

Spatial data analysis & visualisation in R

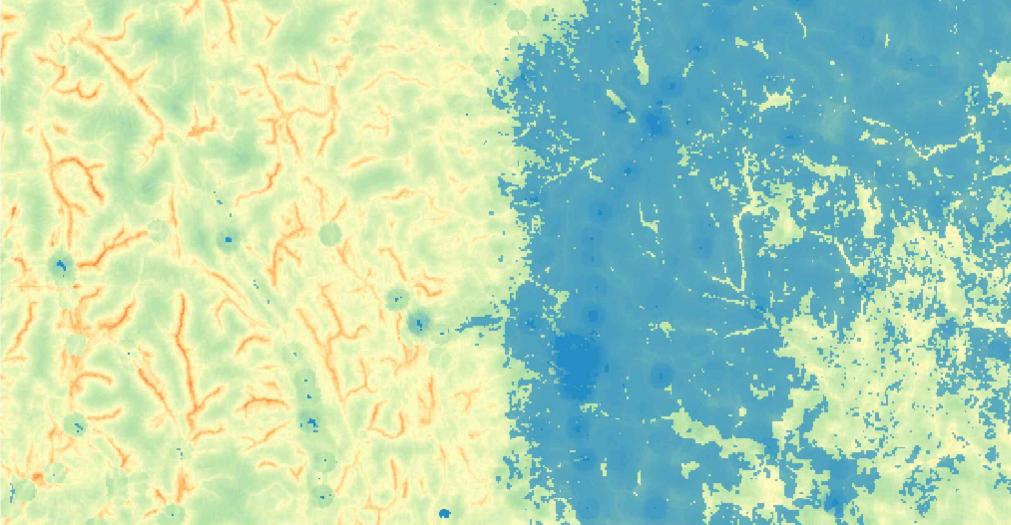
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April 8, 2021



Introduction to GIS & Spatial Analysis in R



Instructor: Marie-Hélène Burle (*Research Computing Training Assistant, WestGrid*)

April 26, 10am-2pm
(1 hr lunch break included)

Cost: Free
Workshop Venue: Zoom

Register Here: <https://www.eventbrite.ca/e/introduction-to-gis-spatial-analysis-in-r-registration-148848631263>

Learn the basics of GIS and spatial analysis using R!

This workshop is an introduction to the fundamentals of GIS in R. You will learn how to import, handle, and analyze spatial data in R and how to create static and interactive maps. The workshop will focus on the new generation of packages: sf, raster, and tmap.

No prior knowledge of the topic is required, but some basic experience with R is highly recommended.

You will be given access to an RStudio server, so no prior local installation is needed.

Workshop Topics: basics of spatial data, introduction to key packages, fundamentals of spatial coding, basic map making.

The workshop is being organized by UBC's Biodiversity Research Centre. Please Contact Matt Mitchell (mattthew.mitchell@ubc.ca) for more information if required.

Great resources

Open GIS data

[Free GIS Data](#) : list of free GIS datasets

Books

[Geocomputation with R](#) by Robin Lovelace, Jakub Nowosad & Jannes Muenchow

[Spatial Data Science](#) by Edzer Pebesma & Roger Bivand

[Spatial Data Science with R](#) by Robert J. Hijmans

[Using Spatial Data with R](#) by Claudia A. Engel

Tutorial

[An Introduction to Spatial Data Analysis and Visualisation in R](#) by the CDRC

Website

[r-spatial](#) by Edzer Pebesma, Marius Appel & Daniel Nüst

CRAN package list

[Analysis of Spatial Data](#)

Mailing list

[R Special Interest Group on using Geographical data and Mapping](#)

Data

For this webinar, we will use:

- the Alaska as well as the Western Canada & USA subsets of the [Randolph Glacier Inventory](#) version 6.0¹
- the [USGS time series of the named glaciers of Glacier National Park](#)²
- the Alaska as well as the Western Canada & USA subsets of the [consensus estimate for the ice thickness distribution of all glaciers on Earth dataset](#)³

The datasets can be downloaded as zip files from these websites.

1. RGI Consortium (2017). Randolph Glacier Inventory – A Dataset of Global Glacier Outlines: Version 6.0: Technical Report, Global Land Ice Measurements from Space, Colorado, USA. Digital Media. DOI: <https://doi.org/10.7265/N5-RGI-60>.
2. Fagre, D.B., McKeon, L.A., Dick, K.A. & Fountain, A.G., 2017, Glacier margin time series (1966, 1998, 2005, 2015) of the named glaciers of Glacier National Park, MT, USA: U.S. Geological Survey data release. DOI: <https://doi.org/10.5066/F7P26WB1>.
3. Farinotti, Daniel, 2019, A consensus estimate for the ice thickness distribution of all glaciers on Earth - dataset, Zurich. ETH Zurich. DOI: <https://doi.org/10.3929/ethz-b-000315707>.

Basemap

We will use data from [Natural Earth](#), a public domain map dataset.

This dataset can be accessed directly from within R thanks to the packages `rnatuearth` (provides the functions) & `rnatuearthdata` (provides the data).

Packages

Packages need to be installed before they can be loaded in a session.

Packages on CRAN can be installed with:

```
install.packages("package-name")
```

`basemaps` is not on CRAN and needs to be installed from GitHub thanks to `devtools`:

```
install.packages("devtools")
devtools::install_github("16EAGLE/basemaps")
```

Packages

```
library(sf)                      # spatial vector data manipulation
library(tmap)                     # map production & tiled web map
library(dplyr)                    # non GIS specific (tabular data manipulation)
library(magrittr)                 # non GIS specific (pipes)
library(purrr)                    # non GIS specific (functional programming)
library(rnaturalearth)            # basemap data access functions
library(rnaturalearthdata)         # basemap data
library(mapview)                  # tiled web map
library(grid)                     # (part of base R) used to create inset map
library(ggmap)                    # download basemap data
library(ggplot2)                  # alternative to tmap for map production
library(basemaps)                 # download basemap data
library(raster)                   # gridded spatial data manipulation
```

sf

Package for spatial vector data

Reading in data

Download and unzip `02_rgi60_WesternCanadaUS` & `01_rgi60_Alaska` from the [Randolph Glacier Inventory](#) version 6.0.

Data get imported and turned into `sf` objects with the function `sf::st_read()`:

```
ak <- st_read("01_rgi60_Alaska")
wes <- st_read("02_rgi60_WesternCanadaUS")
```

Make sure to use the absolute paths or the paths relative to your working directory (which can be obtained with `getwd()`)

Reading in data

```
> Reading layer '01_rgi60_Alaska' using driver 'ESRI Shapefile'  
Simple feature collection with 27108 features and 22 fields  
geometry type:  POLYGON  
dimension:        XY  
bbox:             xmin: -176.1425 ymin: 52.05727 xmax: -126.8545 ymax: 69.35167  
geographic CRS: WGS 84  
> Reading layer '02_rgi60_WesternCanadaUS' using driver 'ESRI Shapefile'  
Simple feature collection with 18855 features and 22 fields  
geometry type:  MULTIPOLYGON  
dimension:       XY  
bbox:             xmin: -133.7324 ymin: 36.38625 xmax: -105.6082 ymax: 65.15664  
geographic CRS: WGS 84
```

First look at the data

```
> ak

Simple feature collection with 27108 features and 22 fields

geometry type:  POLYGON
dimension:      XY
bbox:           xmin: -176.1425 ymin: 52.05727 xmax: -126.8545 ymax: 69.35167
geographic CRS: WGS 84

First 10 features:

    RGIId      GLIMSID BgnDate EndDate   CenLon   CenLat O1Region
1  RGI60-01.00001 G213177E63689N 20090703 -9999999 -146.8230 63.68900      1
2  RGI60-01.00002 G213332E63404N 20090703 -9999999 -146.6680 63.40400      1
3  RGI60-01.00003 G213920E63376N 20090703 -9999999 -146.0800 63.37600      1
4  RGI60-01.00004 G213880E63381N 20090703 -9999999 -146.1200 63.38100      1
5  RGI60-01.00005 G212943E63551N 20090703 -9999999 -147.0570 63.55100      1
```

Structure of the data

```
> str(ak)

Classes 'sf' and 'data.frame': 27108 obs. of 23 variables:

$ RGIId    : chr  "RGI60-01.00001" "RGI60-01.00002" "RGI60-01.00003" ...
$ GLIMSIId : chr  "G213177E63689N" "G213332E63404N" "G213920E63376N" ...
$ BgnDate   : chr  "20090703" "20090703" "20090703" "20090703" ...
$ EndDate   : chr  "-9999999" "-9999999" "-9999999" "-9999999" ...
$ CenLon    : num  -147 -147 -146 -146 -147 ...
$ CenLat    : num  63.7 63.4 63.4 63.4 63.6 ...
$ O1Region : chr  "1" "1" "1" "1" ...
$ O2Region : chr  "2" "2" "2" "2" ...
$ Area      : num  0.36 0.558 1.685 3.681 2.573 ...
$ Zmin     : int  1936 1713 1609 1273 1494 1201 1918 2826 1750 1280 ...
$ Zmax     : int  2725 2144 2182 2317 2317 3547 2811 3555 2514 1998 ...
```

Mapping with tmap

Combining datasets

- The Coordinate Reference Systems (CRS) must be the same

```
> st_crs(ak) == st_crs(wes)
[1] TRUE
```

The spatial bounding boxes (`bbox`) however are different
(of course, since the 2 datasets cover different geographic areas)

```
> st_bbox(ak) == st_bbox(wes)
xmin  ymin  xmax  ymax
FALSE FALSE FALSE FALSE
```

Union of bounding boxes

```
nwa_bbox <- st_bbox(  
  st_union(  
    st_as_sfc(st_bbox(wes)),  
    st_as_sfc(st_bbox(ak)))  
  )  
)
```

Our new bounding box for the map of Western North America:

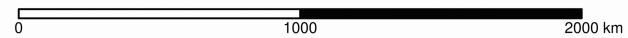
```
> nwa_bbox  
  xmin      ymin      xmax      ymax  
-176.14247  36.38625 -105.60821  69.35167
```

Glaciers of Western North America

```
tm_shape(ak, bbox = nwa_bbox) +
  tm_polygons() +
  tm_shape(wes) +
  tm_polygons() +
  tm_layout(
    title = "Glaciers of Western North America",
    title.position = c("center", "top"),
    title.size = 1.1,
    bg.color = "#fcfcfc",
    inner.margins = c(0.06, 0.01, 0.09, 0.01),
    outer.margins = 0,
    frame.lwd = 0.2
  ) +
```

Glaciers of Western North America

N



Basemaps

Basemaps

Let's add one to our map of the glaciers of WNA

Getting a basemap from rnaturalearth

```
states_all <- ne_states(  
  country = c("canada", "united states of america"),  
  returnclass = "sf"  
)
```

Selection of relevant data

```
states <- states_all %>%  
  filter(name_en == "Alaska" |  
         name_en == "British Columbia" |  
         name_en == "Yukon" |  
         name_en == "Northwest Territories" |  
         name_en == "Alberta" |  
         name_en == "California" |  
         name_en == "Washington" |  
         name_en == "Oregon" |  
         name_en == "Idaho" |  
         name_en == "Montana" |  
         name_en == "Wyoming" |  
         name_en == "Colorado" |
```

A few notes

Always make sure the CRS match!

```
> st_crs(states) == st_crs(ak)
[1] TRUE
```

The bounding boxes are different and we are only interested in the basemap within the bounding box of our data, so this is the only part of the basemap that we will plot.

```
> st_bbox(states) == nwa_bbox
xmin  ymin  xmax  ymax
FALSE FALSE FALSE FALSE
```

Play with colors of borders and fill, as well as the width of the borders.

Add the basemap to our map

```
tm_shape(states, bbox = nwa_bbox) +
  tm_polygons(col = "#f2f2f2",
              lwd = 0.2) +
  tm_shape(ak) +
  tm_borders(col = "#3399ff") +
  tm_fill(col = "#86baff") +
  tm_shape(wes) +
  tm_borders(col = "#3399ff") +
  tm_fill(col = "#86baff") +
  tm_layout(
    title = "Glaciers of Western North America",
    title.position = c("center", "top"),
    title.size = 1.1,
```



Maps based on an attribute variable

Retreat of glaciers over time in Glacier National Park

We will use the USGS time series of the named glaciers of Glacier National Park .

These 4 datasets have the contour lines of 39 glaciers for the years 1966, 1998, 2005, and 2015.

Cleaning datasets

```
## create a function that reads and cleans the data

prep <- function(dir) {

  g <- st_read(dir)

  g %>% rename_with(~ tolower(gsub("Area....", "area", .x)))

  g %>% dplyr::select(
    year,
    objectid,
    glacname,
    area,
    shape_leng,
    x_coord,
    y_coord,
    source_sca,
```

We use `dplyr::select()` because `raster` also has a `select()` function.

Combining datasets into one sf object

Checking that the CRS are the same:

```
> st_crs(gnp[[1]]) == st_crs(gnp[[2]])
[1] TRUE
> st_crs(gnp[[1]]) == st_crs(gnp[[3]])
[1] TRUE
> st_crs(gnp[[1]]) == st_crs(gnp[[4]])
[1] TRUE
```

We can `rbind` our lists:

```
gnp <- do.call("rbind", gnp)
```

The Glacier National Park data

```
> gnp
Simple feature collection with 156 features and 9 fields
geometry type:  MULTIPOLYGON
dimension:        XY
bbox:             xmin: 263221.4 ymin: 5355550 xmax: 314490 ymax: 5430612
projected CRS:   NAD83 / UTM zone 12N
First 10 features:

  year objectid      glacname    area shape_leng      x_coord
1 1966       1 Agassiz Glacier 1600559.73 15177.8599 268743.351899585
2 1966       2 Ahern Glacier  589185.63  3435.4477 295758.255307284
3 1966       3 Baby Glacier  117171.13  1615.1598 268883.636523344
4 1966       4 Blackfoot Glacier 1832451.35 13980.9680 303273.800396565
5 1966       5 Boulder Glacier 231017.73  2847.2854 273967.708607631
```

Structure of Glacier National Park data

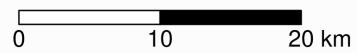
```
> str(gnp)
Classes 'sf' and 'data.frame': 156 obs. of 10 variables:
$ year       : chr  "1966" "1966" "1966" "1966" ...
$ objectid   : num  1 2 3 4 5 6 7 8 9 10 ...
$ glacname   : chr  "Agassiz Glacier" "Ahern Glacier" "Baby Glacier" ...
$ area        : num  1600560 589186 117171 1832451 231018 ...
$ shape_leng : num  15178 3435 1615 13981 2847 ...
$ x_coord    : chr  "268743.351899585" "295758.255307284" ...
$ y_coord    : chr  "5424909.85602688" "5413721.34271866" ...
$ source_sca : chr  "1:24000" "1:24000" "1:24000" "1:24000" ...
$ source     : chr  "USGS 7.5 minute quadrangle map, 1966-1968" ...
$ geometry   : sfc_MULTIPOLYGON of length 156; first list element: List of 1
..$ :List of 12
```

Map of Glacier National Park

```
tm_shape(gnp) +
  tm_polygons("year", palette = "Blues") +
  tm_layout(
    title = "Glaciers of Glacier National Park",
    title.position = c("center", "top"),
    legend.title.color = "#fcfcfc",
    legend.text.size = 1,
    bg.color = "#fcfcfc",
    inner.margins = c(0.07, 0.03, 0.07, 0.03),
    outer.margins = 0
  ) +
  tm_compass(
    type = "arrow",
```

Glaciers of Glacier National Park

N



Inset maps

Let's plot our GNP map as an inset of our Western North America map.

As always, first we check that the CRS are the same:

```
> st_crs(ak) == st_crs(gnp)  
[1] FALSE
```

Inset maps

Let's plot our GNP map as an inset of our Western North America map.

As always, first we check that the CRS are the same:

```
> st_crs(ak) == st_crs(gnp)  
[1] FALSE
```

:(
:(

CRS transformation

We need to reproject `gnp`:

```
gnp <- st_transform(gnp, st_crs(ak))
```

We can verify that the CRS of both our maps are now the same:

```
> st_crs(ak) == st_crs(gnp)
[1] TRUE
```

Inset maps

First step: add a rectangle showing the bounding box of `gnp` in the `nwa` map.

This will show the location of the GNP map in the main North America map.

We add a new `sfc_POLYGON` from the `gnp` bounding box as a new layer:

```
gnp_zone <- st_bbox(gnp) %>%  
  st_as_sfc()
```

We will use it as the following layer within the new map:

```
tm_shape(gnp_zone) +  
  tm_borders(lwd = 1.5, col = "#ff9900")
```

Inset maps

Second step: create a `tmap` object for our main map:

```
main_map <- tm_shape(states, bbox = nwa_bbox) +  
  tm_polygons(col = "#f2f2f2",  
              lwd = 0.2) +  
  tm_shape(ak) +  
  tm_borders(col = "#3399ff") +  
  tm_fill(col = "#86baff") +  
  tm_shape(wes) +  
  tm_borders(col = "#3399ff") +  
  tm_fill(col = "#86baff") +  
  tm_shape(gnp_zone) +  
  tm_borders(lwd = 1.5, col = "#ff9900") +  
  tm_layout(  
    title = "Glaciers of Glacier National Park",
```

Inset maps

Third step: create a `tmap` object for the inset map.

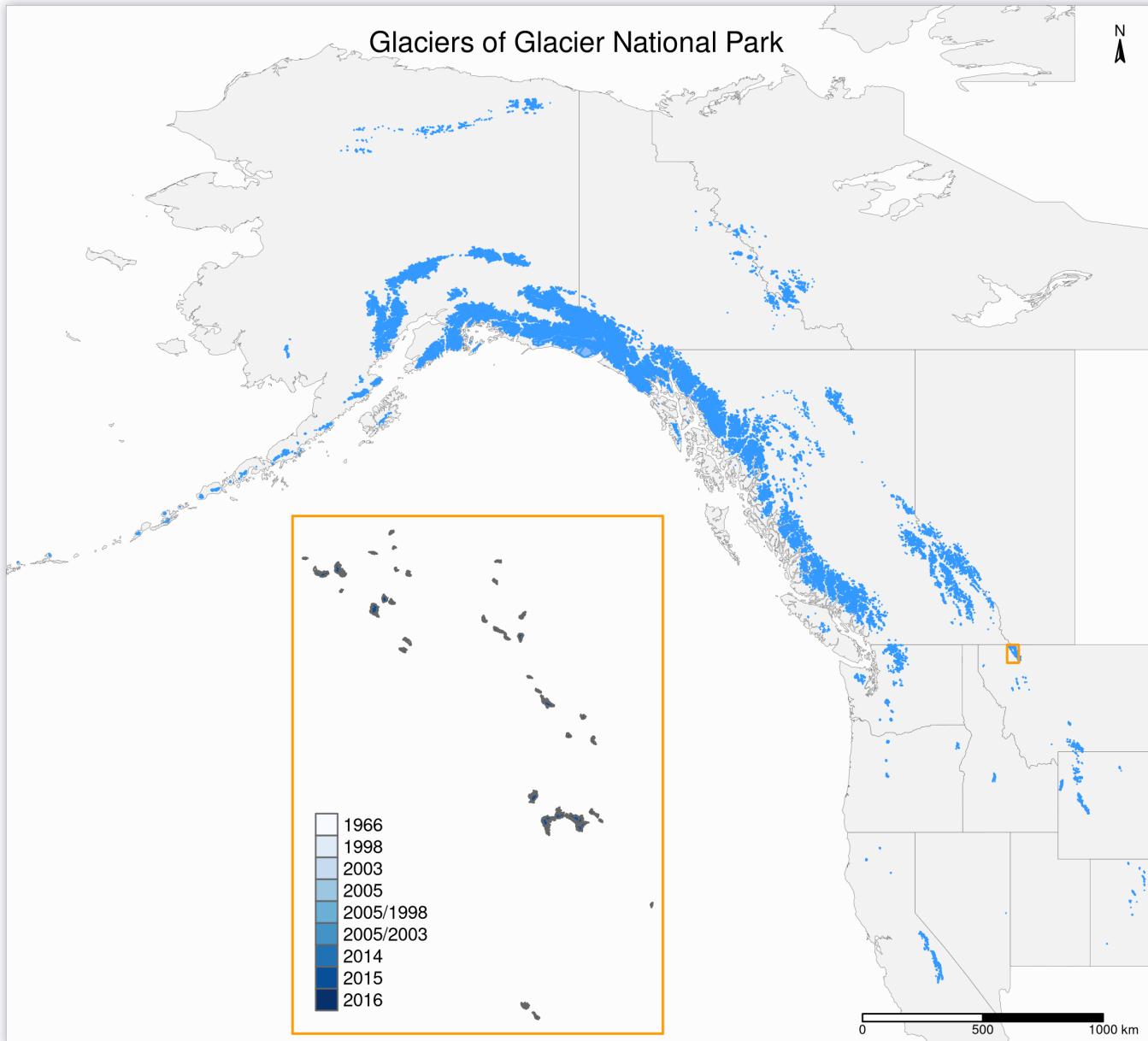
Matching colors and edited layouts will help with readability:

```
inset_map <- tm_shape(gnp) +  
  tm_polygons("year", palette = "Blues") +  
  tm_layout(  
    legend.title.color = "#fcfcfc",  
    legend.text.size = 0.7,  
    bg.color = "#fcfcfc",  
    inner.margins = c(0.03, 0.03, 0.03, 0.03),  
    outer.margins = 0,  
    frame = "#ff9900",  
    frame.lwd = 3  
)
```

Inset maps

Final step: we combine the two `tmap` objects with `grid::viewport()`:

```
main_map  
print(inset_map, vp = viewport(0.41, 0.26, width = 0.5, height = 0.5))
```



Adjustments

The scale is too small to show the retreat of the glaciers on this map. So it might be better to remove the legend and the palette per year and to make the borders and fill of the same colors as in the main map instead:

```
inset_map <- tm_shape(gnp) +  
  tm_borders(col = "#3399ff") +  
  tm_fill(col = "#86baff") +  
  tm_layout(  
    legend.show = F,  
    bg.color = "#fcfcfc",  
    inner.margins = c(0.03, 0.03, 0.03, 0.03),  
    outer.margins = 0,  
    frame = "#ff9900",  
    frame.lwd = 3  
)
```



Mapping a subset of the data

To see the retreat of the glaciers, we need to zoom in. Let's focus on a single glacier: Agassiz.

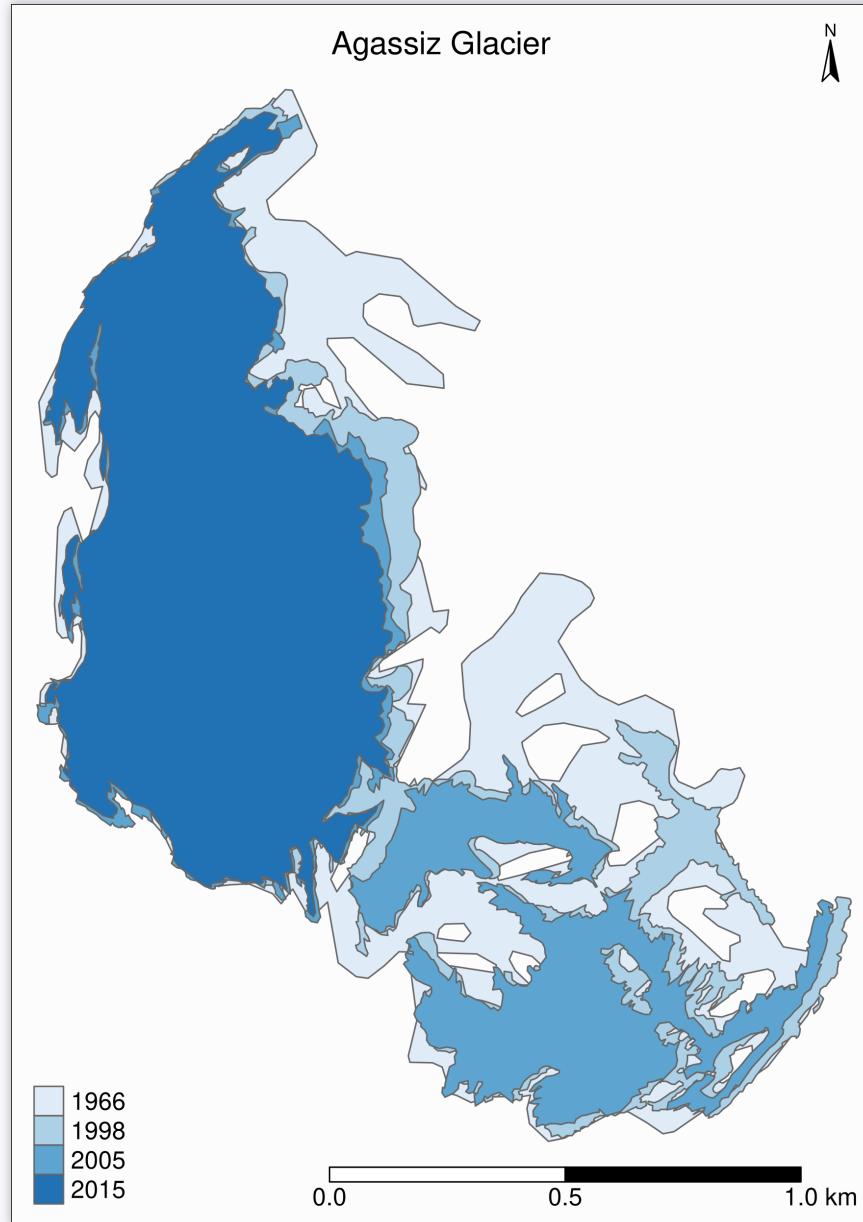
Map of the Agassiz Glacier

Select the data points corresponding to the Agassiz Glacier:

```
ag <- g %>% filter(glacname == "Agassiz Glacier")
```

Map of the Agassiz Glacier

```
tm_shape(ag) +
  tm_polygons("year", palette = "Blues") +
  tm_layout(
    title = "Agassiz Glacier",
    title.position = c("center", "top"),
    legend.position = c("left", "bottom"),
    legend.title.color = "#fcfcfc",
    legend.text.size = 1,
    bg.color = "#fcfcfc",
    inner.margins = c(0.07, 0.03, 0.07, 0.03),
    outer.margins = 0
) +
  tm_compass()
```



Using `ggplot2` instead of `tmap`

As an alternative to the `tmap` package, `ggplot2` can plot maps with the `geom_sf()` function. The previous map can be reproduced (with some tweaking of style and layout) with:

```
ggplot(ag) +  
  geom_sf(aes(fill = year)) +  
  scale_fill_brewer(palette = "Blues")
```

Other ways to add a basemap

Basemap with ggmap

```
basemap <- get_map(  
  bbox = c(  
    left = st_bbox(ag)[1],  
    bottom = st_bbox(ag)[2],  
    right = st_bbox(ag)[3],  
    top = st_bbox(ag)[4]  
,  
  source = "osm"  
)
```

ggmap is a powerful package, but Google now requires an API key obtained through registration.

Basemap with basemaps

The package **basemaps** allows to download open source basemap data from several sources, but those cannot easily be combined with `sf` objects.

This plots a satellite image of the Agassiz Glacier:

```
basemap_plot(ag, map_service = "esri", map_type = "world_imagery")
```

Satellite image of the Agassiz Glacier



Faceted maps

Faceted map of the retreat of Agassiz Glacier

```
tm_shape(ag) +
  tm_polygons(col = "#86baff") +
  tm_layout(
    main.title = "Agassiz Glacier",
    main.title.position = c("center", "top"),
    main.title.size = 1.2,
    legend.position = c("left", "bottom"),
    legend.title.color = "#fcfcfc",
    legend.text.size = 1,
    bg.color = "#fcfcfc",
    ## inner.margins = c(0, 0.03, 0, 0.03),
    outer.margins = 0,
    panel.label.bg.color = "#fcfcfc",
```

Agassiz Glacier

1966

1998

2005

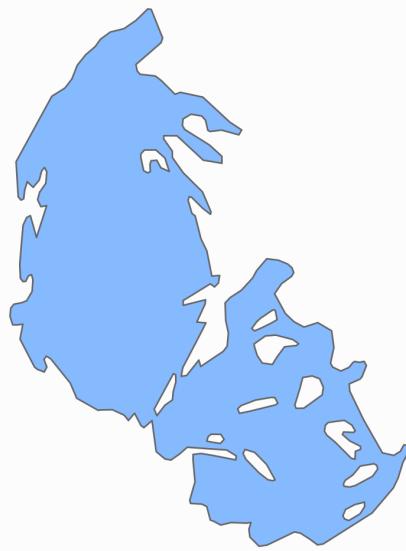
2015

N

N

N

N



Animated maps

Animated map of the Retreat of Agassiz Glacier

First, we need to create a `tmap` object with facets:

```
agassiz_anim <- tm_shape(ag) +  
  tm_borders() +  
  tm_fill(col = "#86baff") +  
  tm_layout(  
    title = "Agassiz Glacier",  
    title.position = c("center", "top"),  
    legend.position = c("left", "bottom"),  
    legend.title.color = "#fcfcfc",  
    legend.text.size = 1,  
    bg.color = "#fcfcfc",  
    inner.margins = c(0.08, 0, 0.08, 0),  
    outer.margins = 0  
) +
```

Animated map of the Retreat of Agassiz Glacier

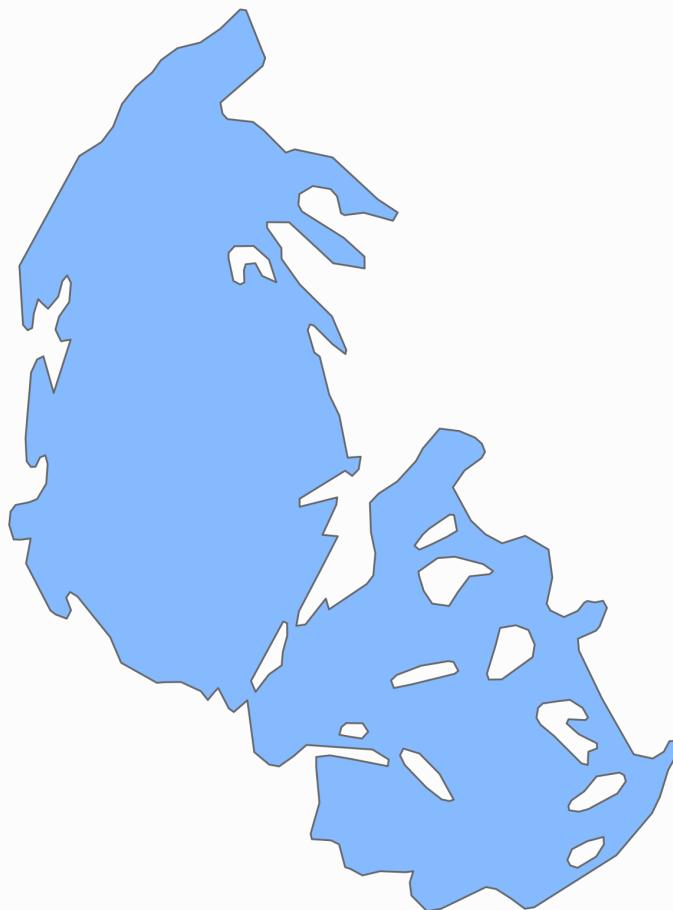
Then we can pass that object to `tmap_animation()`:

```
tmap_animation(  
    agassiz_anim,  
    filename = "ag.gif",  
    dpi = 300,  
    inner.margins = c(0.08, 0, 0.08, 0),  
    delay = 100  
)
```

1966

Agassiz Glacier

N



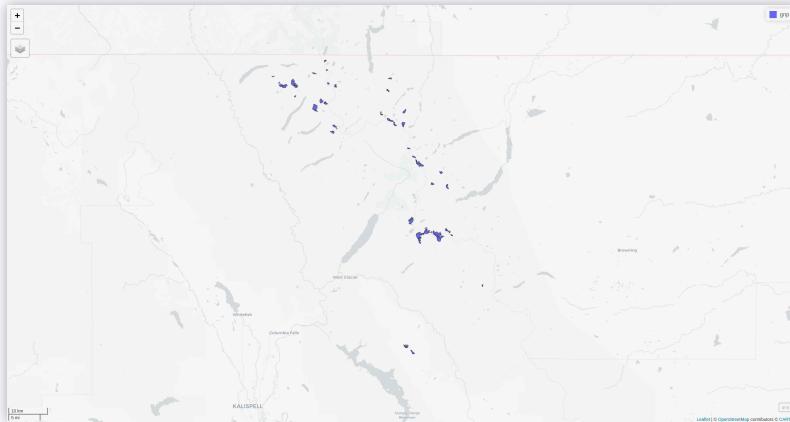
0.0 0.5 1.0 km

Tiled web maps with Leaflet

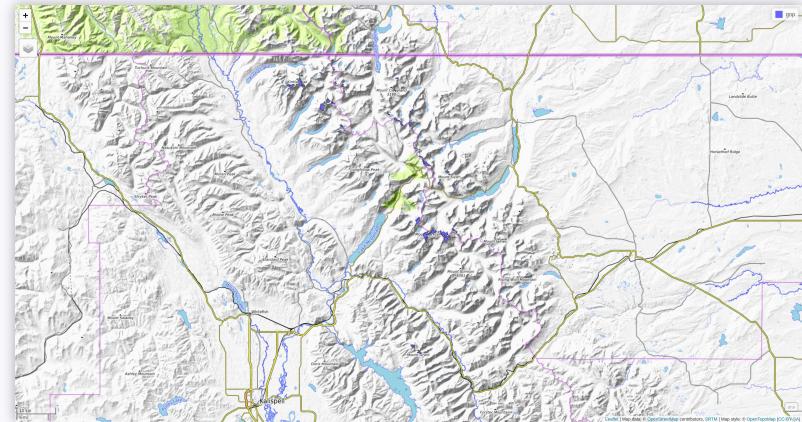
mapview

```
mapview(gnp)
```

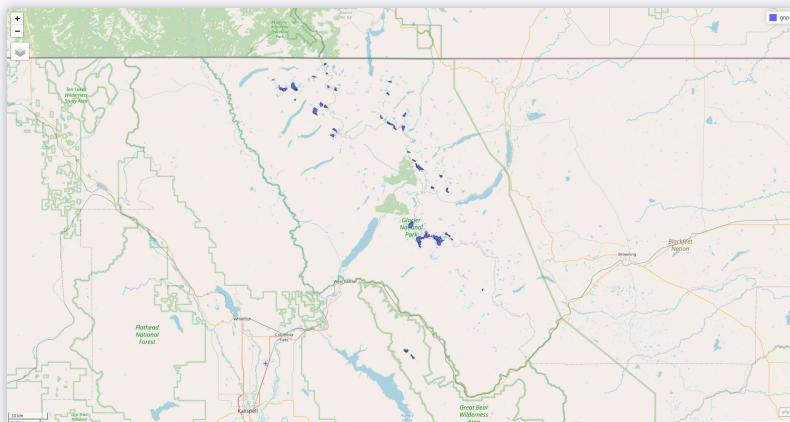
mapview



CartoDB.Positron



OpenTopoMap



OpenStreetMap



Esri.WorldImagery

tmap

So far, we have used the `plot` mode of **tmap**. There is also a `view` mode which allows interactive viewing in a browser through Leaflet .

Change to `view` mode:

```
tmap_mode("view")
```

| you can also toggle between modes with `ttm()`

Re-plot the last map we plotted with **tmap**:

```
tmap_last()
```

leaflet

`leaflet()` creates a map widget to which you add layers.

```
map <- leaflet()  
addTiles(map)
```

raster

Package for spatial raster data

raster

Package for spatial raster data

Note that there is a faster package in beta from the same team:

terra

Ice thickness

The nomenclature for glaciers and regions in the ice thickness dataset follows the Randolph Glacier Inventory (RGI) version 6.0.

Let's look for the Agassiz Glacier data.

RGIId for Agassiz Glacier

```
> wes %>%
  filter(Name == "Agassiz Glacier MT") %>%
  select(RGIId)

Simple feature collection with 1 feature and 1 field

geometry type:  MULTIPOLYGON
dimension:      XY
bbox:           xmin: -114.1673 ymin: 48.92498 xmax: -114.1442 ymax: 48.94501
geographic CRS: WGS 84

RGIId               geometry
1 RGI60-02.16664 MULTIPOLYGON (((-114.1487 4...
```

Now we now which file we need to look for in the ice thickness dataset: `RGI60-02.16664_thickness.tif`.

Load raster data for Agassiz Glacier

First, we want to see how many bands are available:

```
> nlayers(stack("RGI60-02/RGI60-02.16664_thickness.tif"))
[1] 1
```

This is not a multi-layer band (such as an RGB file), so we don't have to worry about band selection:

```
agras <- raster("RGI60-02/RGI60-02.16664_thickness.tif")
```

Inspect raster data

```
> agras
class      : RasterLayer
dimensions : 93, 74, 6882  (nrow, ncol, ncell)
resolution : 25, 25  (x, y)
extent     : 707362.5, 709212.5, 5422962, 5425288  (xmin, xmax, ymin, ymax)
crs        : +proj=utm +zone=11 +datum=WGS84 +units=m +no_defs
source     : /RGI60-02/RGI60-02.16664_thickness.tif
names      : RGI60.02.16664_thickness
```

Inspect raster data

```
> str(agras)
Formal class 'RasterLayer' [package "raster"] with 12 slots
..@ file      :Formal class '.RasterFile' [package "raster"] with 13 slots
.. . . . .@ name       : chr "RGI60-02/RGI60-02.16664_thickness.tif"
.. . . . .@ datanotation: chr "FLT4S"
.. . . . .@ byteorder   : chr "little"
.. . . . .@ nodatavalue : num -Inf
.. . . . .@ NAchanged   : logi FALSE
.. . . . .@ nbands     : int 1
.. . . . .@ bandorder   : chr "BIL"
.. . . . .@ offset      : int 0
.. . . . .@ toptobottom : logi TRUE
.. . . . .@ blockrows   : int 27
```

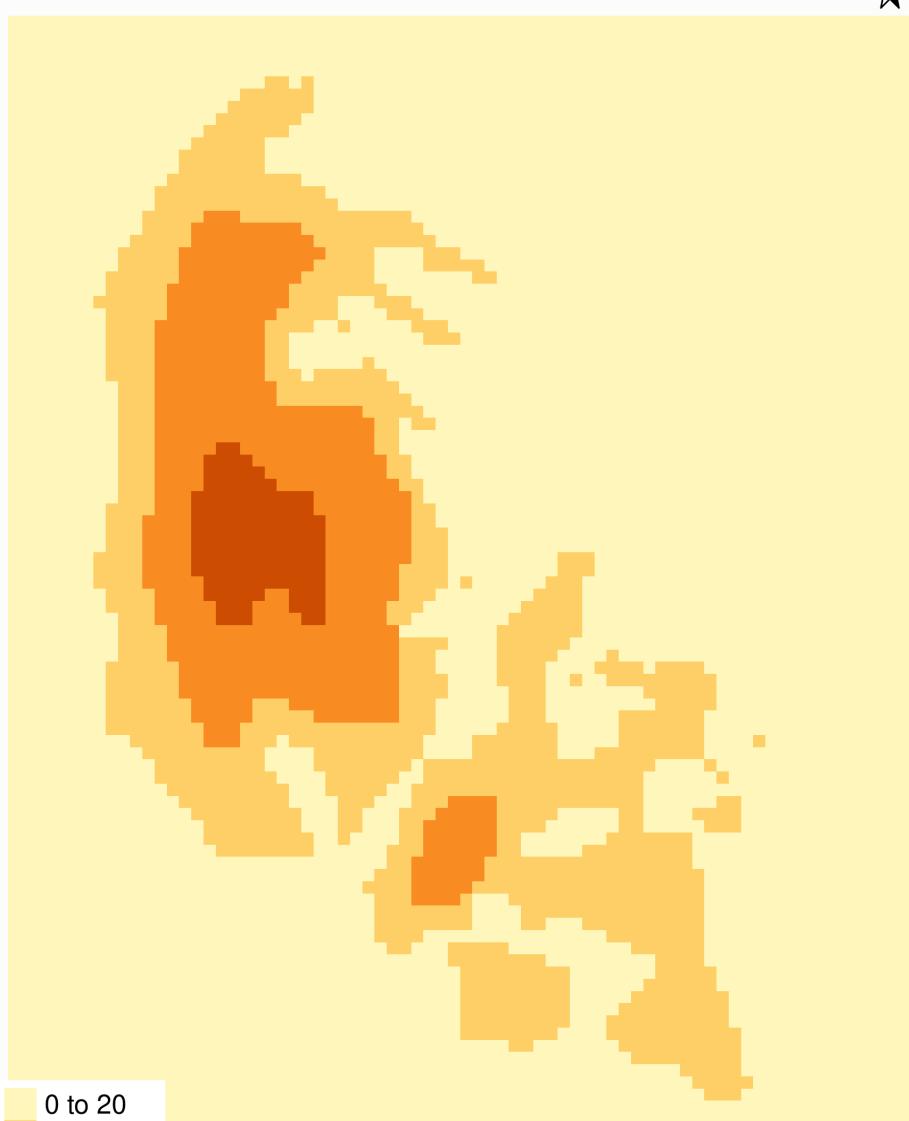
Map of ice thickness Agassiz Glacier

This time, we use `tm_raster()`:

```
tm_shape(agras) +
  tm_raster() +
  tm_layout(
    title = "Ice thickness (m) of Agassiz Glacier",
    title.position = c("center", "top"),
    legend.position = c("left", "bottom"),
    legend.bg.color = "#d9d9d9",
    legend.title.color = "#d9d9d9",
    legend.text.size = 1,
    bg.color = "#fcfcfc",
    inner.margins = c(0.07, 0.03, 0.07, 0.03),
    outer.margins = 0
  ) +
```

Ice thickness (m) of Agassiz Glacier

N



0 to 20
20 to 40
40 to 60
60 to 80

0.0 0.5 1.0 km

Combining with Randolph data

As always, we check whether the CRS are the same:

```
> st_crs(ag) == st_crs(agrass)
[1] FALSE
```

We need to reproject `ag` (easier than reprojecting the `raster` object):

```
ag %<>% st_transform(st_crs(agrass))
```

We can verify that the CRS of both our maps are now the same:

```
> st_crs(ag) == st_crs(agrass)
[1] TRUE
```

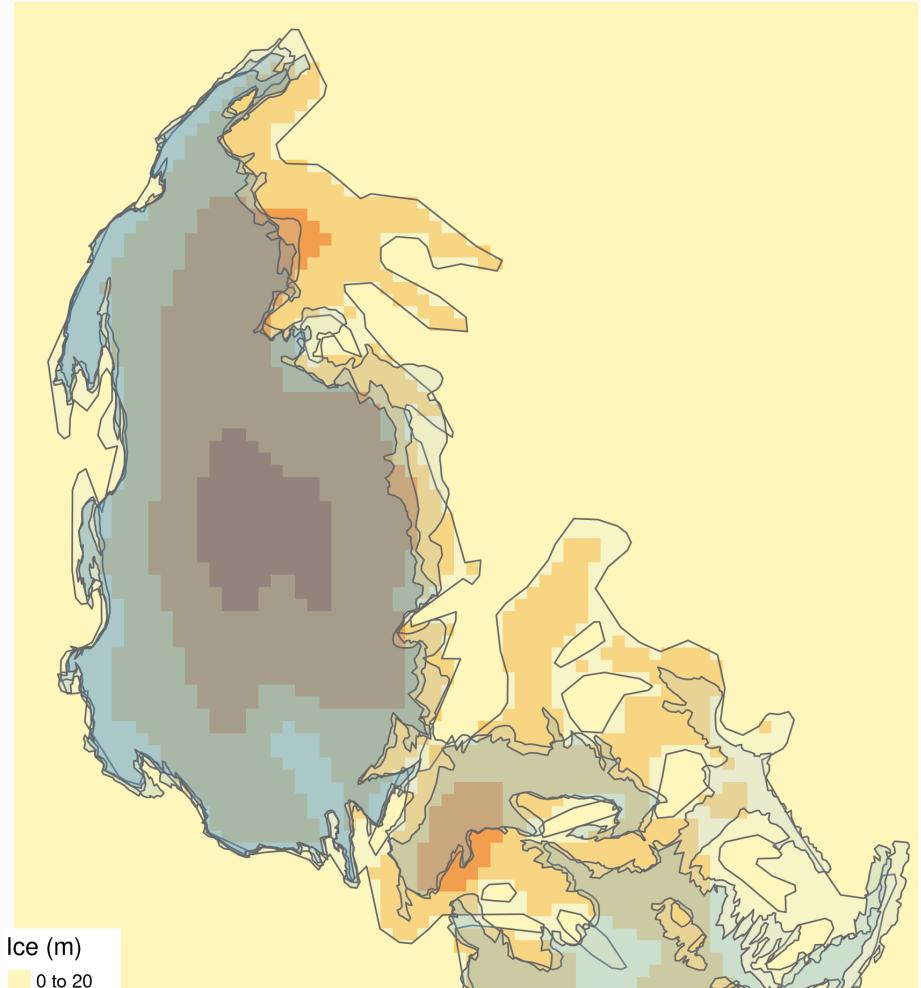
The retreat and ice thickness layers will hide each other (the order matters!).

One option is to use `tm_borders()` only for one of them, or we can use transparency (alpha):

```
tm_shape(agras) +
  tm_raster() +
  tm_shape(ag) +
  tm_polygons("year", palette = "Blues", alpha = 0.2) +
  tm_layout(
    title = "Ice thickness (m) and retreat of Agassiz Glacier",
    title.position = c("center", "top"),
    legend.position = c("left", "bottom"),
    legend.bg.color = "#e6e6e6",
    legend.title.color = "#e6e6e6",
    legend.text.size = 0.7,
    bg.color = "#fcfcfc",
    inner.margins = c(0.07, 0.03, 0.07, 0.03),
```

Ice thickness (m) and retreat of Agassiz Glacier

N



Ice (m)

- 0 to 20
- 20 to 40
- 40 to 60
- 60 to 80

Contour

- 1966
- 1998
- 2005
- 2015

0.0 0.5 1.0 km

Questions?