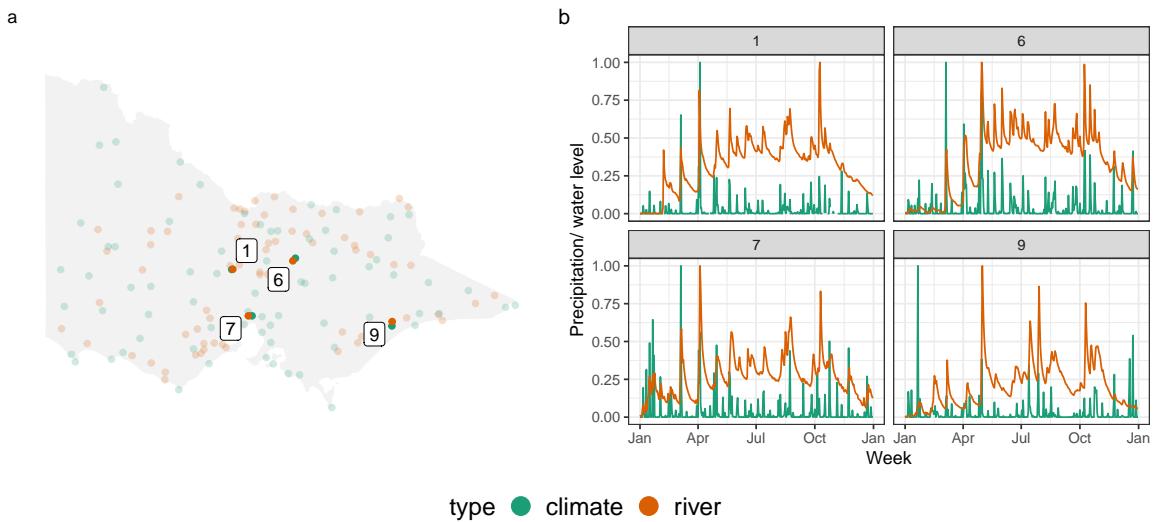


Figure 4: Weather stations and river gauges with matched pairs labelled on the map (a) and plotted across time (b). Precipitation and water level have been standardised between 0 and 1 to be displayed on the same scale. The water level reflects the increase in precipitation. The numbers (1, 7, 6, 9) indicate the group index derived from spatial matching, only those that were selected by temporal matching are shown here.

Figure 4 shows four matched pairs on the map (a) and standardized data as time series (b) with concurrent increasing.

4.4. ERA5: climate reanalysis data

Figure 5 reproduces the ERA5 data row of Figure 19 in Hersbach *et al.* (2020). Here we explain how this would be done using in the **cubble** package. 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 in Simmons *et al.* (2020) and 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 **ecmwfr** package (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 (**raw**) is first converted to a **cubble** object:

```
R> dt <- as_cubble(
+   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

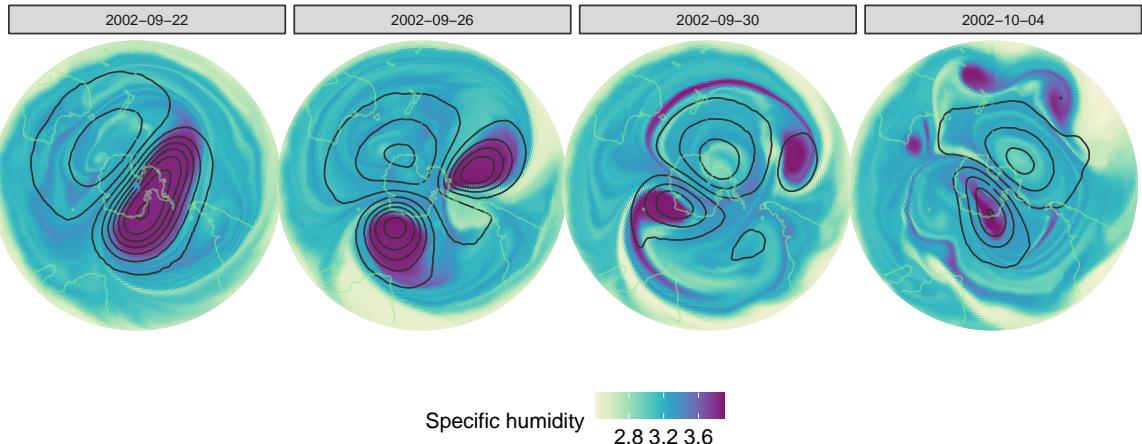


Figure 5: A reproduction of the second row (ERA5 data) of Figure 19 in Hersbach et al (2020) to illustrate the break-up of southern polar vortex in late September and early October 2002. The polar vortex, signalled by the high specific humidity, splits into two on 2002-09-26 and further splits into four on 2002-10-04.

the statistic of interest, which is plotted directly as a contour plot with `ggplot`. Code is provided to accomplish this in the supplementary material.

4.5. Interactive graphics

Interactive graphics can be useful because they make it possible to look at the data in multiple 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 the `cubicle` package with the `crosstalk` package 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 6 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")

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 constant

5. Conclusion

This paper presents an R package **cubble** for organizing, manipulating and visualizing spatio-temporal data. The package introduces a new data class 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 include 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](#)).

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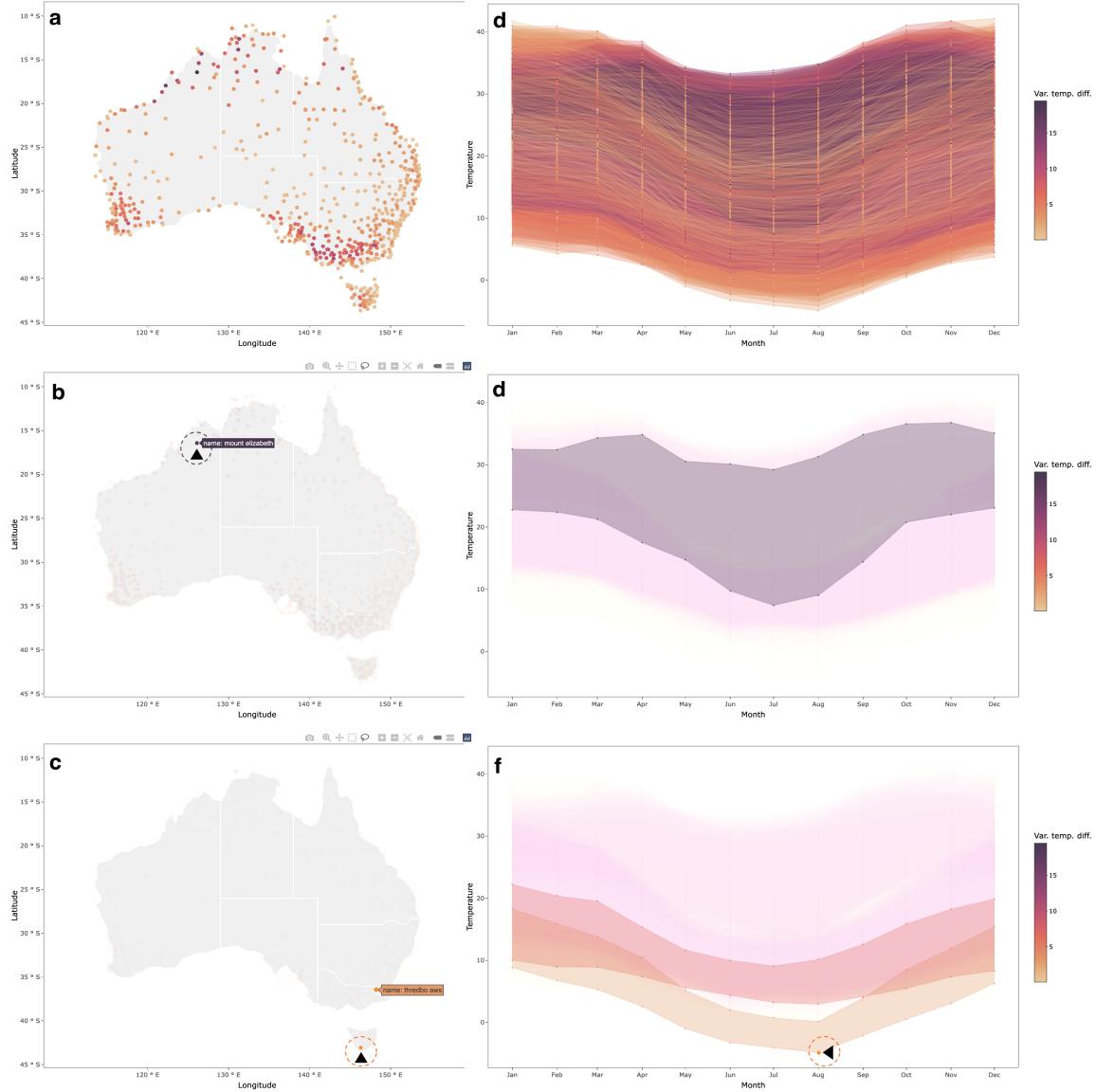


Figure 6: Exploring temperature variation using linking of a map and seasonal display. Each row is a screen dump of the process. The top row shows all locations and all temperature profiles. Selecting a particular location on the map (here Mount Elizabeth) produces the plot in the second row. The maximum 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). Another station, located in the Tasmania Island, is then selected to compare its temperature variation with the Thredbo station.

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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: dicook@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