

Classes and methods for spatio-temporal data in **R**: the spacetime package



ifgi
Institute for Geoinformatics
University of Münster

Edzer Pebesma

May 25, 2011

Abstract

This document describes a set of classes and methods for spatio-temporal data in R. It builds upon the classes and methods for spatial data taken from package **sp**, and all temporal classes supported by package **xts**. The goal is to cover a number of useful representations for spatio-temporal sensor data, or results from predicting (spatial and/or temporal interpolation or smoothing), aggregating, or subsetting them.

The goals of this package are to explore how spatio-temporal data can be sensibly represented in classes, and to find out which analysis and visualisation methods are useful and feasible for the classes implemented. It reuses existing classes, methods, and functions present in packages for spatial data (**sp**) and time series data (**zoo** and **xts**). Coercion to the appropriate reduced spatial and temporal classes is provided, as well as to **data.frame** objects in the obvious long or wide format.

Contents

1	Introduction	2
2	Space-time data in wide and long formats	3
3	Space-time layouts	4
3.1	Full space-time grid	5
3.2	Sparse space-time grid	5
3.3	Irregular space-time data.frame	5
4	Spatio-temporal full grid data.frames (STFDF)	5
4.1	Class definition	5
4.2	Coercion to data.frame	10
4.3	Coercion to matrix or objects of class xts	11
4.4	Attribute retrieval and replacement: [[and \$	11
4.5	Space and time selection with [.	12

5	Space-time sparse data.frames (STSDF)	15
5.1	Class definition	15
6	Spatio-temporal irregular data.frames (STIDF)	16
6.1	Class definition	16
6.2	Methods	17
7	Further methods: snapshot, history, coercion	18
7.1	<i>Snap</i> and <i>Hist</i>	18
7.2	Coercion between <i>STxxx</i> classes	19
8	Graphs of spatio-temporal data: stplot	20
8.1	stplot: panels, space-time plots, animation	20
8.2	Time series plots	20
9	Spatial footprint or support, time intervals	21
9.1	Time periods	21
9.2	Spatial support	21
10	Worked examples	21
10.1	North Carolina SIDS	22
10.2	Panel data	22
10.3	Interpolating Irish wind	23
10.4	Calculation of EOFs	26
10.5	Conversion from and to trip	27
10.6	Trajectory data: lttraj in adehabitatLT	29
10.7	Country shapes in cshapes	31

1 Introduction

Spatio-temporal data are abundant, and easily obtained. Examples are satellite images of parts of the earth, temperature readings for a number of nearby stations, election results for voting districts and a number of consecutive elections, GPS tracks for people or animals possibly with additional sensor readings, disease outbreaks or volcano eruptions.

Schabenberger and Gotway (2004) argue that analysis of spatio-temporal data often happens *conditionally*, meaning that either first the spatial aspect is analysed, after which the temporal aspects are analysed, or reversed, but not in a joint, integral modelling approach, where space and time are not separated. As a possible reason they mention the lack of good software, data classes and methods to handle, import, export, display and analyse such data. This R package is a start to fill this gap.

Spatio-temporall data are often relatively abundant in either space, or time, but not in both. Satellite imagery is typically very abundant in space, giving lots of detail in high spatial resolution for large areas, but relatively sparse in time. Analysis of repeated images over time may further be hindered by difference in light conditions, errors in georeferencing resulting in spatial mismatch, and changes in obscured areas due to changed cloud coverage. On the other side, data from fixed sensors give often very detailed signals over time, allowing for elaborate modelling, but relatively little detail in space because a very limited

number of sensors is available. The cost of an in situ sensor network typically depends primarily on its spatial density; the choice of the temporal resolution with which the sensors register signals may have little effect on total cost.

Although for example Botts et al. (2007) describe a number of open standards that allow the interaction with sensor data (describing sensor characteristics, requesting observed values, planning sensors, and processing raw sensed data to predefined events), the available statistical or GIS software for this is in an early stage, and scattered. This paper describes an attempt to combine available infrastructure in the R statistical environment to a set of useful classes and methods for manipulating, plotting and analysing spatio-temporal data. A number of case studies from different application areas will illustrate its use.

The current version of the package is experimental, class definitions and methods are subject to change.

We use `xts` for time, not only because it supports various basic types to represent type, but also because it has good tools for aggregation over time and a very flexible syntax to select time periods that adheres ISO 8601¹. We do not use the `xts` objects to store the spatio-temporal attribute information, as it is restricted to `matrix` objects, and hence can only store a single type, and not combine numeric and factor. Instead, as in the classes of `sp`, we use `data.frame` to store measured values. For information that is purely temporal, the `xts` objects can be used, and will be recycled appropriately when coercing to a long format `data.frame`.

2 Space-time data in wide and long formats

Spatio-temporal data for which each location has data for each time can be provided in two so-called **wide formats**. An example where a single column refers to a single moment in time is found in the North Carolina Sudden Infant Death Syndrome (sids) data set, which is in the **time wide format**:

```
> library(foreign)
> read.dbf(system.file("shapes/sids.dbf", package = "maptools"))[1:5,
+   c(5, 9:14)]
```

	NAME	BIR74	SID74	NWBIR74	BIR79	SID79	NWBIR79
1	Ashe	1091	1	10	1364	0	19
2	Alleghany	487	0	10	542	3	12
3	Surry	3188	5	208	3616	6	260
4	Currituck	508	1	123	830	2	145
5	Northampton	1421	9	1066	1606	3	1197

where **columns** refer to a particular **time**: `SID74` contains to the infant death syndrome cases for each county at a particular time period (1974-1978).

The Irish wind data, for which the first six records are

```
> data(wind, package = "gstat")
> wind[1:6, ]
```

¹see http://en.wikipedia.org/wiki/ISO_8601

	year	month	day	RPT	VAL	ROS	KIL	SHA	BIR	DUB	CLA	MUL	CLO
1	61	1	1	15.04	14.96	13.17	9.29	13.96	9.87	13.67	10.25	10.83	12.58
2	61	1	2	14.71	16.88	10.83	6.50	12.62	7.67	11.50	10.04	9.79	9.67
3	61	1	3	18.50	16.88	12.33	10.13	11.17	6.17	11.25	8.04	8.50	7.67
4	61	1	4	10.58	6.63	11.75	4.58	4.54	2.88	8.63	1.79	5.83	5.88
5	61	1	5	13.33	13.25	11.42	6.17	10.71	8.21	11.92	6.54	10.92	10.34
6	61	1	6	13.21	8.12	9.96	6.67	5.37	4.50	10.67	4.42	7.17	7.50
	BEL		MAL										
1	18.50		15.04										
2	17.54		13.83										
3	12.75		12.71										
4	5.46		10.88										
5	12.92		11.83										
6	8.12		13.17										

are in **space wide format**: each *column* refers to another wind measurement **location**, and the rows reflect a single time period; wind was reported as daily average wind speed in knots (1 knot = 0.5418 m/s).

Finally, panel data are shown in **long form**, where the full spatio-temporal information is held in a single column, and other columns denote location and time. In the *Produc* data set (Baltagi, 2001), a panel of 48 observations from 1970 to 1986, the first five records are

```
> data("Produc", package = "plm")
> Produc[1:5, ]
```

	state	year	pcap	hwy	water	util	pc	gsp	emp	unemp
1	ALABAMA	1970	15032.67	7325.80	1655.68	6051.20	35793.80	28418	1010.5	4.7
2	ALABAMA	1971	15501.94	7525.94	1721.02	6254.98	37299.91	29375	1021.9	5.2
3	ALABAMA	1972	15972.41	7765.42	1764.75	6442.23	38670.30	31303	1072.3	4.7
4	ALABAMA	1973	16406.26	7907.66	1742.41	6756.19	40084.01	33430	1135.5	3.9
5	ALABAMA	1974	16762.67	8025.52	1734.85	7002.29	42057.31	33749	1169.8	5.5

where the first two columns denote space and time (a default assumption in package *plm*), and e.g. *pcap* reflects private capital stock.

None of these examples documents has strongly *referenced* spatial or temporal information: it is from the data alone not clear whether the number 1970 refers to a year, or ALABAMA to a state, and where this is. Section ?? shows for each of these three cases how the data can be converted into classes with strongly referenced space and time information.

3 Space-time layouts

In the following we will use spatial location to denote a particular point, (set of) line(s), (set of) polygon(s), or pixel, for which one or more measurements are registered at particular moments in time.

Three layouts of space-time data have been implemented, along with convenience methods and coercion methods to get from one to the other. These will be introduced next.

3.1 Full space-time grid

A full space-time grid² of observations for spatial location (points, lines, polygons, grid cells) $s_i, i = 1, \dots, n$ and observation time $t_j, j = 1, \dots, m$ is obtained when the full set of $n \times m$ set of observations z_k is stored, with $k = 1, \dots, nm$. We choose to cycle spatial locations first, so observation k corresponds to location $s_i, i = ((k - 1) \% n) + 1$ and with time moment $t_j, j = ((k - 1)/n) + 1$, with / integer division and % integer division remainder (modulo). The t_j need to be in time order, as `xts` objects are used to store them.

In this data class (figure 1), for each location, the same temporal sequence of data is sampled. Alternatively one could say that for each moment in time, the same set of spatial entities is sampled. Unsourced combinations of (space, time) are stored in this class, but are assigned a missing value `NA`.

3.2 Sparse space-time grid

A sparse grid has the same general layout, with measurements laid out on a space time grid (figure 2), but instead of storing the full grid, only non-missing valued observations z_k are stored. For each k , an index $[i, j]$ is stored that refers which spatial location i and time point j the value belongs to. Storing data this way can be efficient if full space-time lattices have many missing values, or if a limited set of spatial locations each have different time instances (times of crime cases for a set of administrative regions), or if for a set of times the set of spatial locations varies (locations of crimes, registered per year).

3.3 Irregular space-time data.frame

Space-time irregular `data.frames` (STIDF, figure 3) are those where time and space points of measured values can have no organization: for each measured value the spatial location and time point is stored, as in the long format. This is equivalent to the most sparse grid where the index for observation k is $[k, k]$, and hence can be dropped. For these objects, $n = m$ equals the number of records. Locations and time points need not be unique, but will be replicated in case they are not.

4 Spatio-temporal full grid data.frames (STFDF)

For objects of class `STFDF`, time representation can be regular or irregular, as is supported by class `xts` in package `xts`. Spatial locations need to be of a class deriving from `Spatial` in package `sp`.

4.1 Class definition

```
> library(spacetime)
> showClass("ST")
```

```
Class "ST" [package "spacetime"]
```

```
Slots:
```

²note that neither locations nor time points need to be laid out in a regular sequence

STFDF (Space-time full data.frame) layout

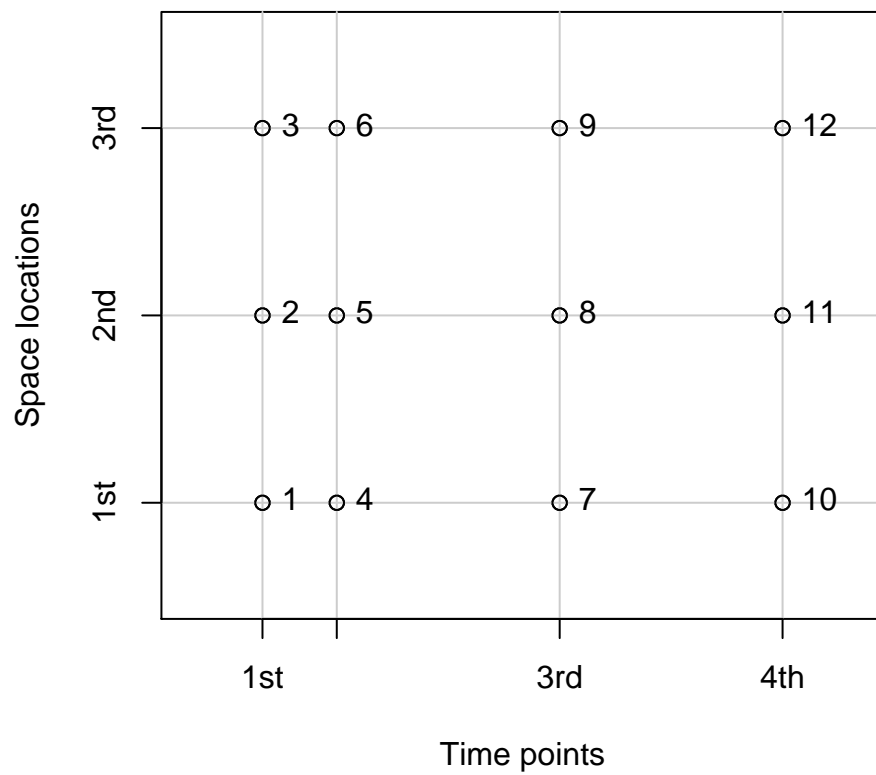


Figure 1: space-time layout of STFDF (STF: ST-Full) objects: all space-time combinations are stored; numbers refer to the ordering of rows in the `data.frame` with measured values: time is kept ordered, space cycles first

STSDF (Space-time sparse data.frame) layout

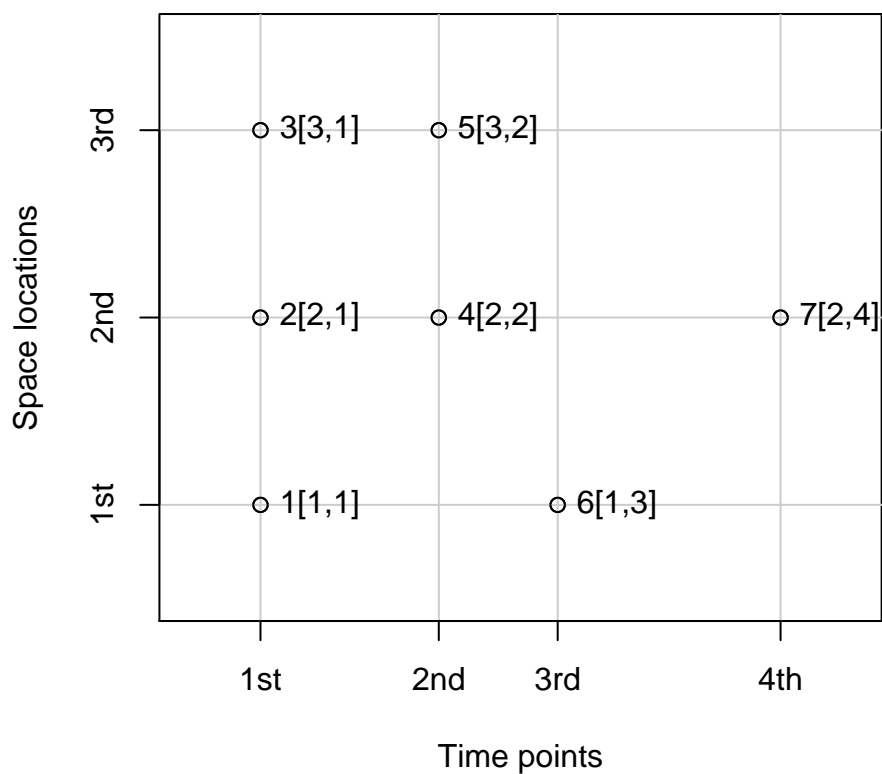


Figure 2: space-time layout of STSDF (STS: ST-Sparse) objects: only the non-missing part of the space-time combinations on a lattice are stored; numbers refer to the ordering of rows in the `data.frame`; an index is kept where `[3,4]` refers to the third item in the list of spatial locations and fourth item in the list of temporal points.

STIDF (Space–time irregular data.frame) layout

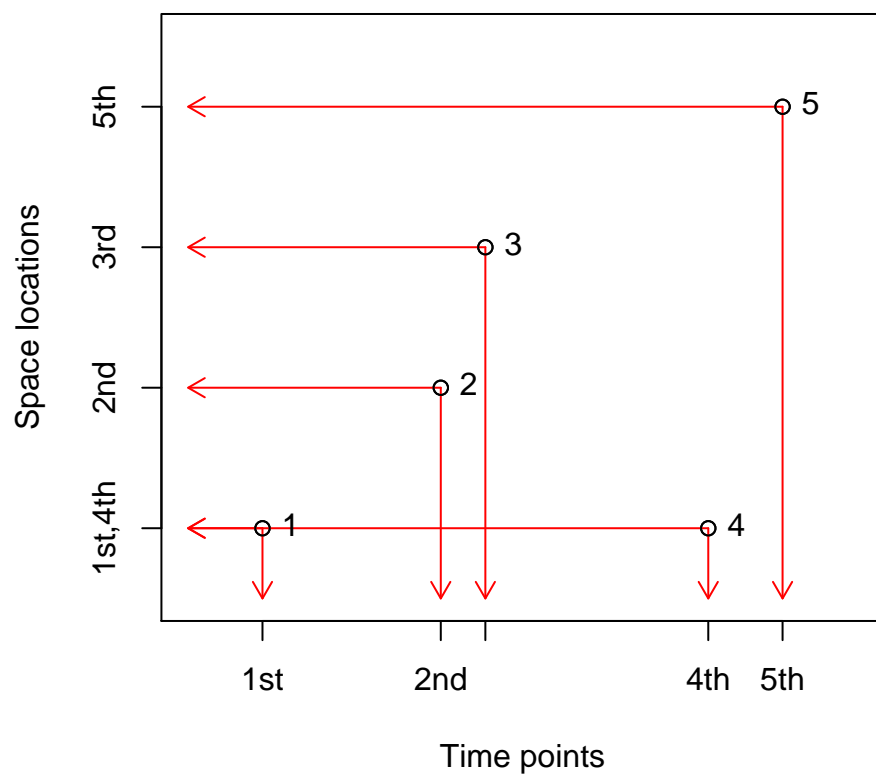


Figure 3: space-time layout of STIDF (STI: ST-Irregular) objects: each observation has its spatial location and time stamp stored; in this example, spatial location 1 is stored twice—observations 1 and 4 having the same location is not registered.


```
Name:      sp      time
Class: Spatial      xts
```

Known Subclasses:

```
Class "STS", directly
Class "STI", directly
Class "STF", directly
Class "STSDF", by class "STS", distance 2
Class "STIDF", by class "STI", distance 2
Class "STFDF", by class "STF", distance 2
Class "STIDFtraj", by class "STIDF", distance 3
```

```
> showClass("STFDF")
```

```
Class "STFDF" [package "spacetime"]
```

Slots:

```
Name:      data      sp      time
Class: data.frame  Spatial      xts
```

Extends:

```
Class "STF", directly
Class "ST", by class "STF", distance 2
```

```
> sp = cbind(x = c(0,0,1), y = c(0,1,1))
> row.names(sp) = paste("point", 1:nrow(sp), sep="")
> sp = SpatialPoints(sp)
> time = as.POSIXct("2010-08-05", tz = "GMT")+3600*(10:13)
> m = c(10,20,30) # means for each of the 3 point locations
> mydata = rnorm(length(sp)*length(time),mean=rep(m, 4))
> IDs = paste("ID",1:length(mydata), sep = "_")
> mydata = data.frame(values = signif(mydata,3), ID=IDs)
> stfdf = STFDF(sp, time, mydata)
> str(stfdf)
```

```
Formal class 'STFDF' [package "spacetime"] with 3 slots
..@ data:'data.frame':      12 obs. of  2 variables:
.. ..$ values: num [1:12] 8.39 19.7 29.5 9.57 19.5 31.6 8.51 18.3 30 10.2 ...
.. ..$ ID      : Factor w/ 12 levels "ID_1","ID_10",...: 1 5 6 7 8 9 10 11 12 2 ...
..@ sp :Formal class 'SpatialPoints' [package "sp"] with 3 slots
.. ..@ coords      : num [1:3, 1:2] 0 0 1 0 1 1
.. .. ..- attr(*, "dimnames")=List of 2
.. .. .. ..$ : chr [1:3] "point1" "point2" "point3"
.. .. .. ..$ : chr [1:2] "x" "y"
.. .. ..@ bbox      : num [1:2, 1:2] 0 0 1 1
.. .. ..- attr(*, "dimnames")=List of 2
.. .. .. ..$ : chr [1:2] "x" "y"
.. .. .. ..$ : chr [1:2] "min" "max"
.. .. ..@ proj4string:Formal class 'CRS' [package "sp"] with 1 slots
```

```

... ..@ projargs: chr NA
..@ time:An 'xts' object from 2010-08-05 10:00:00 to 2010-08-05 13:00:00 containing:
Data: int [1:4, 1] 1 2 3 4
Indexed by objects of class: [POSIXct,POSIXt] TZ: GMT
xts Attributes:
NULL

```

4.2 Coercion to data.frame

The following coercion function creates a **data.frame** using both the S3 (to set row.names) and S4 “as()” method. It gives data in the long format, meaning that time and space are replicated appropriately:

```
> as.data.frame(stfdf, row.names = IDs)
```

	V1	V2	sp.ID	time	timedata	values	ID
ID_1	0	0	point1	2010-08-05 10:00:00	1	8.39	ID_1
ID_2	0	1	point2	2010-08-05 10:00:00	1	19.70	ID_2
ID_3	1	1	point3	2010-08-05 10:00:00	1	29.50	ID_3
ID_4	0	0	point1	2010-08-05 11:00:00	2	9.57	ID_4
ID_5	0	1	point2	2010-08-05 11:00:00	2	19.50	ID_5
ID_6	1	1	point3	2010-08-05 11:00:00	2	31.60	ID_6
ID_7	0	0	point1	2010-08-05 12:00:00	3	8.51	ID_7
ID_8	0	1	point2	2010-08-05 12:00:00	3	18.30	ID_8
ID_9	1	1	point3	2010-08-05 12:00:00	3	30.00	ID_9
ID_10	0	0	point1	2010-08-05 13:00:00	4	10.20	ID_10
ID_11	0	1	point2	2010-08-05 13:00:00	4	19.80	ID_11
ID_12	1	1	point3	2010-08-05 13:00:00	4	29.70	ID_12

```
> as(stfdf, "data.frame")[1:4, ]
```

	V1	V2	sp.ID	time	timedata	values	ID
1	0	0	point1	2010-08-05 10:00:00	1	8.39	ID_1
2	0	1	point2	2010-08-05 10:00:00	1	19.70	ID_2
3	1	1	point3	2010-08-05 10:00:00	1	29.50	ID_3
4	0	0	point1	2010-08-05 11:00:00	2	9.57	ID_4

Note that **sp.ID** denotes the ID of the spatial location; coordinates are shown for point, pixel or grid cell centre locations; in case locations refer to lines or polygons, the line’s start coordinate and coordinate centre of weight are given, respectively, as the coordinate values in this representation.

For a single attribute, we can obtain a **data.frame** object if we properly unstack the column, giving the data in both its wide formats when in addition we apply transpose **t()**:

```
> unstack(stfdf)
```

	point1	point2	point3
2010-08-05 10:00:00	8.39	19.7	29.5
2010-08-05 11:00:00	9.57	19.5	31.6
2010-08-05 12:00:00	8.51	18.3	30.0
2010-08-05 13:00:00	10.20	19.8	29.7

```

> t(unstack(stfdf))

      2010-08-05 10:00:00 2010-08-05 11:00:00 2010-08-05 12:00:00
point1           8.39                9.57                8.51
point2           19.70               19.50               18.30
point3           29.50               31.60               30.00
      2010-08-05 13:00:00
point1           10.2
point2           19.8
point3           29.7

> unstack(stfdf, which = 2)

              point1 point2 point3
2010-08-05 10:00:00  ID_1  ID_2  ID_3
2010-08-05 11:00:00  ID_4  ID_5  ID_6
2010-08-05 12:00:00  ID_7  ID_8  ID_9
2010-08-05 13:00:00 ID_10 ID_11 ID_12

```

4.3 Coercion to matrix or objects of class xts

We can coerce an object of class STFDF to an xts if we select a single numeric attribute:

```

> as(stfdf[, , "values"], "xts")

              point1 point2 point3
2010-08-05 10:00:00  8.39  19.7  29.5
2010-08-05 11:00:00  9.57  19.5  31.6
2010-08-05 12:00:00  8.51  18.3  30.0
2010-08-05 13:00:00 10.20  19.8  29.7

```

An xts object is a matrix, with time increasing over rows.

4.4 Attribute retrieval and replacement: [[and \$

We can define the [[and \$ retrieval and replacement methods for all classes deriving from ST at once. Here are some examples:

```

> stfdf[[1]]

[1]  8.39 19.70 29.50  9.57 19.50 31.60  8.51 18.30 30.00 10.20 19.80 29.70

> stfdf[["values"]]

[1]  8.39 19.70 29.50  9.57 19.50 31.60  8.51 18.30 30.00 10.20 19.80 29.70

> stfdf[["newVal"]] = rnorm(12)
> stfdf$ID

[1] ID_1 ID_2 ID_3 ID_4 ID_5 ID_6 ID_7 ID_8 ID_9 ID_10 ID_11 ID_12
Levels: ID_1 ID_10 ID_11 ID_12 ID_2 ID_3 ID_4 ID_5 ID_6 ID_7 ID_8 ID_9

```

```
> stfdf$ID = paste("OldIDs", 1:12, sep = "")
> stfdf$NewID = paste("NewIDs", 12:1, sep = "")
> stfdf
```

An object of class "STFDF"

Slot "data":

	values	ID	newVal	NewID
1	8.39	OldIDs1	0.86245698	NewIDs12
2	19.70	OldIDs2	-0.29796297	NewIDs11
3	29.50	OldIDs3	-0.76773964	NewIDs10
4	9.57	OldIDs4	0.04596959	NewIDs9
5	19.50	OldIDs5	-0.08149826	NewIDs8
6	31.60	OldIDs6	-0.24624728	NewIDs7
7	8.51	OldIDs7	-1.93071740	NewIDs6
8	18.30	OldIDs8	0.35722410	NewIDs5
9	30.00	OldIDs9	-1.28504273	NewIDs4
10	10.20	OldIDs10	0.16816120	NewIDs3
11	19.80	OldIDs11	0.17924852	NewIDs2
12	29.70	OldIDs12	0.38945970	NewIDs1

Slot "sp":

SpatialPoints:

	x	y
point1	0	0
point2	0	1
point3	1	1

Coordinate Reference System (CRS) arguments: NA

Slot "time":

	[,1]
2010-08-05 10:00:00	1
2010-08-05 11:00:00	2
2010-08-05 12:00:00	3
2010-08-05 13:00:00	4

4.5 Space and time selection with [

The idea behind the `[` method for classes in `sp` was that objects would behave as much as possible similar to a matrix or `data.frame` – this is one of the stronger intuitive areas of R syntax. A construct like `a[i,j]` selects row(s) `i` and column(s) `j`. In `sp`, rows were taken as the spatial entities (points, lines, polygons, pixels) and rows as the attributes. This convention was broken for objects of class `SpatialGridDataFrame`, where `a[i,j,k]` would select the k -th attribute of the spatial grid selection with spatial grid row(s) `i` and column(s) `j`.

For spatio-temporal data, `a[i,j,k]` selects spatial entity/entities `i`, temporal entity/entities `j`, and attribute(s) `k`:

example:

```
> stfdf[,1] # SpatialPointsDataFrame
```

	coordinates	values	ID	newVal	NewID
1	(0, 0)	8.39	OldIDs1	0.8624570	NewIDs12
2	(0, 1)	19.70	OldIDs2	-0.2979630	NewIDs11
3	(1, 1)	29.50	OldIDs3	-0.7677396	NewIDs10

```
> stfdf[, ,1]
```

An object of class "STFDF"

Slot "data":

	values
1	8.39
2	19.70
3	29.50
4	9.57
5	19.50
6	31.60
7	8.51
8	18.30
9	30.00
10	10.20
11	19.80
12	29.70

Slot "sp":

SpatialPoints:

	x	y
point1	0	0
point2	0	1
point3	1	1

Coordinate Reference System (CRS) arguments: NA

Slot "time":

	[,1]
2010-08-05 10:00:00	1
2010-08-05 11:00:00	2
2010-08-05 12:00:00	3
2010-08-05 13:00:00	4

```
> stfdf[1, ,1] # xts
```

	values
2010-08-05 10:00:00	8.39
2010-08-05 11:00:00	9.57
2010-08-05 12:00:00	8.51
2010-08-05 13:00:00	10.20

```
> stfdf[, , "ID"]
```

An object of class "STFDF"

Slot "data":

ID

```

1   OldIDs1
2   OldIDs2
3   OldIDs3
4   OldIDs4
5   OldIDs5
6   OldIDs6
7   OldIDs7
8   OldIDs8
9   OldIDs9
10  OldIDs10
11  OldIDs11
12  OldIDs12

Slot "sp":
SpatialPoints:
      x y
point1 0 0
point2 0 1
point3 1 1
Coordinate Reference System (CRS) arguments: NA

Slot "time":
      [,1]
2010-08-05 10:00:00    1
2010-08-05 11:00:00    2
2010-08-05 12:00:00    3
2010-08-05 13:00:00    4

> stfdf[1,,"values", drop = FALSE] # stays STFDF:

An object of class "STFDF"
Slot "data":
      values
1      8.39
4      9.57
7      8.51
10     10.20

Slot "sp":
SpatialPoints:
      x y
point1 0 0
Coordinate Reference System (CRS) arguments: NA

Slot "time":
      [,1]
2010-08-05 10:00:00    1
2010-08-05 11:00:00    2
2010-08-05 12:00:00    3
2010-08-05 13:00:00    4

```

```

> stfdf[,1, drop=FALSE] #stays STFDF

An object of class "STFDF"
Slot "data":
      values      ID      newVal      NewID
1    8.39 OldIDs1  0.8624570 NewIDs12
2   19.70 OldIDs2 -0.2979630 NewIDs11
3   29.50 OldIDs3 -0.7677396 NewIDs10

Slot "sp":
SpatialPoints:
      x y
point1 0 0
point2 0 1
point3 1 1
Coordinate Reference System (CRS) arguments: NA

Slot "time":
      ..1
2010-08-05 10:00:00 1

```

Clearly, unless `drop=FALSE`, selecting a single time or single location object results in an object that is no longer spatio-temporal; see also section 7.

5 Space-time sparse data.frames (STSDf)

Space-time sparse `data.frames` have a layout over a grid, meaning that particular times and locations are typically present more than once, but only the data for the time/location combinations are stored. An index keeps the link between the measured values in the data entries (rows), and the locations and times.

5.1 Class definition

```

> showClass("STSDf")

Class "STSDf" [package "spacetime"]

Slots:

Name:      data      index      sp      time
Class: data.frame  matrix  Spatial  xts

Extends:
Class "STS", directly
Class "ST", by class "STS", distance 2

```

In this class, index is an $n \times 2$ matrix. If in this index row i has entry $[j, k]$, it means that the i -th row in the data slot corresponds to location j and time k .

6 Spatio-temporal irregular data.frames (STIDF)

Space-time irregular `data.frames` store for each data record the location and time. No index is kept. Location and time need not be organized. Data are stored such that time is ordered (as it is an `xts` object).

6.1 Class definition

```
> showClass("STIDF")

Class "STIDF" [package "spacetime"]

Slots:

Name:      data      sp      time
Class: data.frame   Spatial    xts

Extends:
Class "STI", directly
Class "ST", by class "STI", distance 2

Known Subclasses: "STIDFtraj"

> sp = expand.grid(x = 1:3, y = 1:3)
> row.names(sp) = paste("point", 1:nrow(sp), sep="")
> sp = SpatialPoints(sp)
> time = as.POSIXct("2010-08-05", tz = "GMT")+3600*(11:19)
> m = 1:9 * 10 # means for each of the 9 point locations
> mydata = rnorm(length(sp), mean=m)
> IDs = paste("ID", 1:length(mydata))
> mydata = data.frame(values = signif(mydata,3), ID=IDs)
> stidf = STIDF(sp, time, mydata)
> stidf

An object of class "STIDF"
Slot "data":
      values   ID
1    10.4 ID 1
2    19.7 ID 2
3    30.2 ID 3
4    39.4 ID 4
5    50.6 ID 5
6    60.6 ID 6
7    69.6 ID 7
8    80.9 ID 8
9    88.9 ID 9

Slot "sp":
SpatialPoints:
      x y
[1,] 1 1
```



```

[2,] 2 1
[3,] 3 1
[4,] 1 2
[5,] 2 2
[6,] 3 2
[7,] 1 3
[8,] 2 3
[9,] 3 3
Coordinate Reference System (CRS) arguments: NA

```

```

Slot "time":
              [,1]
2010-08-05 11:00:00    1
2010-08-05 12:00:00    2
2010-08-05 13:00:00    3
2010-08-05 14:00:00    4
2010-08-05 15:00:00    5
2010-08-05 16:00:00    6
2010-08-05 17:00:00    7
2010-08-05 18:00:00    8
2010-08-05 19:00:00    9

```

6.2 Methods

Selection takes place with the [method:

```
> stidf[1:2, ]
```

An object of class "STIDF"

Slot "data":

```

  values  ID
1  10.4 ID 1
2  19.7 ID 2

```

Slot "sp":

SpatialPoints:

```

      x y
[1,] 1 1
[2,] 2 1

```

Coordinate Reference System (CRS) arguments: NA

```

Slot "time":
              [,1]
2010-08-05 11:00:00    1
2010-08-05 12:00:00    2

```

7 Further methods: snapshot, history, coercion

7.1 *Snap* and *Hist*

A time snapshot (Galton, 2004) to a particular moment in time can be obtained through selecting a particular time moment:

```
> stfdf[, time[3]]
```

	coordinates	values	ID	newVal	NewID
10	(0, 0)	10.2	OldIDs10	0.1681612	NewIDs3
11	(0, 1)	19.8	OldIDs11	0.1792485	NewIDs2
12	(1, 1)	29.7	OldIDs12	0.3894597	NewIDs1

by default, a simplified object of the underlying `Spatial` class for this particular time is obtained (`drop=TRUE`); if we specify `drop = FALSE`, the class will not be changed:

```
> class(stfdf[, time[3]])
```

```
[1] "SpatialPointsDataFrame"
```

```
attr(,"package")
```

```
[1] "sp"
```



```
> class(stfdf[, time[3], drop = FALSE])
```

```
[1] "STFDF"
```

```
attr(,"package")
```

```
[1] "spacetime"
```

A time series (or *history*, according to Galton, 2004) for a single particular location is obtained by selecting this location, e.g.

```
> stfdf[1, , "values"]
```

	values
2010-08-05 10:00:00	8.39
2010-08-05 11:00:00	9.57
2010-08-05 12:00:00	8.51
2010-08-05 13:00:00	10.20

Again, the class is not reduced to the simpler when `drop = FALSE` is specified:

```
> class(stfdf[1, ])
```

```
[1] "xts" "zoo"
```



```
> class(stfdf[1, drop = FALSE])
```

```
[1] "STFDF"
```

```
attr(,"package")
```

```
[1] "spacetime"
```

For objects of class `STIDF`, `drop = TRUE` results in a `Spatial` object when a single time value is selected.

7.2 Coercion between *STxxx* classes

Coercion from full to sparse and/or irregular space-time `data.frames`, we can use as:

```
> class(stfdf)

[1] "STFDF"
attr(,"package")
[1] "spacetime"

> class(as(stfdf, "STSDF"))

[1] "STSDF"
attr(,"package")
[1] "spacetime"

> class(as(as(stfdf, "STSDF"), "STIDF"))

[1] "STIDF"
attr(,"package")
[1] "spacetime"

> class(as(stfdf, "STIDF"))

[1] "STIDF"
attr(,"package")
[1] "spacetime"
```

On our way back, the reverse coercion takes place:

```
> x = as(stfdf, "STIDF")
> class(as(x, "STSDF"))

[1] "STSDF"
attr(,"package")
[1] "spacetime"

> class(as(as(x, "STSDF"), "STFDF"))

[1] "STFDF"
attr(,"package")
[1] "spacetime"

> class(as(x, "STFDF"))

[1] "STFDF"
attr(,"package")
[1] "spacetime"

> xx = as(x, "STFDF")
> identical(stfdf, xx)

[1] TRUE
```

8 Graphs of spatio-temporal data: `stplot`

8.1 `stplot`: panels, space-time plots, animation

The `stplot` method can create a few specialized plot types for the classes in the `spacetime` package. They are:

multi-panel plots In this form, for each time step (selected) a map is plotted in a separate panel, and the strip above the panel indicates the time step. The panels share x- and y-axis, no space is lost by separating white space, and a common legend is used. An example for gridded data is shown in figure 6. The `stplot` is a wrapper around `spplot` in package `sp`, and inherits most of its options.

space-time plots space-time plots show data in a space-time cross section, with e.g. space on the x-axis and time on the y-axis. An example on the sea surface temperature data in Cressie and Wikle (2011) is obtained by

```
> demo(CressieWikle)
```

Obviously, such plots only make sense for full space-time lattices, i.e. objects of class `STFDF`. To obtain such a plot, the arguments `mode` and `scaleX` should be considered; some special care is needed when the x- or y-axis needs to be plotted instead of the spatial index (1...n); details are found in the `stplot` documentation.

animated plots Animation is another way of displaying change over time; a sequence of `spplots`, one for each time step, is looped over when the parameter `animate` is set to a positive value (indicating the time in seconds to pause between subsequent plots).

8.2 Time series plots

Time series plots are a fairly common type of plot in R. For instance package `xts` has a plot method that, surprisingly, only allows univariate time series to be plotted. Many (if not most) plot routines in R support time to be along the x- or y-axis. The plot in figure 7 was generated by the following code:

```
> library(lattice)
> library(RColorBrewer)
> b = brewer.pal(12,"Set3")
> par.settings = list(superpose.symbol = list(col = b, fill = b),
+                     superpose.line = list(col = b),
+                     fontsize = list(text=9))
> print(xyplot(values ~ time, groups = sp.ID, as.data.frame(w),
+             type='l', auto.key=list(space="right"),
+             xlab = "1961", ylab = expression(sqrt(speed)),
+             par.settings = par.settings))
```

9 Spatial footprint or support, time intervals

9.1 Time periods

Time series structures available in R have, explicitly or implicitly, for each record a time stamp, not a time interval. The implicit assumption seems to be (i) the time stamp is a moment, (ii) this indicates either the real moment of measurement / registration, or the start of the interval over which something is aggregated (summed, averaged, maximized). For financial "Open, high, low, close" data, the "Open" and "Close" refer to the values at the moments the stock exchange opens and closes, meaning time instances, whereas "high" and "low" are aggregated values – the minimum and maximum price over the time interval between opening and closing times.

According to [ISO 8601:2004](#), a time stamp like "2010-05" refers to *the full* month of May, 2010, and so reflects a time period rather than a moment. As a selection criterion, `xts` will include everything inside the following interval:

```
> .parseISO8601("2010-05")

$first.time
[1] "2010-05-01 CEST"

$last.time
[1] "2010-05-31 23:59:59 CEST"
```

and this syntax lets one define, unambiguously, yearly, monthly, daily, hourly or minute intervals, but not e.g. 10- or 30-minute intervals; for some particular ten minute interval, the full specification is needed:

```
> .parseISO8601("2010-05-01T13:30/2010-05-01T13:39")

$first.time
[1] "2010-05-01 13:30:00 CEST"

$last.time
[1] "2010-05-01 13:39:59 CEST"
```

9.2 Spatial support

All examples above work with spatial points, i.e. data having a point support. The assumption of data having points support is implicit. For polygons, the assumption will be that values reflect aggregates over the polygon. For gridded data, it is ambiguous whether the value at the grid cell centre is meant (e.g. for DEM data) or an aggregate over the grid cell (typical for remote sensing imagery).

10 Worked examples

This section shows how existing data in various formats can be converted into ST classes, and how they can be analysed and/or visualised.

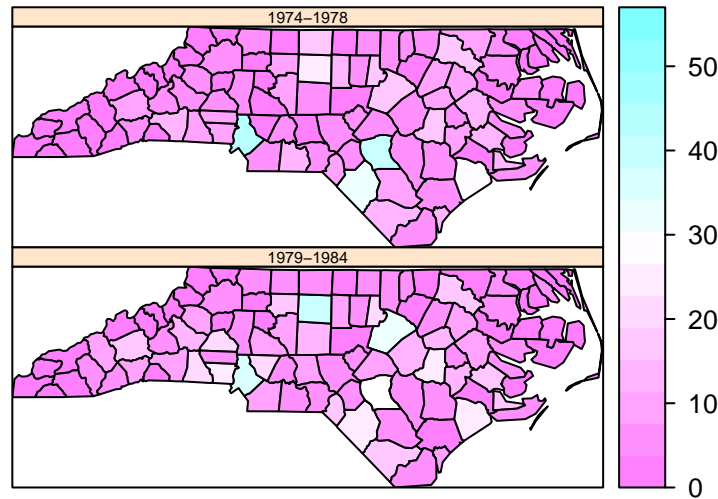


Figure 4: North Carolina sudden infant death syndrome (sids) data

10.1 North Carolina SIDS

As an example, the North Carolina Sudden Infant Death Syndrome (sids) data in package `maptools` will be used; they are sparse in time (aggregated to 2 periods of unequal length, according to the documentation in package `spdep`), but have polygons in space. Figure 4 shows the plot generated.

```
> library(maptools)
> fname = system.file("shapes/sids.shp", package = "maptools")[1]
> nc = readShapePoly(fname, proj4string = CRS("+proj=longlat +datum=NAD27"))
> data = data.frame(BIR = c(nc$BIR74, nc$BIR79), NWBIR = c(nc$NWBIR74,
+ nc$NWBIR79), SID = c(nc$SID74, nc$SID79))
> time = as.POSIXct(strptime(c("1974-01-01", "1979-01-01"), "%Y-%m-%d"),
+ tz = "GMT")
> nct = STFDF(sp = as(nc, "SpatialPolygons"), time = time, data = data)
> stplot(nct[, , "SID"], c("1974-1978", "1979-1984"))
```

10.2 Panel data

The panel data discussed in section 2 are imported as a full ST data.frame (STFDF), and linked to the proper state polygons of maps. Both `Produc` and the states in package `maps` order states alphabetically; the only thing to watch out for is that the former does not include District of Columbia, but the latter does (record 8):

```
> library(maps)
> states.m = map('state', plot=FALSE, fill=TRUE)
> IDs <- sapply(strsplit(states.m$names, ":"), function(x) x[1])
```

```

> library(maptools)
> states = map2SpatialPolygons(states.m, IDs=IDs)
> library(plm)
> data(Produc)
> yrs = 1970:1986
> time = as.POSIXct(paste(yrs, "-01-01", sep=""), tz = "GMT")
> # deselect District of Columbia, polygon 8, which is not present in Produc:
> Produc.st = STFDF(states[-8], time, Produc[order(Produc[2], Produc[1]),])
> stplot(Produc.st[,,"unemp"], yrs)

```

(The plot itself was omitted for reasons of file size.) Time and state were not removed from the data table on construction; printing these data as a `data.frame` confirms that time and state were matched correctly. The `plm` routines can be used on the data, back transformed to a `data.frame`, when `index` is specified (the first two columns from the back-transformed data no longer contain state and year):

```

> zz <- plm(log(gsp) ~ log(pcap) + log(pc) + log(emp) + unemp,
+ data = as.data.frame(Produc.st), index = c("state", "year"))
> summary(zz)

```

Oneway (individual) effect Within Model

Call:

```

plm(formula = log(gsp) ~ log(pcap) + log(pc) + log(emp) + unemp,
     data = as.data.frame(Produc.st), index = c("state", "year"))

```

Balanced Panel: n=48, T=17, N=816

Residuals :

	Min.	1st Qu.	Median	3rd Qu.	Max.
	-0.12000	-0.02370	-0.00204	0.01810	0.17500

Coefficients :

	Estimate	Std. Error	t-value	Pr(> t)
log(pcap)	-0.02614965	0.02900158	-0.9017	0.3675
log(pc)	0.29200693	0.02511967	11.6246	< 2.2e-16 ***
log(emp)	0.76815947	0.03009174	25.5273	< 2.2e-16 ***
unemp	-0.00529774	0.00098873	-5.3582	1.114e-07 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Total Sum of Squares: 18.941

Residual Sum of Squares: 1.1112

R-Squared : 0.94134

Adj. R-Squared : 0.88135

F-statistic: 3064.81 on 4 and 764 DF, p-value: < 2.22e-16

10.3 Interpolating Irish wind

This worked example is a modified version of the analysis presented in `demo(wind)` of package `gstat`. This demo is rather lengthy and reproduces much of the origi-

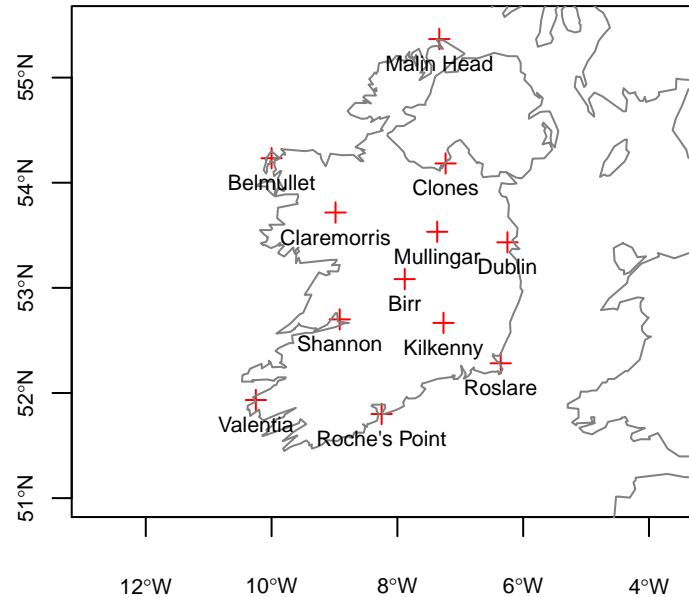


Figure 5: Station locations for Irish wind data

nal analysis in Haslett and Raftery (1989). Here, we will reduce the intermediate plots and focus on the use of spatio-temporal classes.

First, we will load the wind data from package `gstat`. It has two tables, station locations in a `data.frame`, called `wind.loc`, and daily wind speed in `data.frame` `wind`. We now convert character representation (such as 51d56'N) to proper numerical coordinates, and convert the station locations to a `SpatialPointsDataFrame` object. A plot of these data is shown in figure 6.

```
> library(gstat)
> data(wind)
> wind.loc$y = as.numeric(char2dms(as.character(wind.loc[["Latitude"]]))))
> wind.loc$x = as.numeric(char2dms(as.character(wind.loc[["Longitude"]]))))
> coordinates(wind.loc) = ~x + y
> proj4string(wind.loc) = "+proj=longlat +datum=WGS84"
```

The first thing to do with the wind speed values is to reshape these data. Unlike the North Carolina SIDS data of section 10.1, for this data space is sparse and time is rich, and so the data in `data.frame` `wind` come in space wide form with stations time series in columns:


```
> wind[1:3, ]
```

	year	month	day	RPT	VAL	ROS	KIL	SHA	BIR	DUB	CLA	MUL	CLO
1	61	1	1	15.04	14.96	13.17	9.29	13.96	9.87	13.67	10.25	10.83	12.58
2	61	1	2	14.71	16.88	10.83	6.50	12.62	7.67	11.50	10.04	9.79	9.67
3	61	1	3	18.50	16.88	12.33	10.13	11.17	6.17	11.25	8.04	8.50	7.67

	BEL	MAL
1	18.50	15.04
2	17.54	13.83
3	12.75	12.71

We will recode the time columns to an appropriate time data structure, and subtract a smooth time trend of daily means:

```
> wind$time = ISOdate(wind$year + 1900, wind$month, wind$day)
> wind$jday = as.numeric(format(wind$time, "%j"))
> stations = 4:15
> windsqrt = sqrt(0.5148 * wind[stations])
> Jday = 1:366
> daymeans = apply(sapply(split(windsqrt - mean(windsqrt), wind$jday),
+   mean), 2, mean)
> meanwind = lowess(daymeans ~ Jday, f = 0.1)$y[wind$jday]
> velocities = apply(windsqrt, 2, function(x) {
+   x - meanwind
+ })
```

Next, we will match the wind data to its location, and project the longitude/latitude coordinates and country boundary to the appropriate UTM zone:

```
> # order locations to order of columns in wind;
> # connect station names to location coordinates
> wind.loc = wind.loc[match(names(wind[4:15]), wind.loc$Code),]
> pts = coordinates(wind.loc[match(names(wind[4:15]), wind.loc$Code),])
> rownames(pts) = wind.loc$Station
> pts = SpatialPoints(pts)
> # convert to utm zone 29, to be able to do interpolation in
> # proper Euclidian (projected) space:
> proj4string(pts) = "+proj=longlat +datum=WGS84"
> library(rgdal)
> utm29 = CRS("+proj=utm +zone=29 +datum=WGS84")
> pts = spTransform(pts, utm29)
> # construct from space-wide table:
> w = stConstruct(velocities, space = list(values = 1:ncol(velocities)),
+   time = wind$time, SpatialObj = pts)
> library(maptools)
> m = map2SpatialLines(
+   map("worldHires", xlim = c(-11,-5.4), ylim = c(51,55.5), plot=F))
> proj4string(m) = "+proj=longlat +datum=WGS84"
> m = spTransform(m, utm29)
> # setup grid
> grd = SpatialPixels(SpatialPoints(makegrid(m, n = 300)),
```

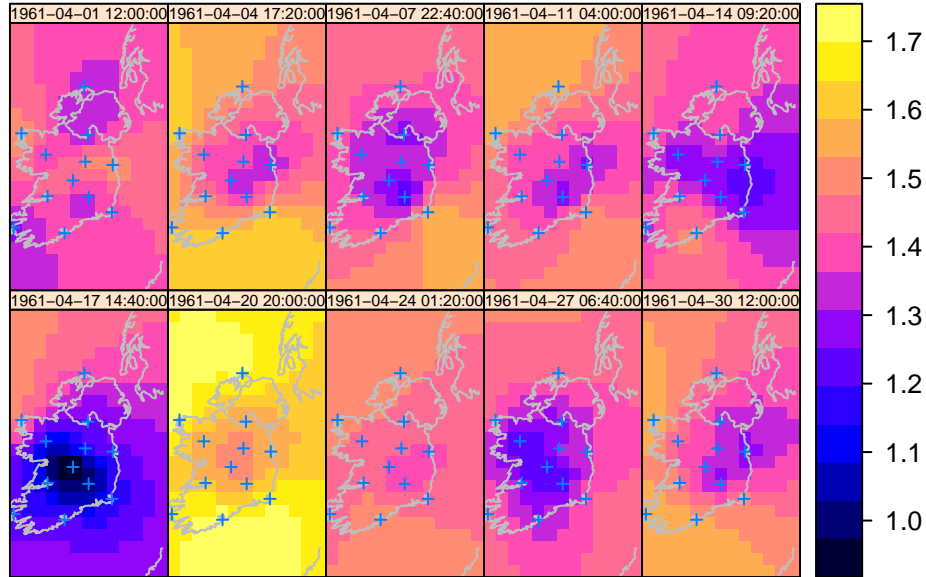


Figure 6: Space-time interpolations of wind (square root transformed, de-trended) over Ireland using a separable product covariance model, for 10 time points regularly distributed over the month for which daily data was considered (April, 1961)

```
+      proj4string = proj4string(m))
> # select april 1961:
> w = w[, "1961-04"]
> # 10 prediction time points, evenly spread over this month:
> n = 10
> tgrd = xts(1:n, seq(min(index(w)), max(index(w)), length=n))
> # separable covariance model, exponential with ranges 750 km and 1.5 day:
> v = list(space = vgm(0.6, "Exp", 750000), time = vgm(1, "Exp", 1.5 * 3600 * 24))
> pred = krigeST(sqrt(values)~1, w, STF(grd, tgrd), v)
> wind.ST = STFDF(grd, tgrd, data.frame(sqrt_speed = pred))
```

the results of which are shown in figure 6, created with `stplot`.

10.4 Calculation of EOFs

Empirical orthogonal functions from `STFDF` objects can be computed in spatial form (default):

```
> eof.sp = EOF(wind.ST)
```

or in temporal form by:

```
> eof.xts = EOF(wind.ST, "temporal")
```

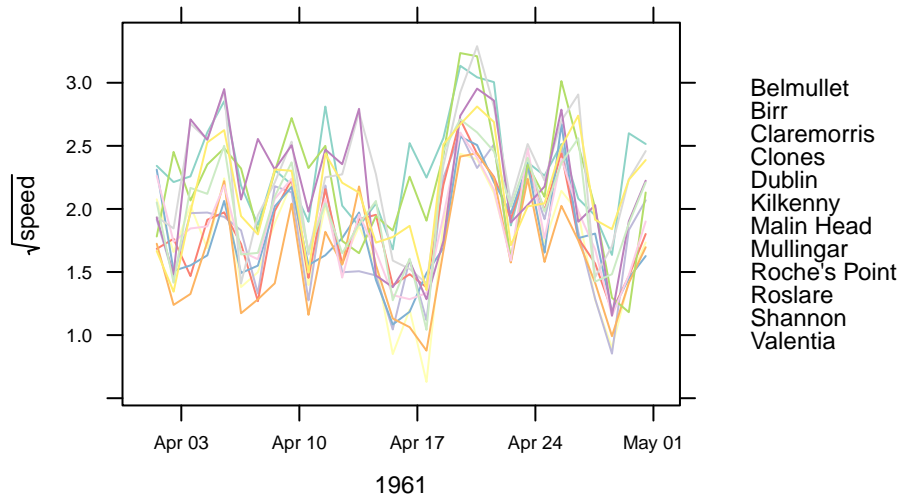


Figure 7: Time series plot of daily wind speed at 12 stations, used for interpolation in figure 6

the resulting object is of the appropriate `Spatial` subclass (`SpatialGrid`, `SpatialPolygons` etc.) in the spatial form, or of class `xts` in the temporal form. Figure 8 shows the 10 spatial EOFs obtained from the interpolated wind data of figure 6.

10.5 Conversion from and to trip

Objects of class `trip` (Sumner, 2010) extend objects of class `SpatialPointsDataFrame` by indicating in which attribute columns time and trip ID are, in slot `TOR.columns`. To not lose this information (in particular, which column contains the IDs), we will extend class `STIDF` to retain this info.

Currently it does assume that time in a `trip` object is in order, as `xts` will order it anyhow:

```
> library(diveMove)
> library(trip)
> locs = readLocs(gzfile(system.file(file.path("data", "sealLocs.csv.gz"),
+   package = "diveMove")), idCol = 1, dateCol = 2, dtformat = "%Y-%m-%d %H:%M:%S",
+   classCol = 3, lonCol = 4, latCol = 5, sep = ";")
> ringy = subset(locs, id == "ringy" & !is.na(lon) & !is.na(lat))
> coordinates(ringy) = ringy[c("lon", "lat")]
> tr = trip(ringy, c("time", "id"))
> setAs("trip", "STIDFtraj", function(from) {
+   from$burst = from[[from@TOR.columns[2]]]
+   time = from[[from@TOR.columns[1]]]
+   new("STIDFtraj", STIDF(as(from, "SpatialPoints"), time, from@data))
+ })
```

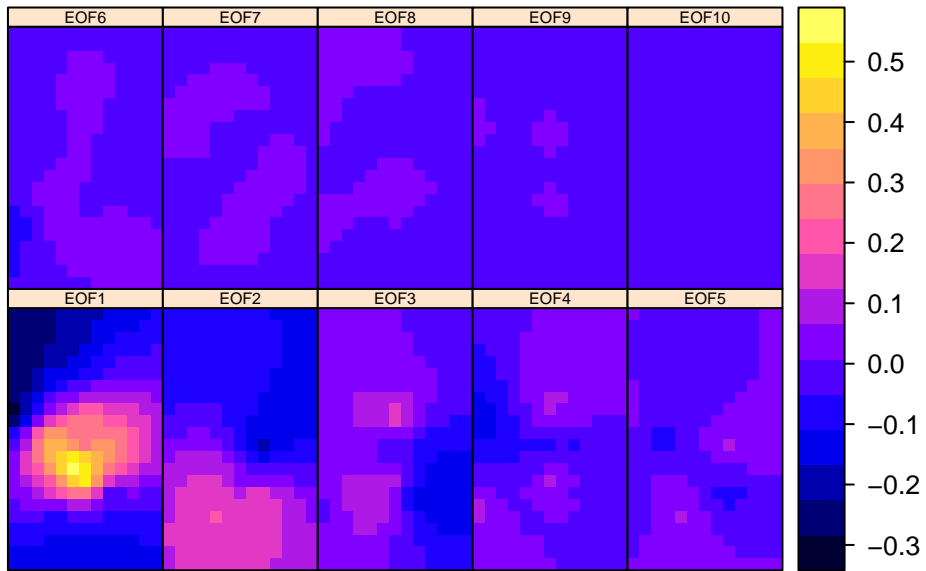


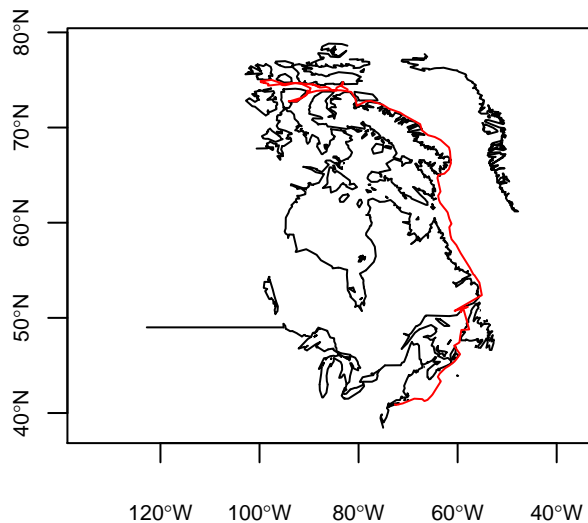
Figure 8: EOFs of space-time interpolations of wind over Ireland (for spatial reference, see figure 6), for the 10 time points at which daily data was chosen above (April, 1961)

```

> x = as(tr, "STIDFtraj")
> m = map2SpatialLines(map("world", xlim = c(-100, -50), ylim = c(40,
+ 77), plot = F))
> proj4string(m) = "+proj=longlat +datum=WGS84"
> plot(m, axes = TRUE, cex.axis = 0.7)
> plot(x, add = TRUE, col = "red")
> setAs("STIDFtraj", "trip", function(from) {
+   from$time = index(from$time)
+   trip(SpatialPointsDataFrame(from@sp, from@data), c("time",
+   "burst"))
+ })
> y = as(x, "trip")
> y$burst = NULL
> all.equal(y, tr, check.attributes = FALSE)

[1] TRUE

```



10.6 Trajectory data: `ltraj` in `adehabitatLT`

Trajectory objects of class `ltraj` are lists of bursts, sets of sequentially, connected space-time points at which an object is registered. When converting a list to a single STIDF object, the ordering is according to time, and the subsequent objects become unconnected. In the coercion back to `ltraj`, based on ID and burst the appropriate bursts are restored. A simple plot is obtained by:

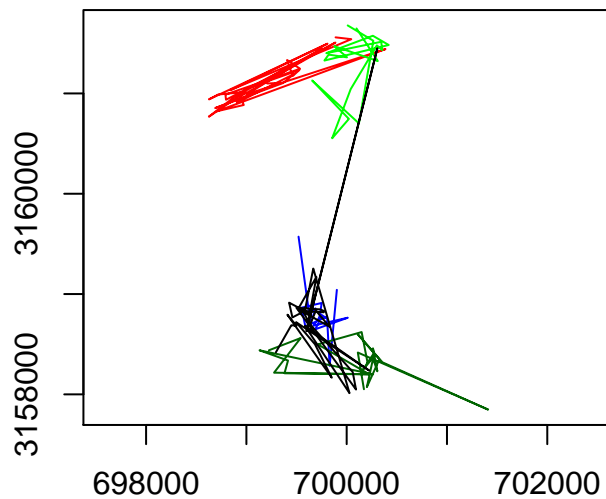
```

> library(adehabitatLT)
> # from: adehabitat/demo/managltraj.r
> # demo(managltraj)
> data(puechabonsp)
> # locations:
> locs = puechabonsp$relocs
> xy = coordinates(locs)
> ### Conversion of the date to the format POSIX
> da = as.character(locs$Date)
> da = as.POSIXct(strptime(as.character(locs$Date), "%y%m%d"), tz = "GMT")
> ## object of class "ltraj"
> ltr = as.ltraj(xy, da, id = locs$Name)
> foo = function(dt) dt > 100*3600*24
> ## The function foo returns TRUE if dt is longer than 100 days
> ## We use it to cut ltr:
> l2 = cutltraj(ltr, "foo(dt)", nextr = TRUE)
> stidfTrj = as(l2, "STIDFtraj")
> ltr0 = as(stidfTrj, "ltraj")
> all.equal(l2, ltr0, check.attributes = FALSE)

[1] TRUE

> plot(stidfTrj, col = c("red", "green", "blue", "darkgreen", "black"),
+      axes=TRUE)

```



A more complicated plot is shown in figure 9, obtained by the command

```
> stplot(stidfTrj, by = "time*id")
```

the output of which is shown in figure 9.

10.7 Country shapes in cshapes

The `cshapes` package contains a GIS dataset of country boundaries (1946-2008), and includes functions for data extraction and the computation of weights matrices. The data set consist of a `SpatialPolygonsDataFrame`, with the following attributes:

```
> library(cshapes)
> cs = cshp()
> names(cs)

[1] "CNTRY_NAME" "AREA"      "CAPNAME"    "CAPLONG"    "CAPLAT"
[6] "FEATUREID"  "COWCODE"    "COWSYEAR"    "COWSMONTH"  "COWSDAY"
[11] "COWEYEAR"   "COWEMONTH"  "COWEDAY"    "GWCODE"     "GWSYEAR"
[16] "GWSMONTH"   "GWSDAY"     "GWEYEAR"    "GWEMONTH"   "GWEDAY"
[21] "ISONAME"    "ISO1NUM"    "ISO1AL2"    "ISO1AL3"
```

where two data bases are used, "COW" (correlates of war project, 2008), and "GW" Gleditsch and Ward (1999). The attributes COWSMONTH and COWE-MONTH denote the start month and end month, respectively, according to the COW data base.

To select the country boundaries corresponding to a particular date and system, one can use

```
> cshp.2002 <- cshp(date = as.Date("2002-6-30"), useGW = TRUE)
```

In the following fragment, an unordered list of times `t` is passed on to `STIDF`, and this will cause the geometries and attributes to be reordered (in the order of `t`):

```
> t = as.POSIXct(strptime(paste(cs$COWSYEAR, cs$COWSMONTH, cs$COWSDAY,
+   sep = "-"), "%Y-%m-%d"), tz = "GMT")
> st = STIDF(geometry(cs), t, as.data.frame(cs))
> pt = SpatialPoints(cbind(7, 52), CRS(proj4string(cs)))
> as.data.frame(st[pt, , 1:5])
```

	V1	V2	sp.ID	time	timedata	CNTRY_NAME	AREA
1	9.41437	50.57623	188	1955-05-05	188	Germany Federal Republic	247366.4
2	10.38084	51.09070	187	1990-10-03	187	Germany	356451.5
	CAPNAME	CAPLONG	CAPLAT				
1	Bonn	7.1	50.73333				
2	Berlin	13.4	52.51667				

Acknowledgements

Michael Sumner provided helpful comments on the trip example. Members from the spatio-temporal modelling lab of the institute for geoinformatics of the University of Muenster contributed in useful discussions.

Brock	Brock	Brock	Brock	Brock	Brock
time	time	time	time	time	time
Calou	Calou	Calou	Calou	Calou	Calou
time	time	time	time	time	time
Chou	Chou	Chou	Chou	Chou	Chou
time	time	time	time	time	time
Jean	Jean	Jean	Jean	Jean	Jean
time	time	time	time	time	time

Figure 9: trajectories, by id (rows) and time (columns)

References

- Baltagi B (2001). *Econometric Analysis of Panel Data*. John Wiley and Sons, 3rd edition. (see <http://www.wiley.com/legacy/wileychi/baltagi/>)
- Botts, M., Percivall, G., Reed, C., and Davidson, J., 2007. OGC Sensor Web Enablement: Overview And High Level Architecture. Technical report, Open Geospatial Consortium. http://portal.opengeospatial.org/files/?artifact_id=25562
- Calenge, C., S. Dray, M. Royer-Carenzi (2008). The concept of animals' trajectories from a data analysis perspective. *Ecological informatics* 4, 34-41.
- Cressie, N., C. Wikle, 2011. *Statistics for spatio-temporal data*. Wiley, NY.
- Croissant Y., G. Millo, 2008. Panel Data Econometrics in R: The plm Package. *Journal of Statistical Software*, 27(2). <http://www.jstatsoft.org/v27/i02/>.
- Galton, A. (2004). Fields and Objects in Space, Time and Space-time. *Spatial cognition and computation* 4(1).
- Gütting, R.H., M. Schneider, 2005. *Moving Objects Databases*. Morgan Kaufmann Publishers.
- Haslett, J. and Raftery, A. E., 1989. Space-time Modelling with Long-memory Dependence: Assessing Ireland's Wind Power Resource (with Discussion). *Applied Statistics* 38, 1-50.
- Schabenberger, O., and Gotway, C.A., 2004. *Statistical methods for spatial data analysis*. Boca Raton: Chapman and Hall.
- Sumner, M., 2010. The tag location problem. Unpublished PhD thesis, Institute of Marine and Antarctic Studies University of Tasmania, September 2010.
- Correlates of War Project. 2008. State System Membership List, v2008.1. Online, <http://correlatesofwar.org/>
- Gleditsch, Kristian S., Michael D. Ward. 1999. Interstate System Membership: A Revised List of the Independent States since 1816. *International Interactions* 25: 393-413. Online, <http://privatwww.essex.ac.uk/~ksg/statelist.html>