Introduction to spatial data in R for paleontologists

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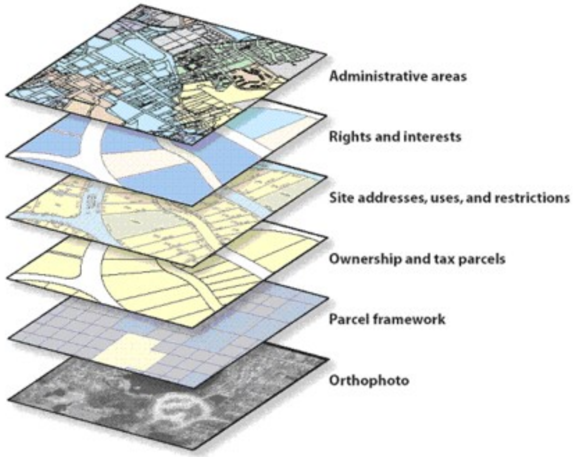
Basic Concepts

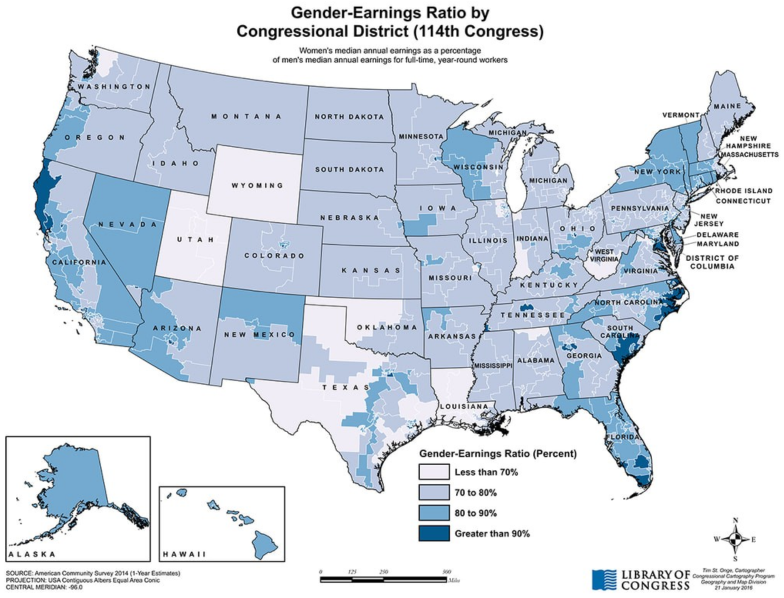
Where, what, why?

GIS basics

G(eographic) I(nformation) S(ystems/oftware) are everywhere

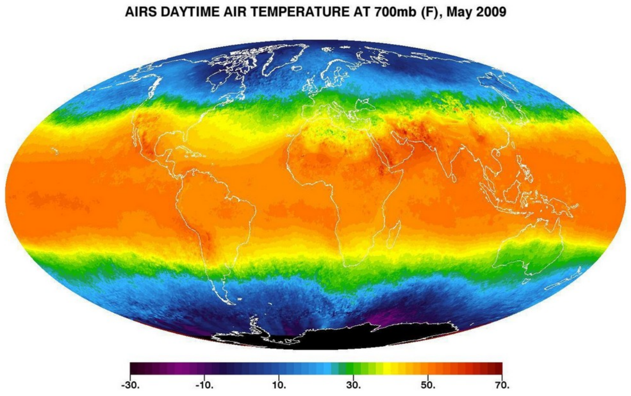
- Science
- Civil Engineering
- Aeronautics
- Military
- Economics
- etc.





SOURCE: American Community Survey 2014 (1-Year Estimates)
PROJECTION: USA Contiguous Albers Equal Area Conic
CENTRAL MERIDIAN: -96.0

Tim St. Onge, Cartographer
Congressional Cartography Program
Geography and Map Division
21 January 2016

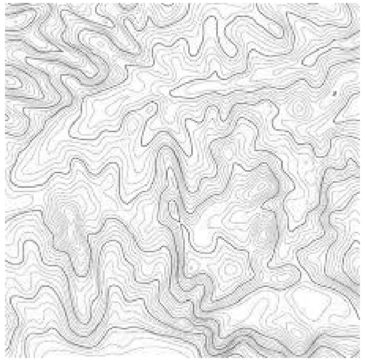


sources: FlightConnections.com/Google

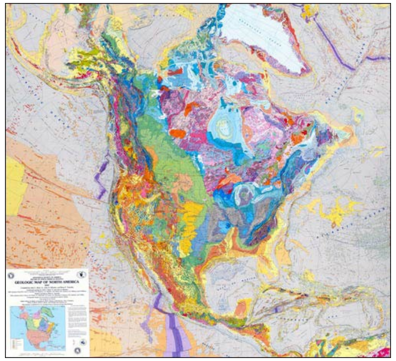
Vital in Earth Sciences

G(eographic) I(nformation) S(ystems) are everywhere

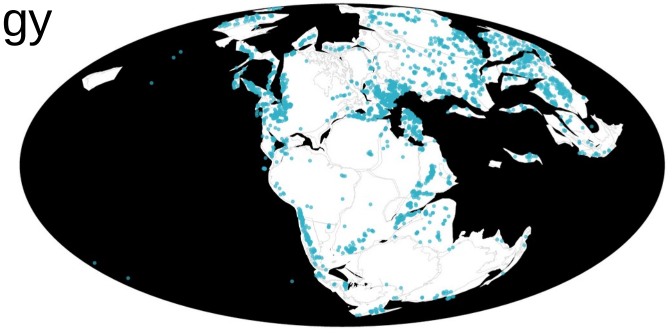
- topography



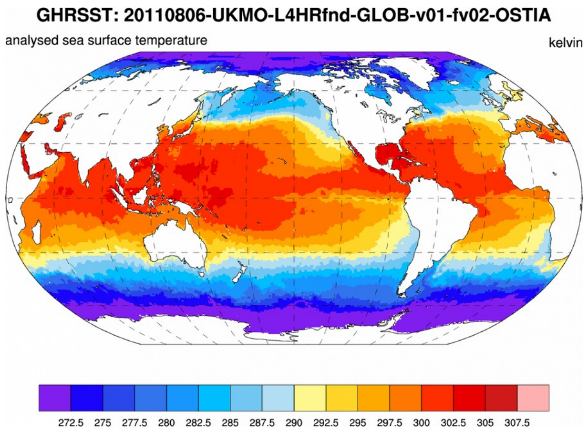
- geology



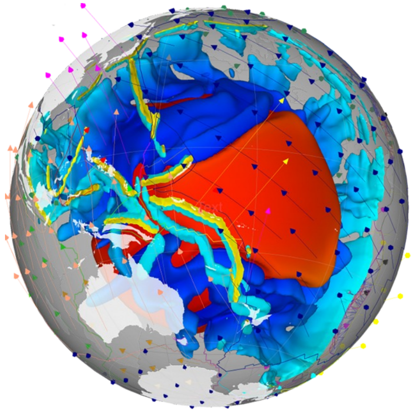
- paleontology



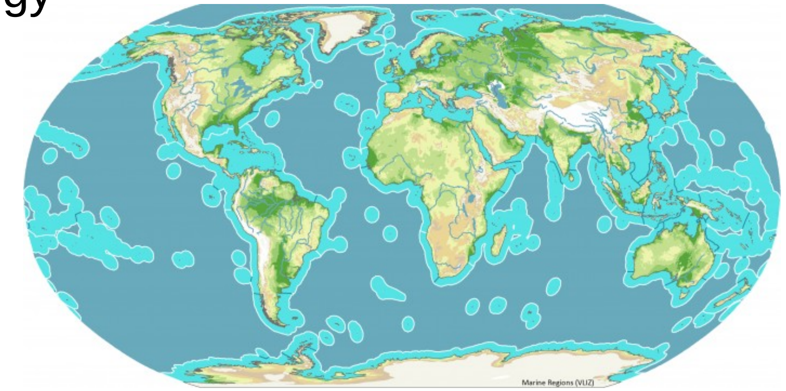
- climate


GHRSST: 20110806-UKMO-L4HRfnd-GLOB-v01-fv02-OSTIA
analysed sea surface temperature
kelvin
272.5
275
277.5
280
282.5
285
287.5
290
292.5
295
297.5
300
302.5
305
307.5

- geophysics



- ecology

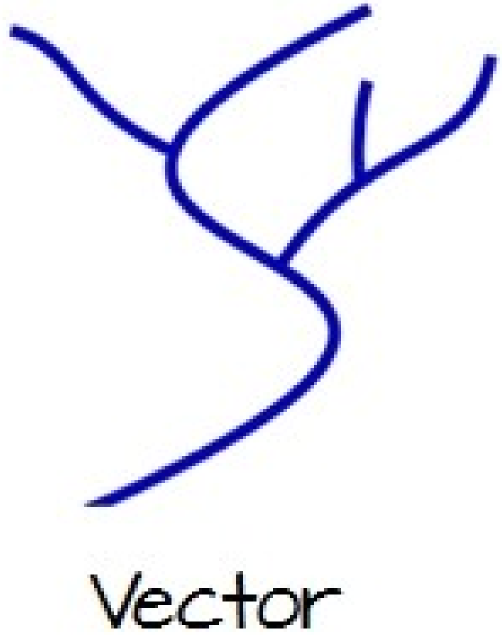


Basic data types

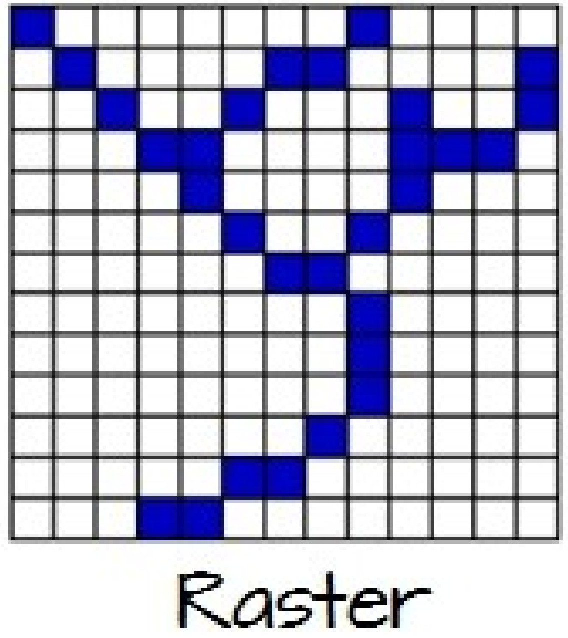
- Similar to computer graphics
- Sometimes in 3D

There is one twist:

Object view



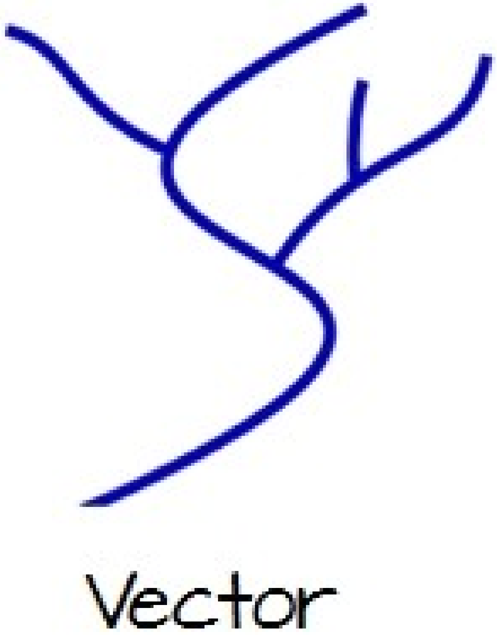
Field view



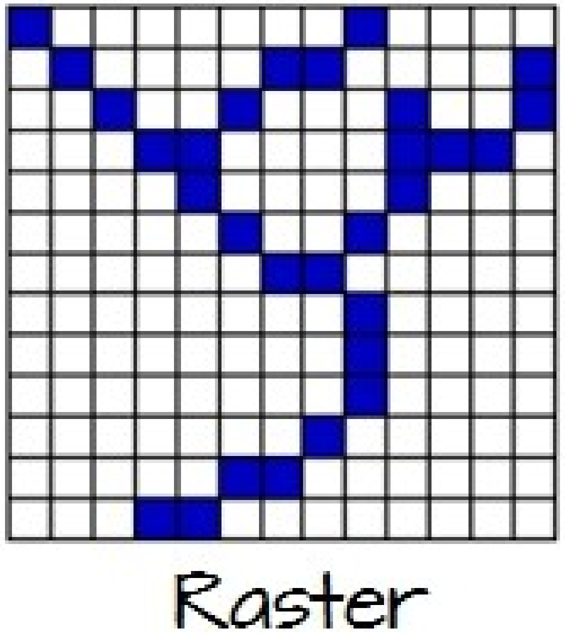
Basic data types

- Similar to computer graphics
- Sometimes in 3D

Object view



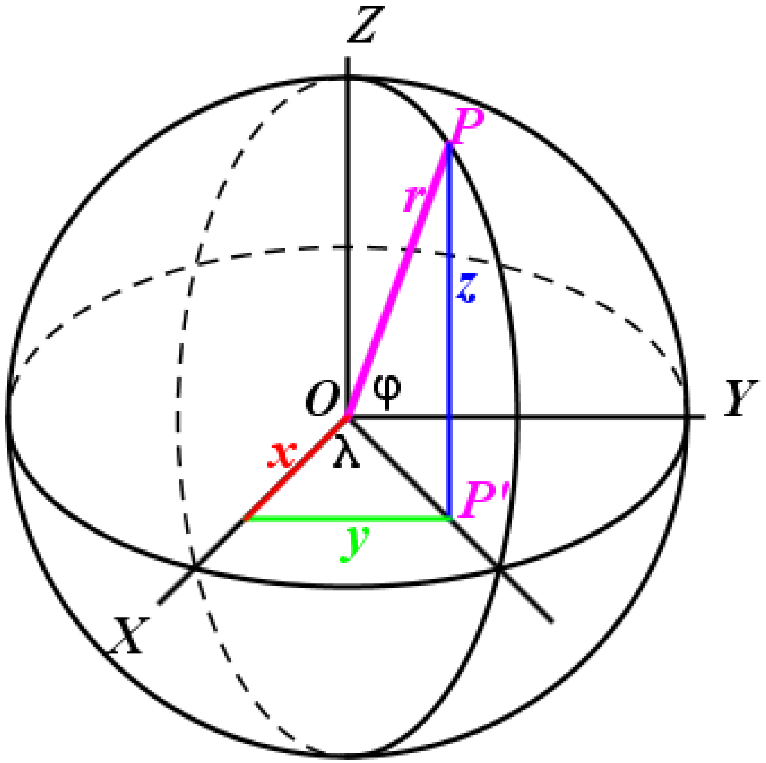
Field view

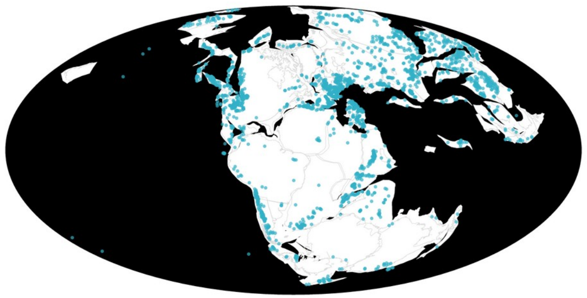


There is one twist:

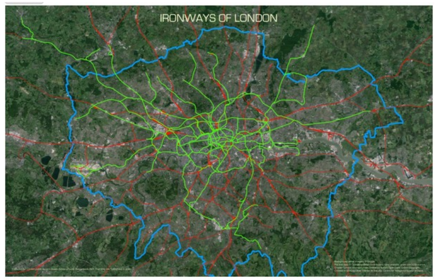
Vector data

- Structure is defined with points that have coordinates
- Spherical coordinates, Cartesian too, or projection-specific
- Additional attributes are rendered to the entities
- 3 primary kind

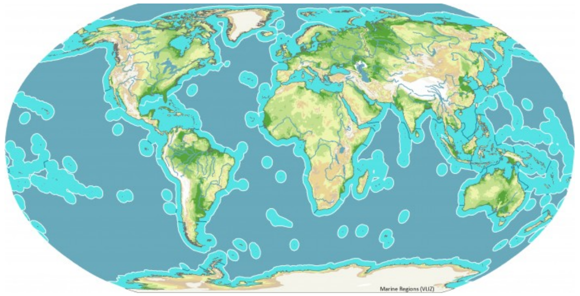




Points



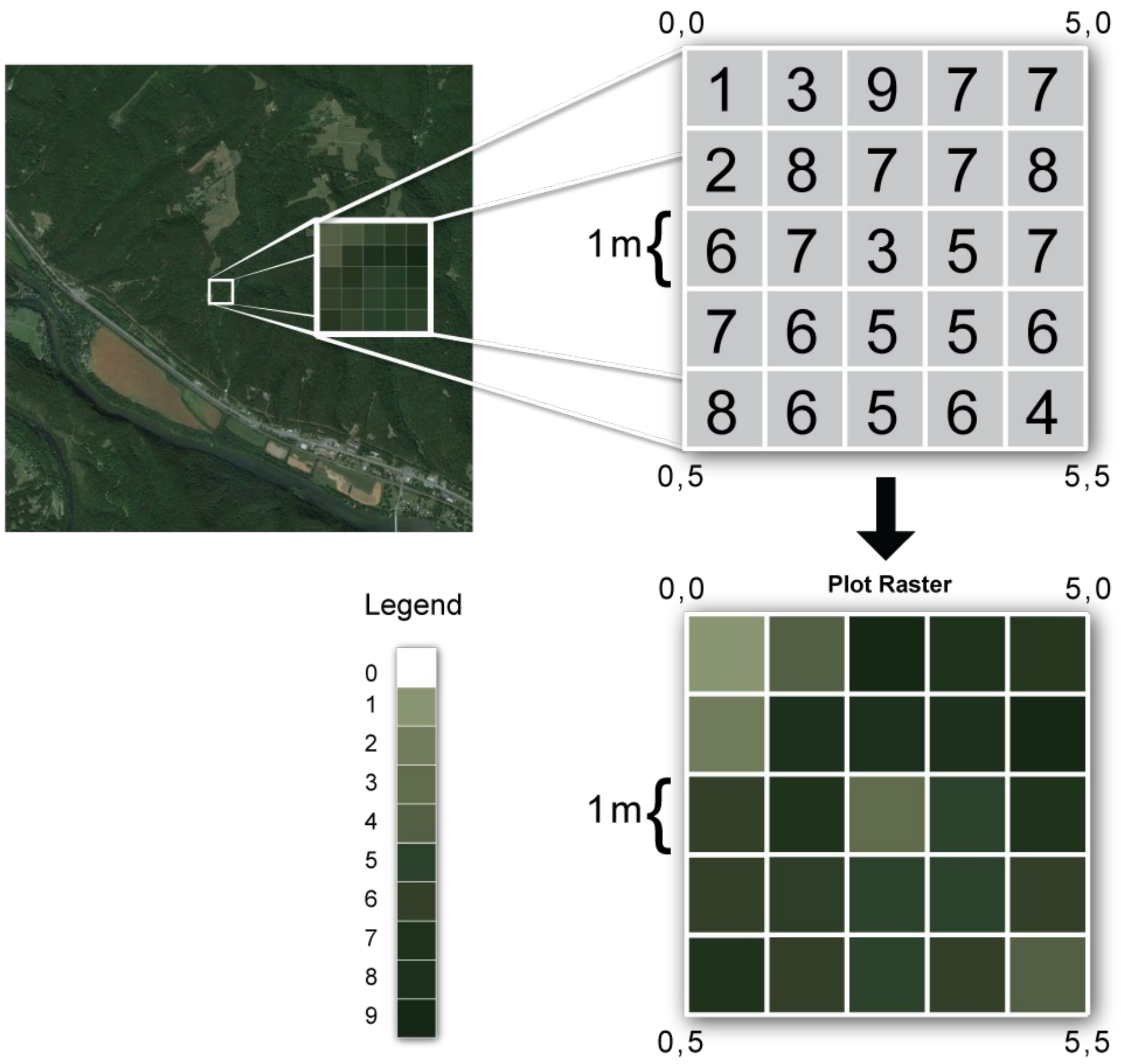
Lines



Polygons (shapes)

Raster data

- Structure is defined by a grid, data is a lattice of values
- The field view of Earth
- Similar to raster graphics, but with georeferencing

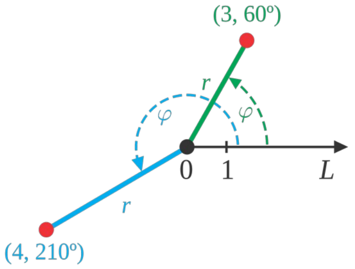


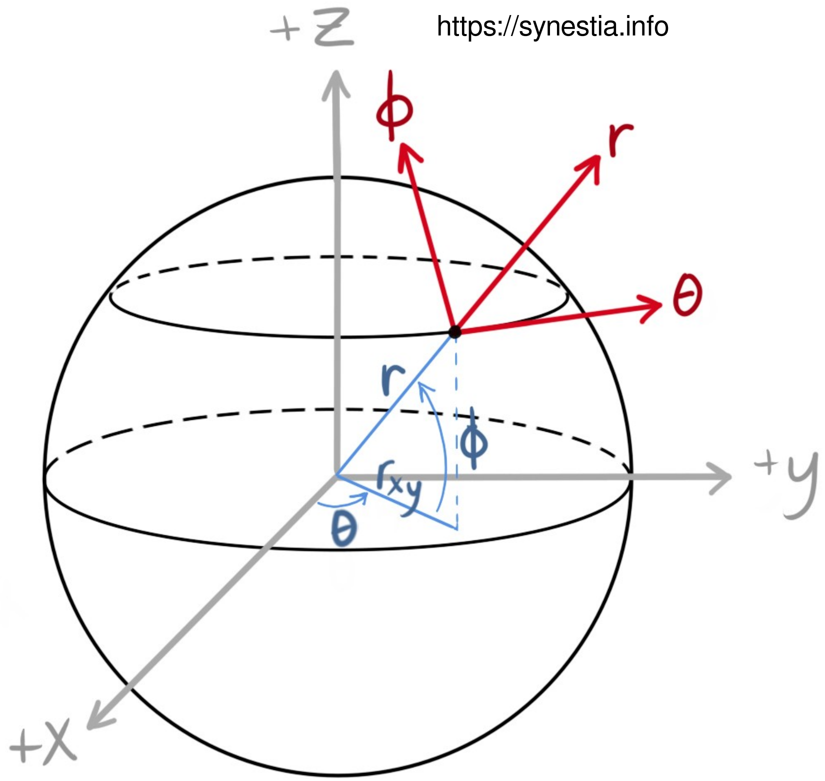
1	3	9	7	7
2	8	7	7	8
6	7	3	5	7
7	6	5	5	6
8	6	5	6	4

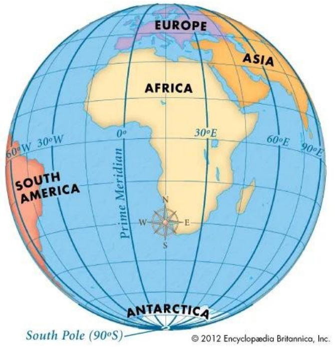
Coordinate Reference Systems

Geographic coordinates

- Based on polar coordinates
- ϕ: latitude
  - [-90°, 90°], equator : 0°
- θ: longitude
  - [-180°, 180°], 0°: prime meridian
- r: elevation




https://synestia.info



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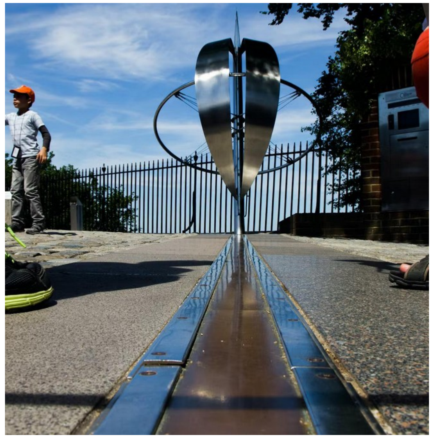
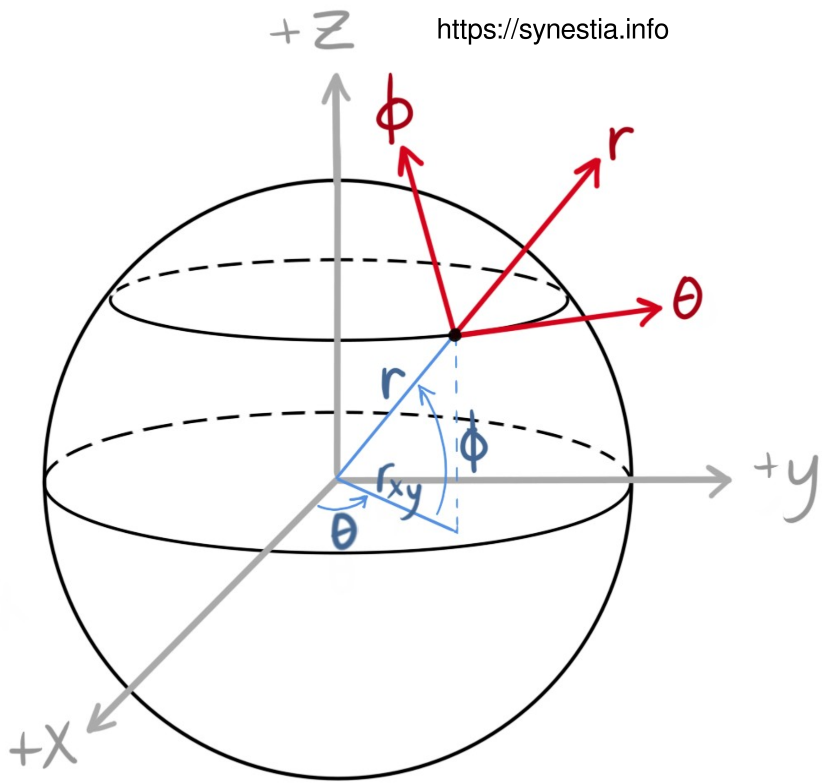


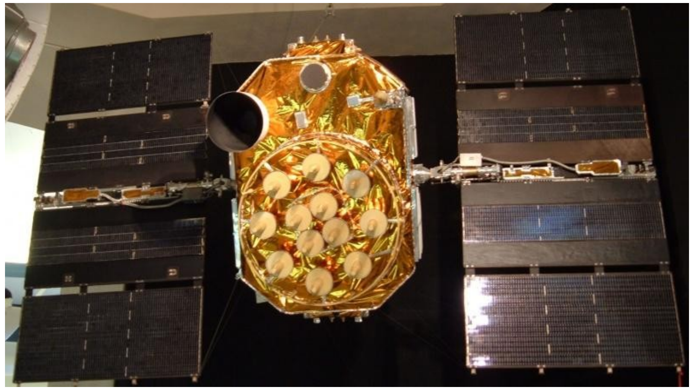
Coordinate Reference Systems

Geocentric coordinates

- x, y, z, Earth-Centered Coordinate System
- Based on center of mass, equator and PM
- Used for satellite tracking and navigation (e.g. GPS)
- WGS84 datum



https://synestia.info

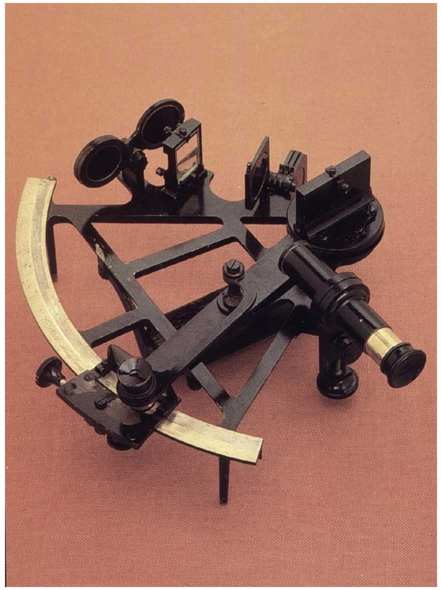


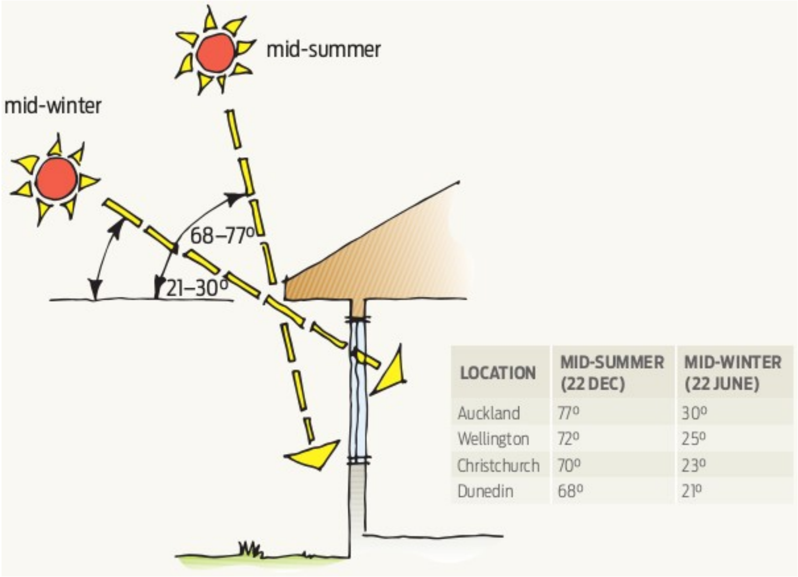
Coordinate Reference Systems

NOVA TOTIVS TERRARVM ORBIS GEOGRAPHICA AC HYDROGRAPHICA TABVLA. Auct: Henr: Hondio

Projection based coordinate systems

- Surface: a 2-dimensional map
- Traditionally: Cartography
- Especially nautical applications





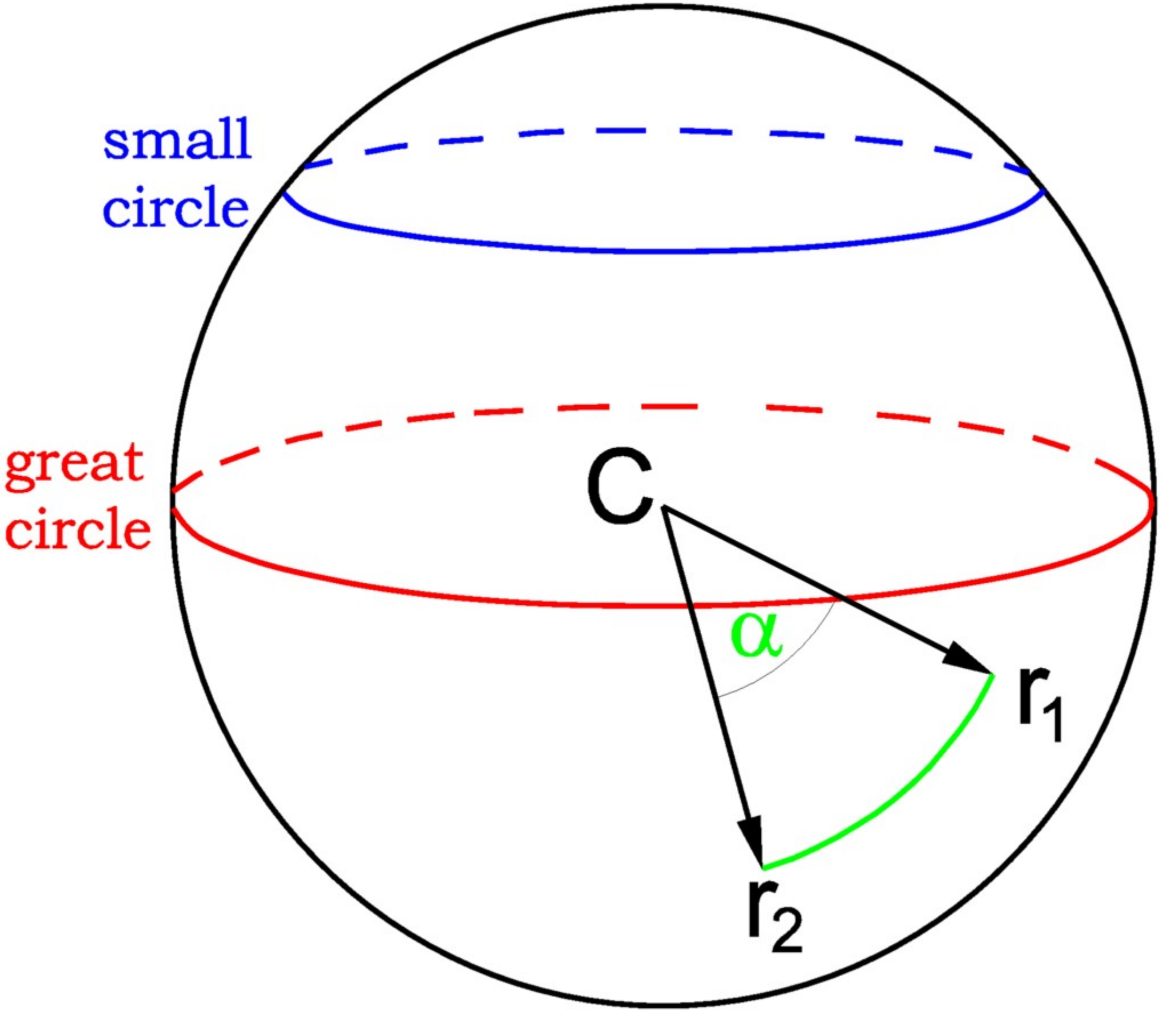
LOCATION	MID-SUMMER (22 DEC)	MID-WINTER (22 JUNE)
Auckland	77°	30°
Wellington	72°	25°
Christchurch	70°	23°
Dunedin	68°	21°

Spheres and Circles

- There are no straight lines
- All points are connected by arcs, either along a great or small circles

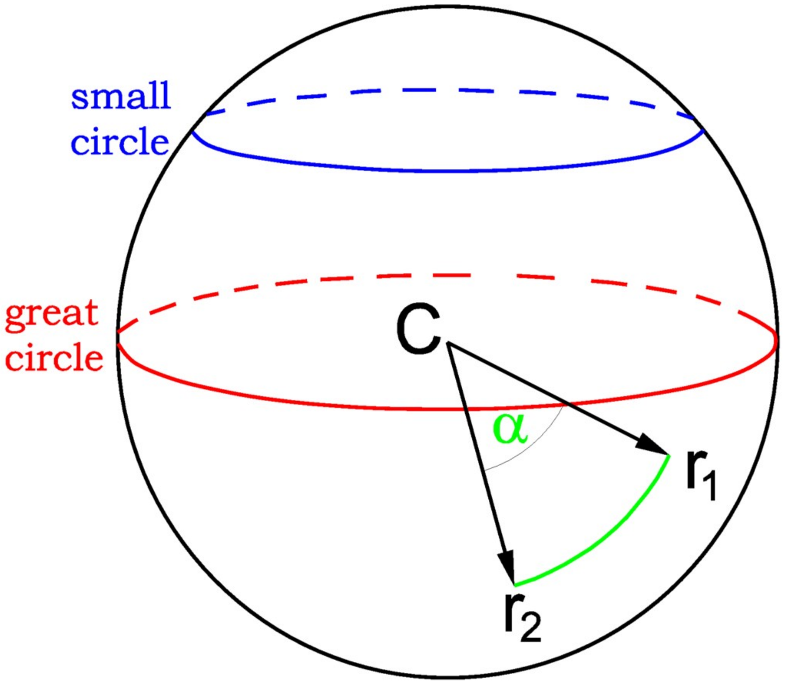
human and robotic exploration
esa
+1.5 h
-1.5 h
TLE vector date: 22 Apr 2021, 16:32:19
© European Space Agency

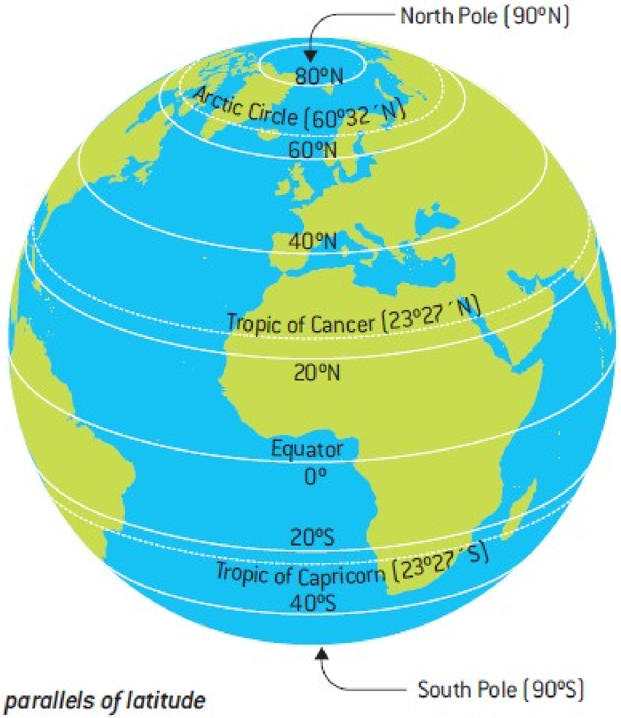
Path of the ISS



Latitude [-90-90˚]

- Latitudinal circles: **parallels**
- The only great circle is the equator!
- Length decrease with a cosine function of latitude
- 10° wide **zone** has different area at different latitudes
- Direction: **zonal (u)**
- Notable circles:

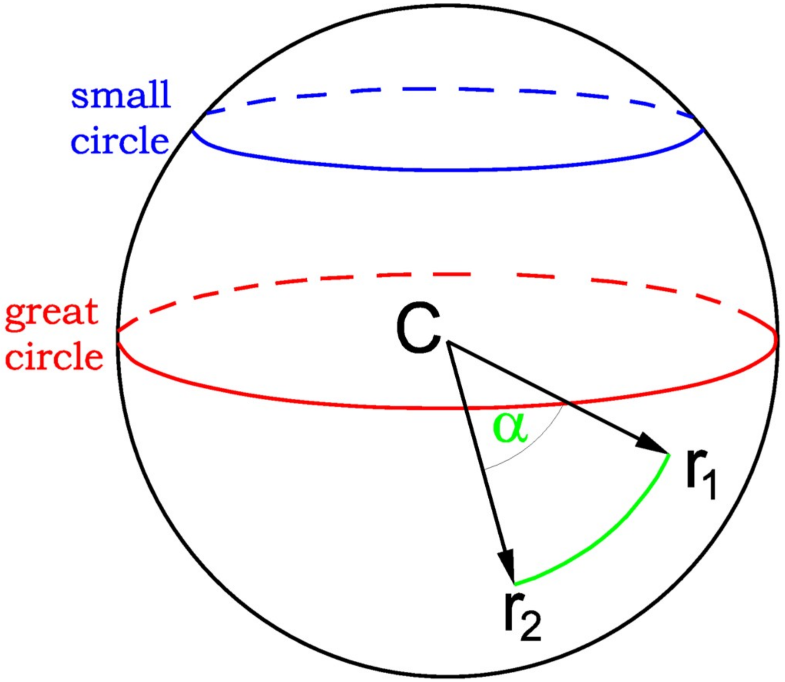


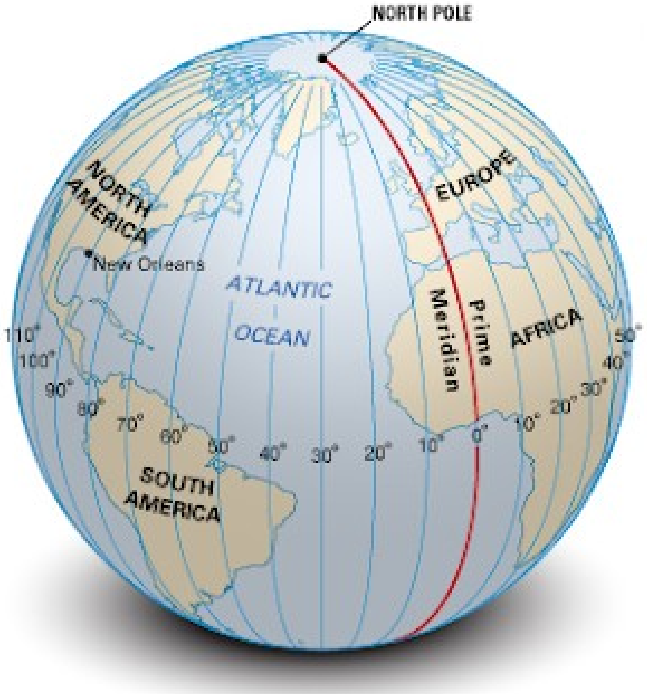


The parallels of latitude

Longitude [-90-90˚]

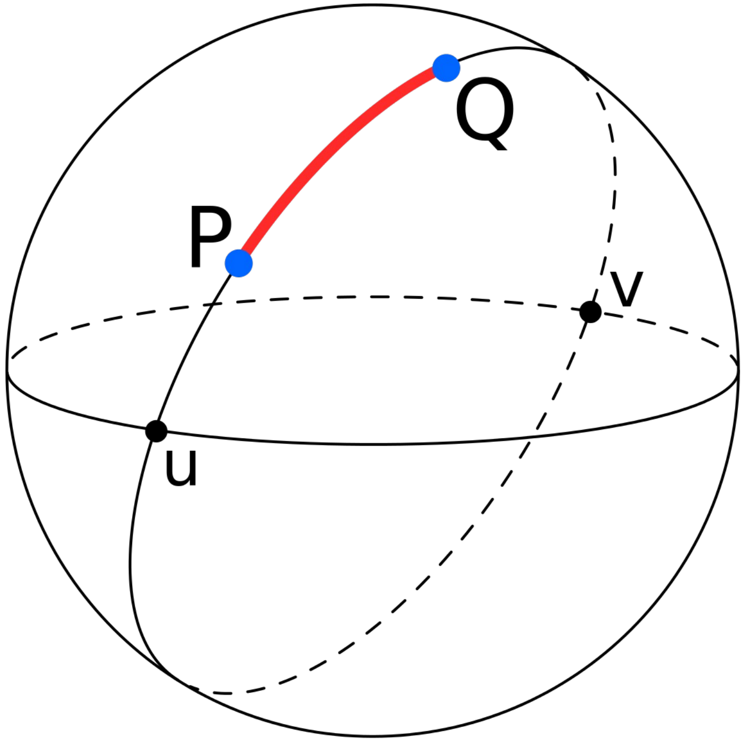
- Latitudinal circles: meridians
- All of them are great circles!
- Their distance decreases at the poles
- Direction: **meridional (v)**
- Notable circle:

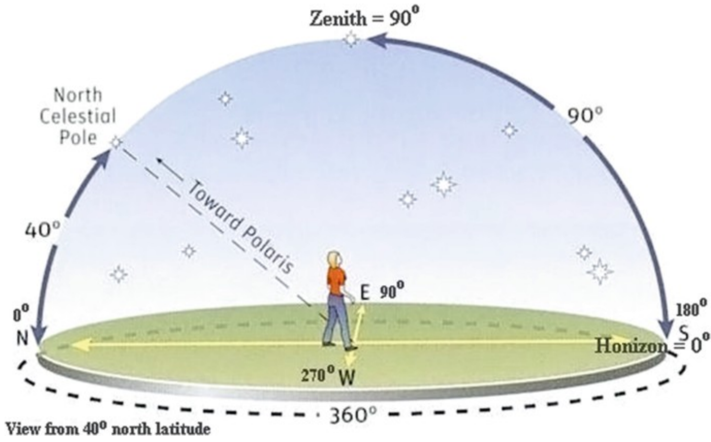


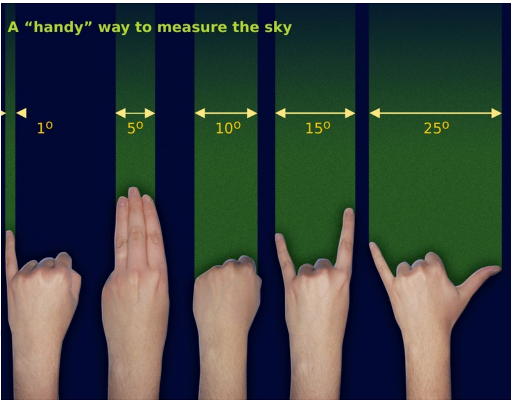


Distances

- Two points define a great circle
- Shortest distance between them is a great circle arc (Great Circle Distance)
- Distance on a surface of a sphere is simplest **in angles (degrees)**
- For practicality we give this in distance:
- 1° (longitude) = 1 nautical mile ~ 111.1 km

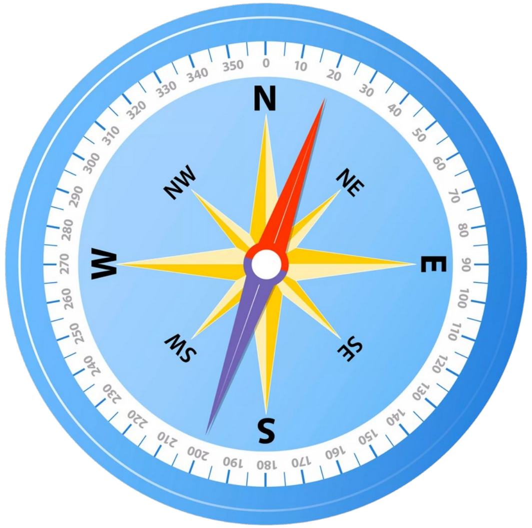


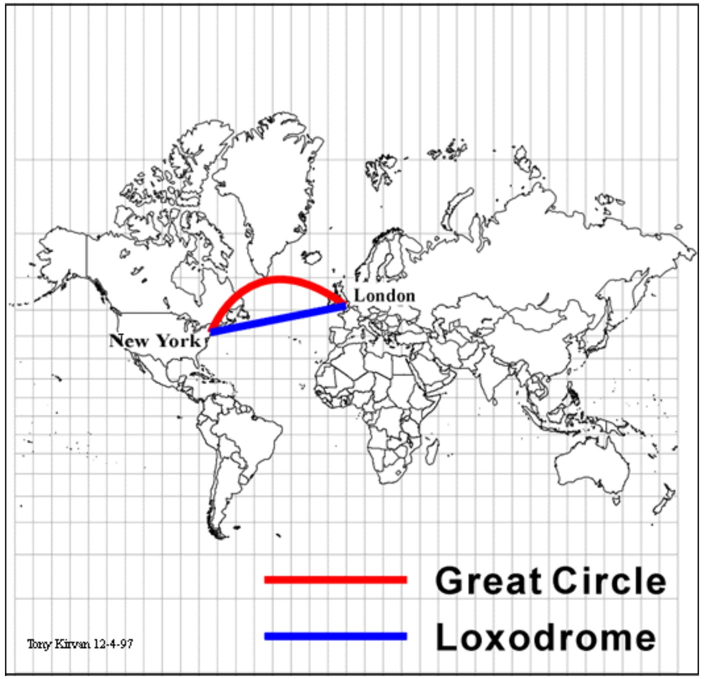




Directions

- Heading: angular distance to north
- Going straight: great circle
- Constant change of heading! (even without the true vs. magnetic difference)

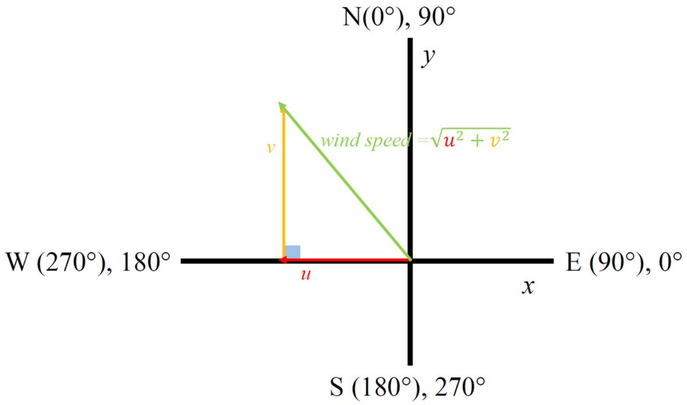




Mercator projection

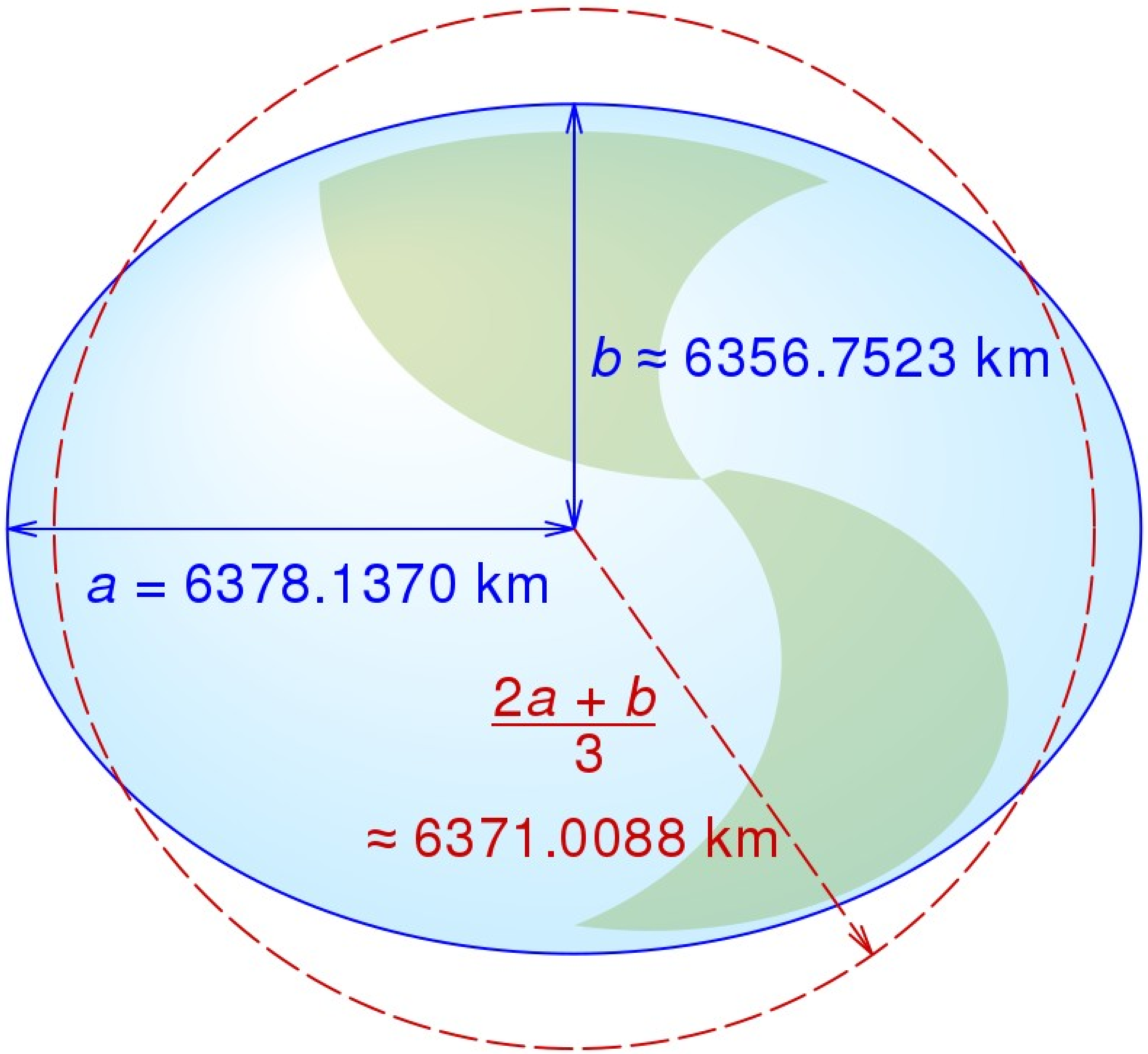
Vectors

- Given with a) initial heading and magnitude or b) as zonal and meridional components



The reference ellipsoid

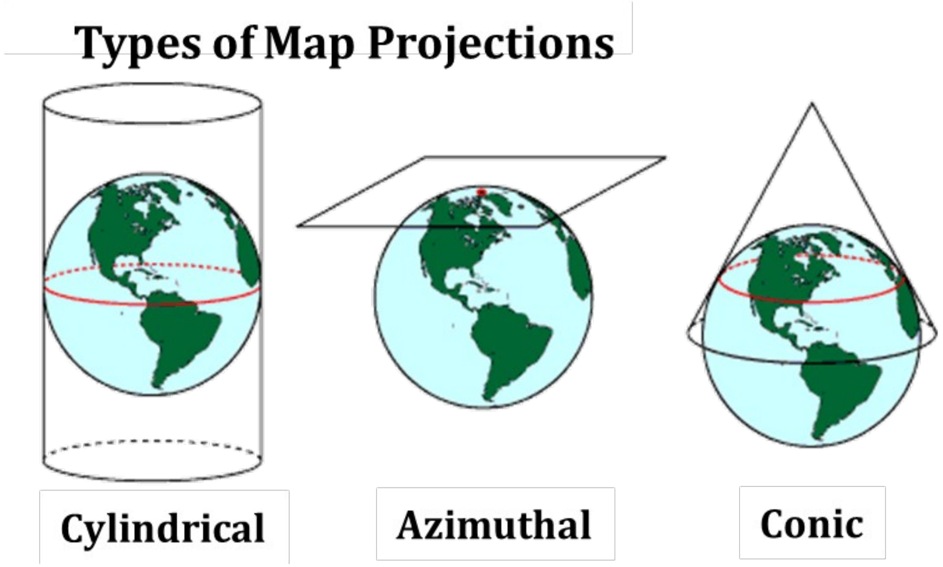
- Approximates the geoid
- Flattened rotational ellipsoid
- Used as a basis for elevation



Coordinate Reference Systems

Map projections

- There is dozens of them
- Complex transformations of spherical coordinates
- They all distort the globe in some sense:
  - conserve area and distort angles *(equal-area projection)*
  - distort area and conserve angles *(conformal projection)*
  - distort both area and angles



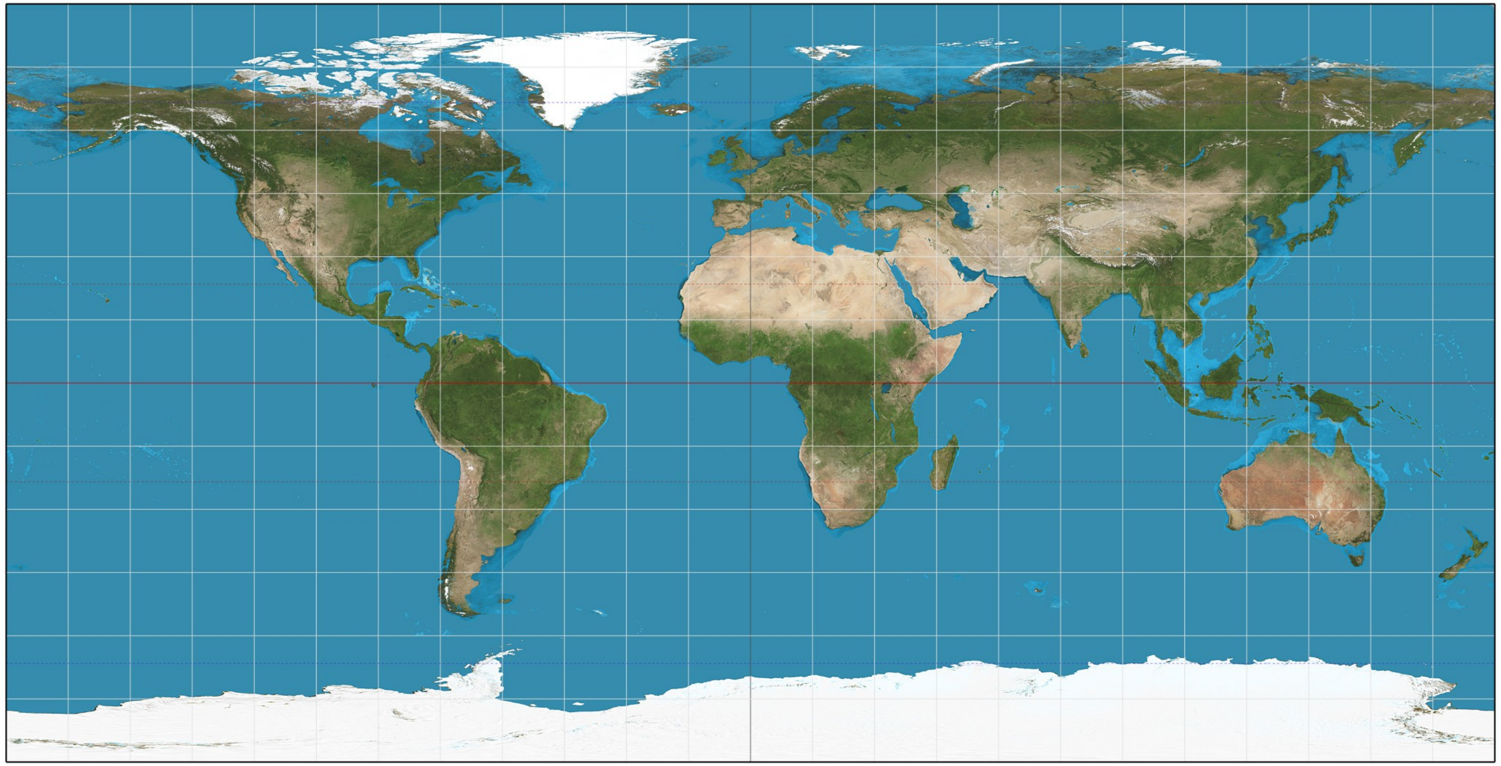
General types...

The True size of.. :
https://www.thetruesize.com

Coordinate Reference Systems

e.g. Equirectangular Projection

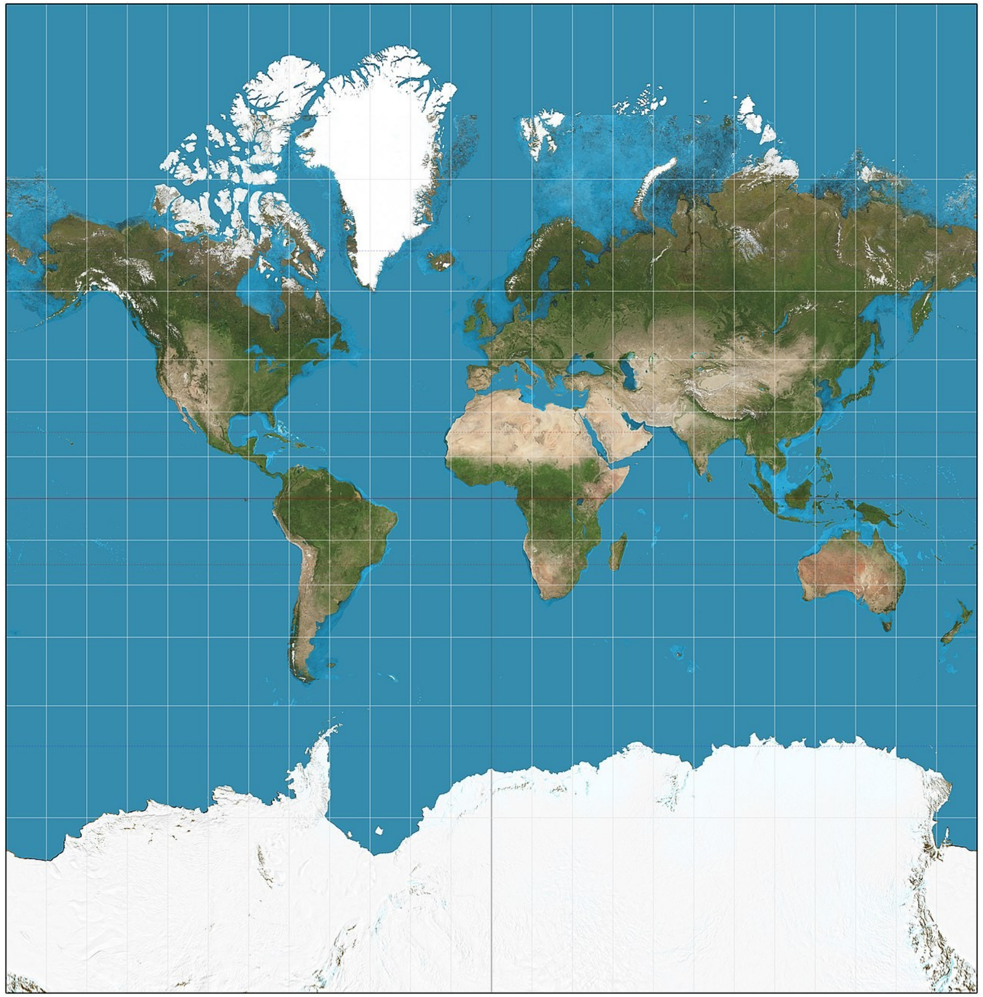
- Longitude (x) – Latitude (y)
- Centered around (0, 0)
- Plate Carée
- Most frequently used for visualization of global-scale data
- Distorts everything



Coordinate Reference Systems

e.g. Mercator projection

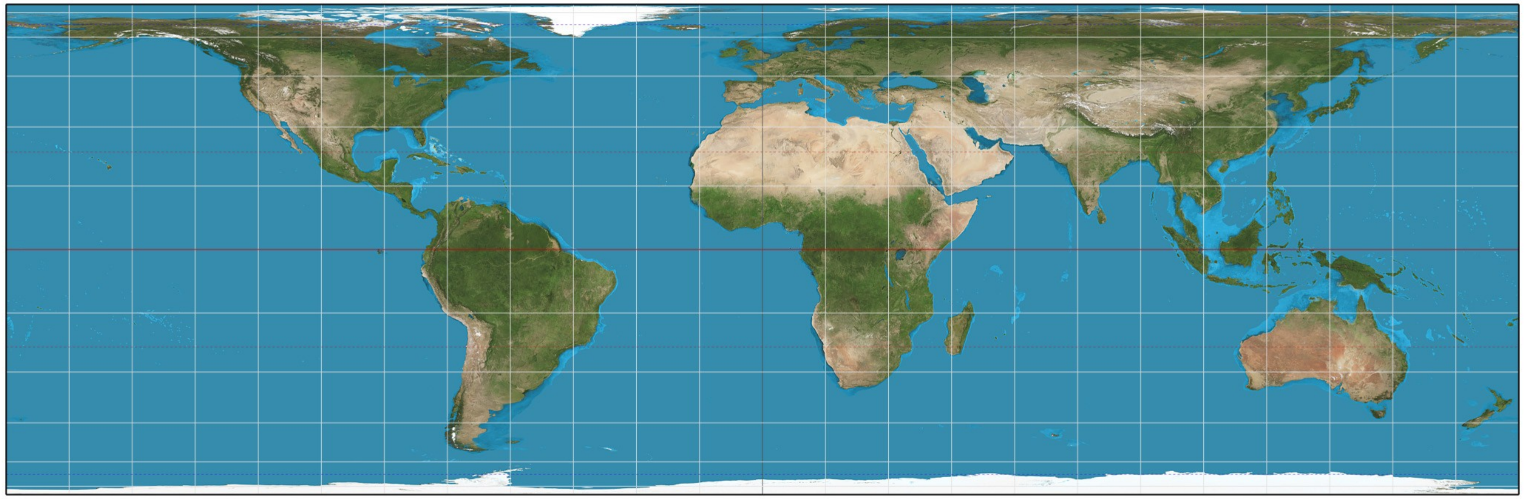
- Conformal
- (nautical use)
- Highly distorts areas
- Cannot represent poles
- Variant: Google Earth



Coordinate Reference Systems

e.g. Lambert’s Cylindrical EA Projection

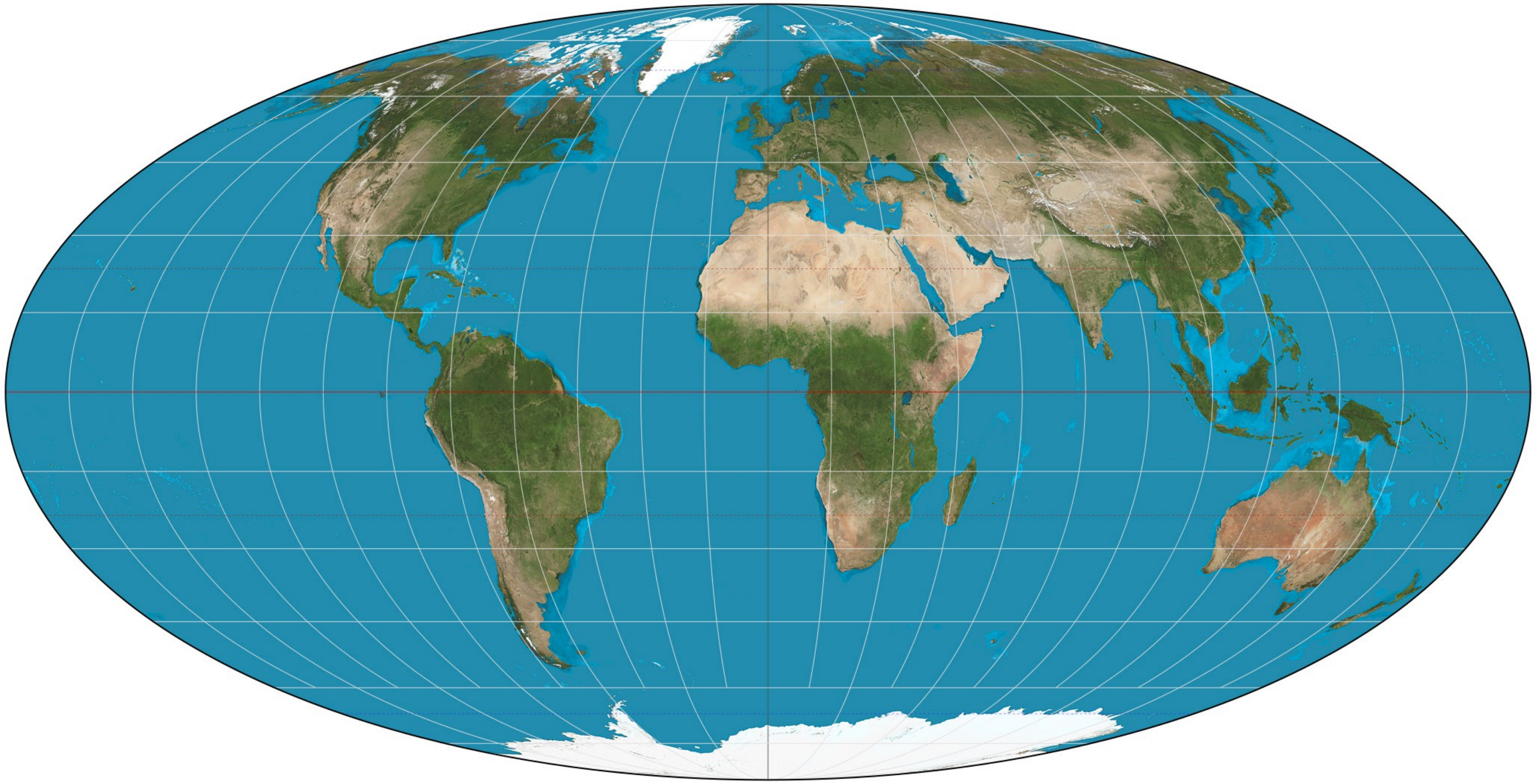
- Equal-area
- Highly distorts angles latitudinally



Coordinate Reference Systems

e.g. Mollweide Projection

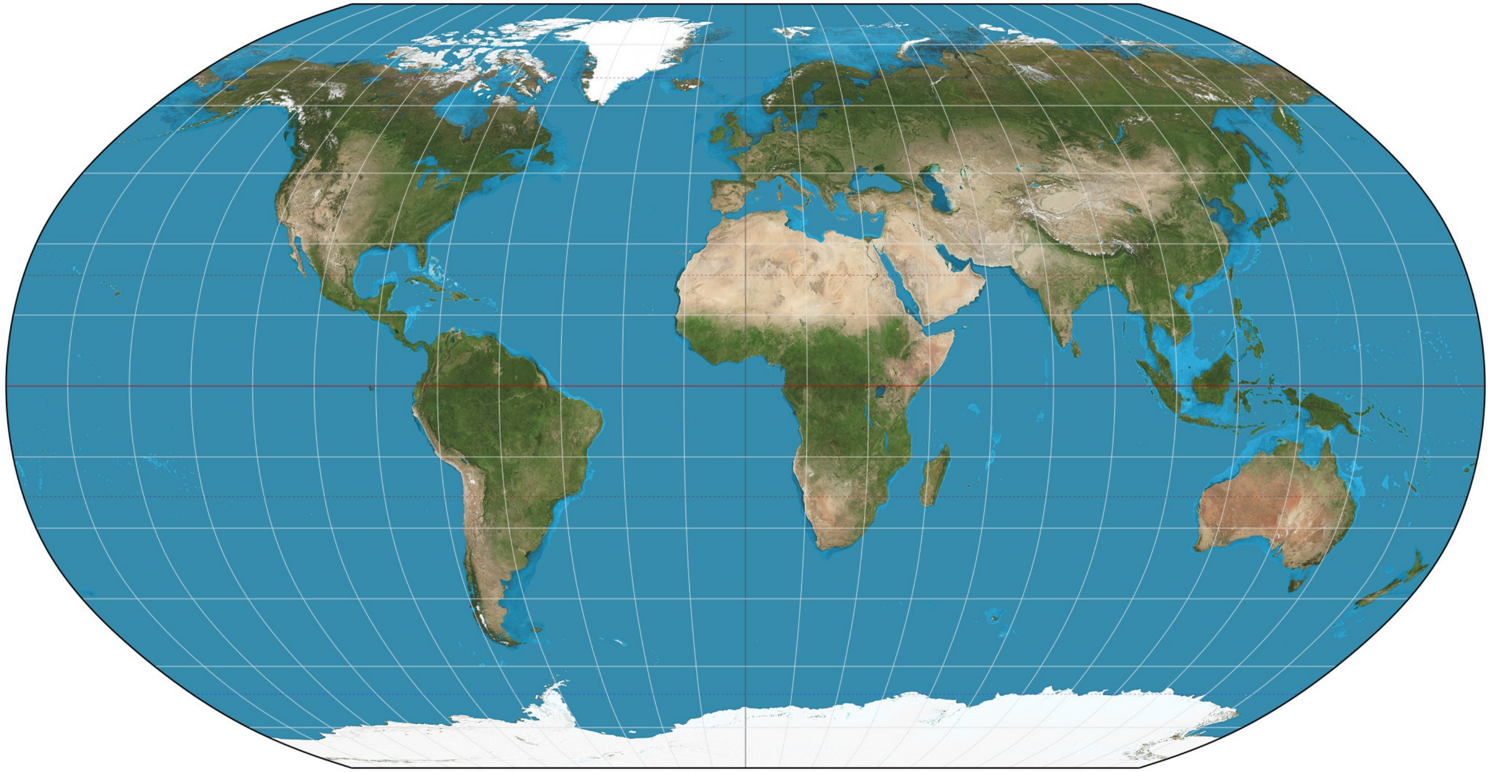
- Equal-area
- Highly distorts angles longitudinally



Coordinate Reference Systems

e.g. Robinson Projection

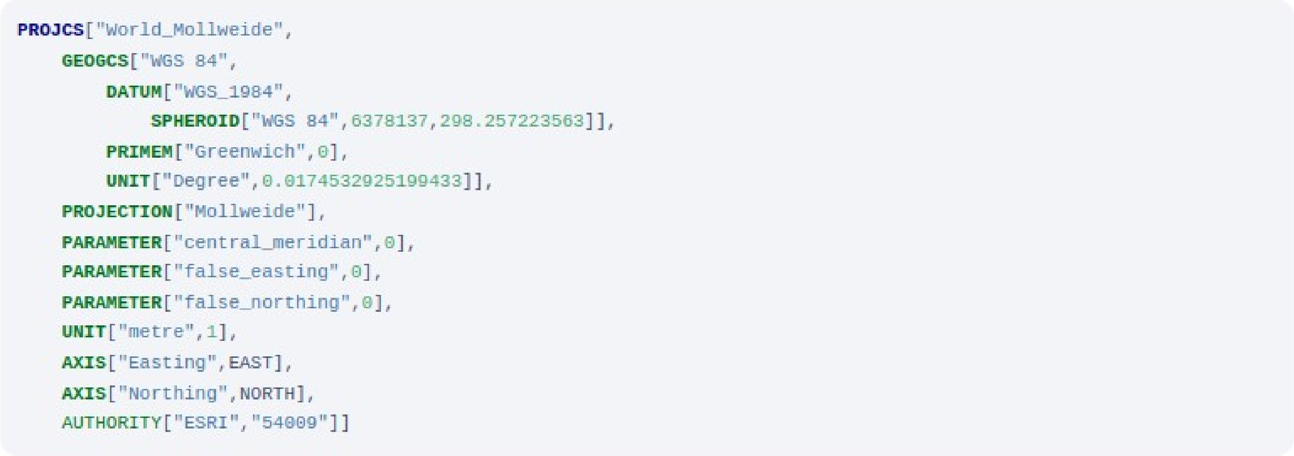
- Distorts both angles and areas
- Relatively representative
- Promoted by NatGeo and now used by IPCC



Coordinate Reference Systems

Representation

- Older: PROJ.4 string: “+proj=moll”
- Well known text WKT2 string



```
PROJCS["World_Mollweide",
    GEOGCS["WGS 84",
        DATUM["WGS_1984",
            SPHEROID["WGS 84",6378137,298.257223563]],
        PRIMEM["Greenwich",0],
        UNIT["Degree",0.0174532925199433]],
    PROJECTION["Mollweide"],
    PARAMETER["central_meridian",0],
    PARAMETER["false_easting",0],
    PARAMETER["false_northing",0],
    UNIT["metre",1],
    AXIS["Easting",EAST],
    AXIS["Northing",NORTH],
    AUTHORITY["ESRI","54009"]]
```

- EPSG registry ID (epsg.io) : ESRI:54009

EPSG

GEODETIC PARAMETER DATASET

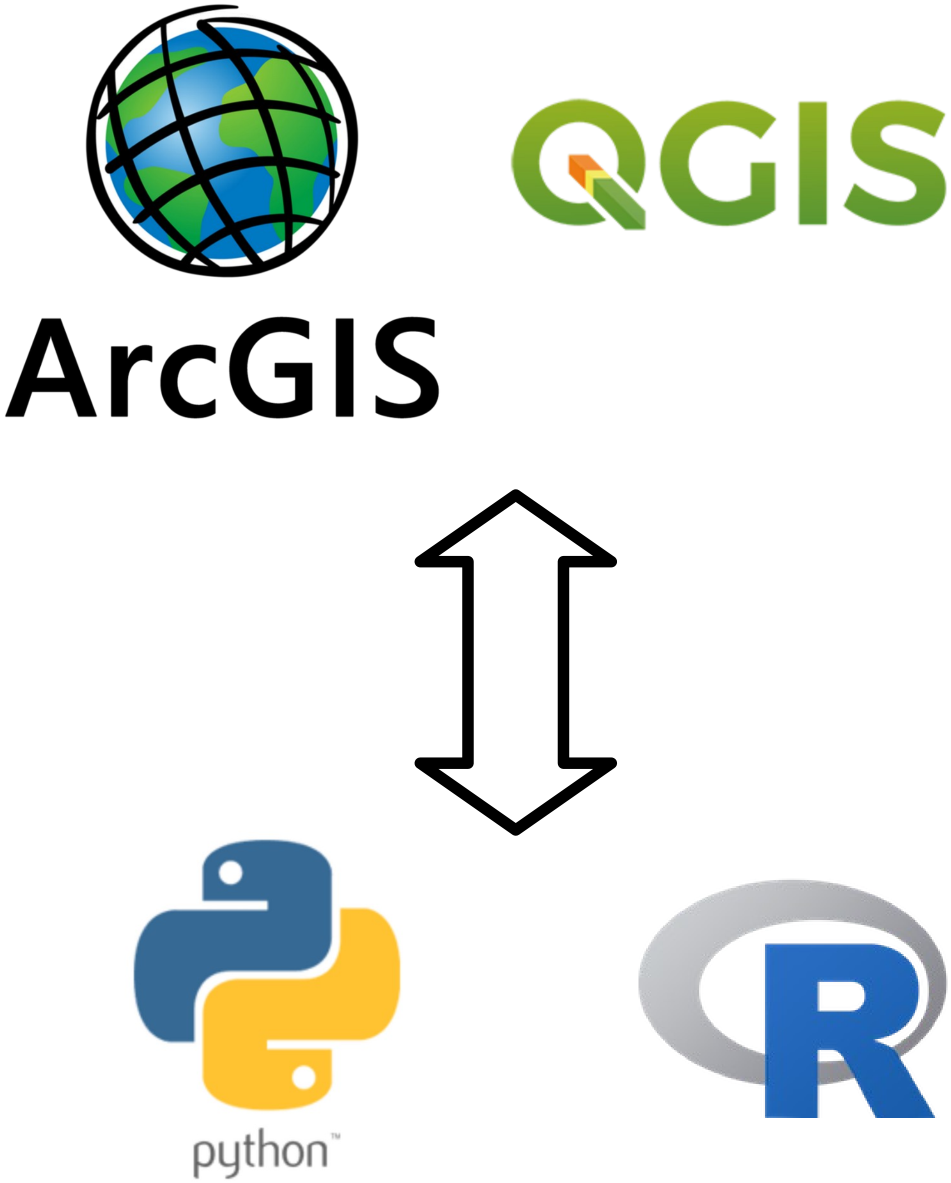
Managed by IOGP’s Geomatics Committee

Implementation

Where, what, why?

GIS tools: Why R?

- Automatized manipulation and extraction of data
- Larger quantity of work then with a GUI
- Python is much more powerful
- Integration with other analyses
- Statistical analyses



The Spatial ecosystem

- Multiple R extension packages form the backbone
- The heart: Open Source Geospatial Foundation
- Recipe:
    - **Open source libraries for calculations + R interface**

- R packages hook on the APIs of these libraries
- + extra calculations in compiled code (C, C++, Fortran)

Open Source Libraries/Projects

GDAL: Geodetic Data Abstraction Library

- Definitions of data formats
- Translation between data formats
- https://gdal.org/

Open Source Libraries/Projects

PROJ

- Coordinate transformation
- Definition of Coordinate Reference Systems (CRS) and translation
- Current version is 9.2.1 (June 2023)
- R packages rely on older versions (PROJ4 or PROJ6)

Open Source Libraries/Projects

GEOS: Geometry Open Source

- Computational geometry especially towards the manipulation of spatial data
- http://libgeos.org/

The R packages

- Only some are essential, they are on the CRAN
- They are using the libraries
- Class definitions and basic methods
- Lots of packages build on these...

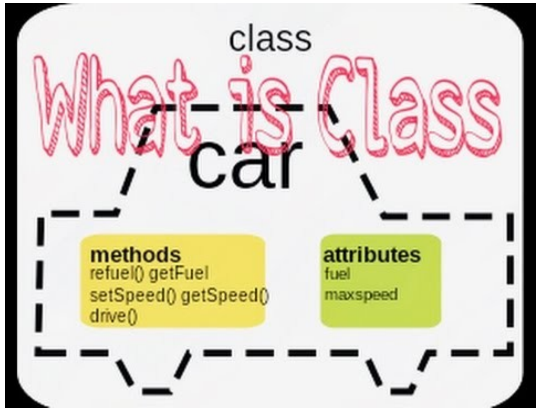
⇩

Lot of dependencies, slow development

⇩

The current mess

What is a class?



https://www.youtube.com/watch?v=XqrkcO42DI8

Packages

	old	new
vector	`sp, rgdal, rgeos`	`sf, terra`
raster	`raster`	`terra, stars`

+ others: e.g. `geosphere`

Installing all of them

Focus on the new but...

- On Windows this is trivial, you can get all from the CRAN with `install.packages()`
- On Mac (and Linux), it is recommended to install them one at a time. They will a) either tell you what libraries need to be installed so they can function properly, 2) only indicate errors and then we have to google :)
- The list, again:

```
sp raster rgdal rgeos terra sf (stars) geosphere
```

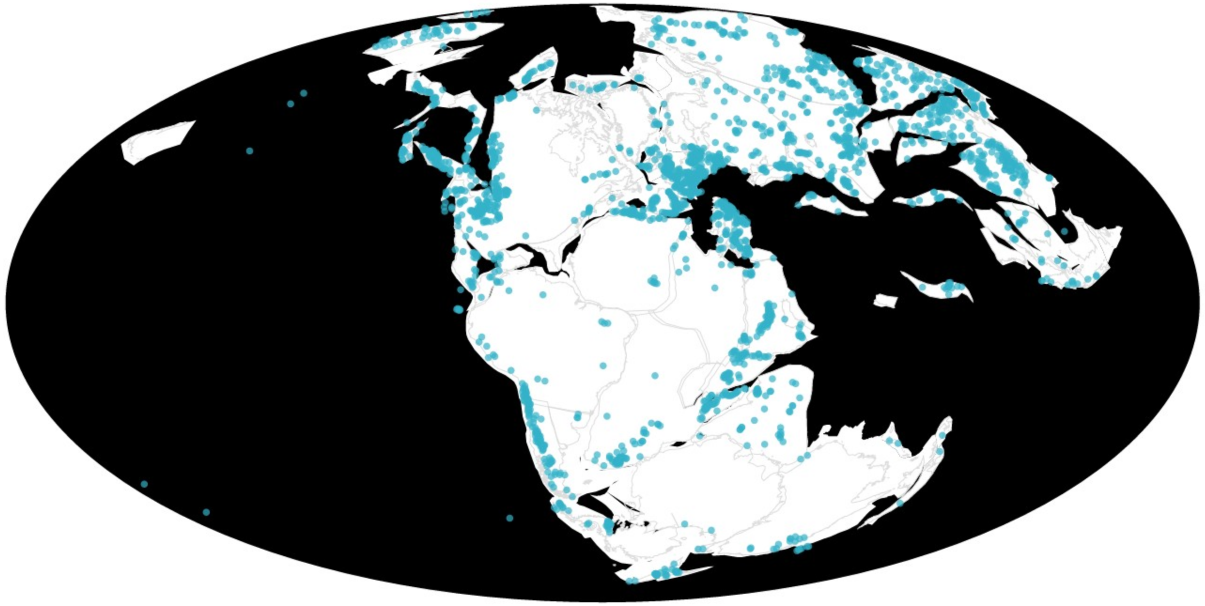
Vector data

with sf (and sp, rgdal, and rgeos)

Data concepts

Feature types: points

- A feature is a thing – everything is a feature, that can be combined to form sets.
  - **Geometry**: It has coordinates and a CRS
  - **Attributes**: every point has data such as age, name, id etc..
- Features can be combined into sets, e.g. Multipoint

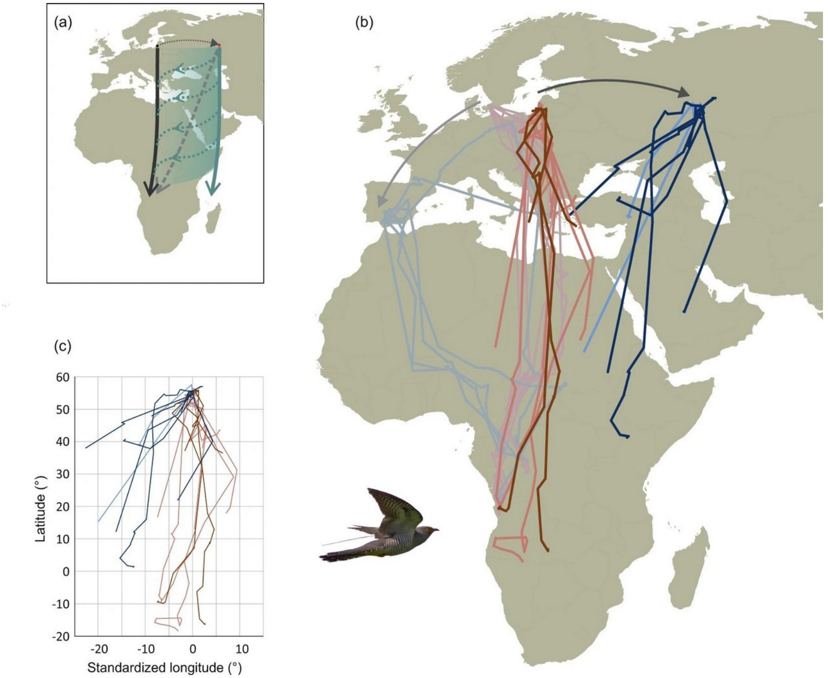


Fossil occurrences in the PBDB

Data concepts

Feature types: line

- Made up of sequence of points
  - One line: path, GPS track
  - Multiline: multiple paths combined that represent one thing
- Both a single line and a multiline can have attributes



Thorup et al. 2020 Sci. Rep.

Data concepts

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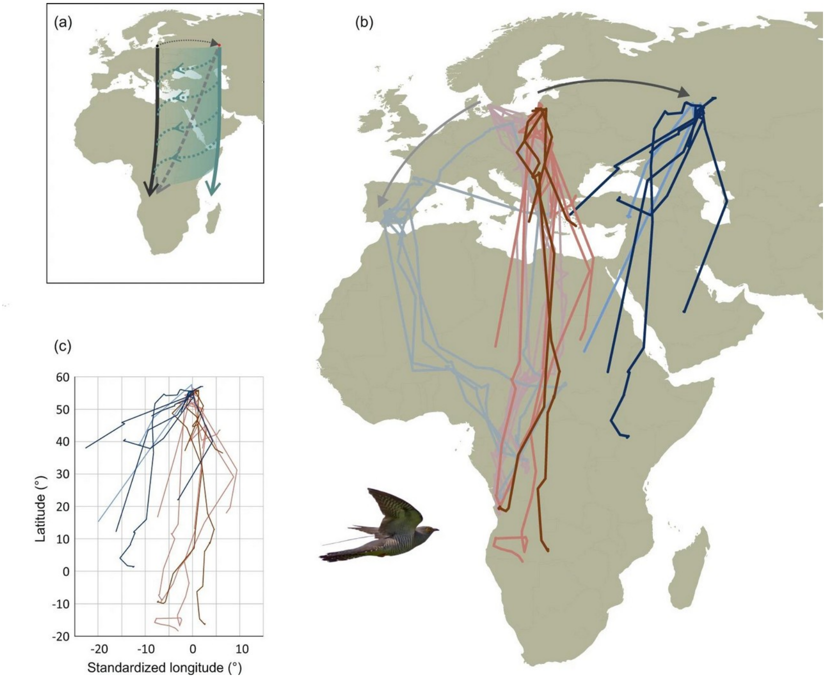
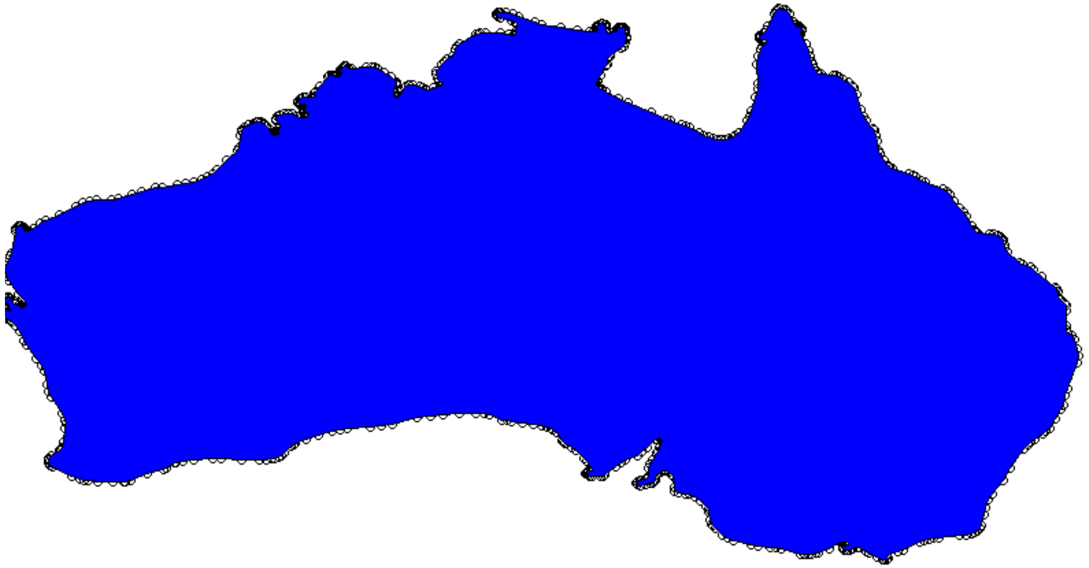


Thorup et al. 2020 Sci. Rep.

Data concepts

Feature types: Single Polygons

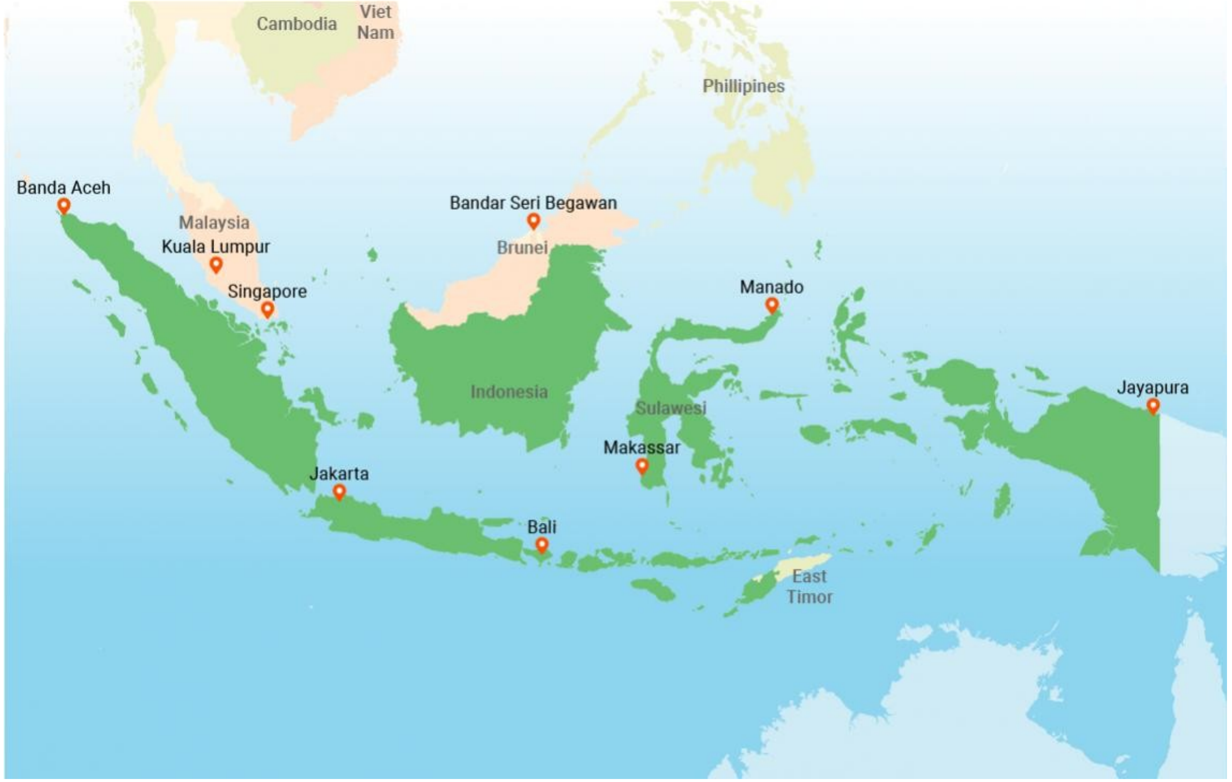
- Made up of sequence of points
- Closed to separate inside from outside
- Every polygon has attributes
- E.g. every island/landmass is by definition one polygon



Data concepts

Feature types: Multiple polygons

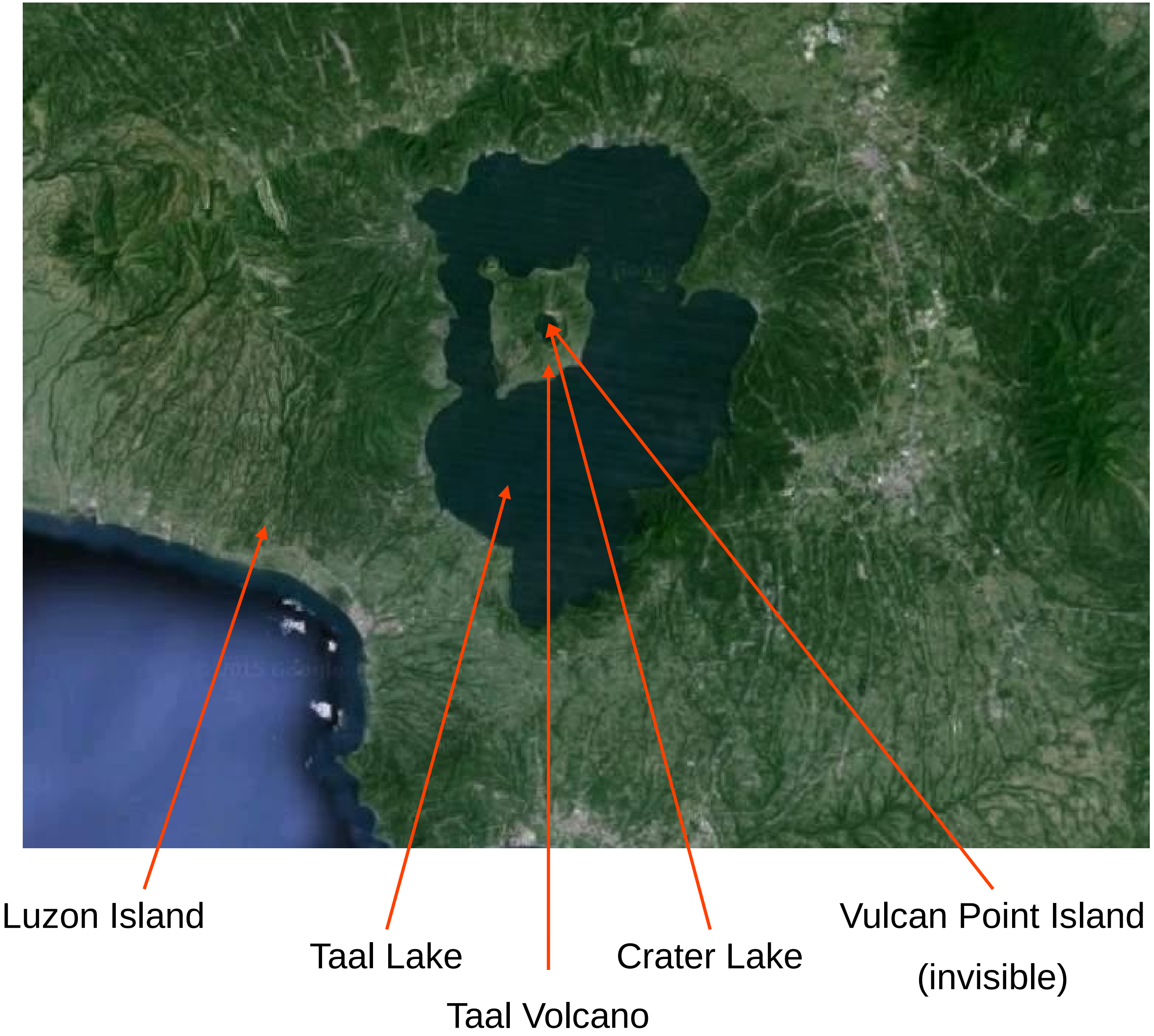
- Polygons can be combined to represent single entities
- One thing is represented by multiple polygons, e.g. a country



Data concepts

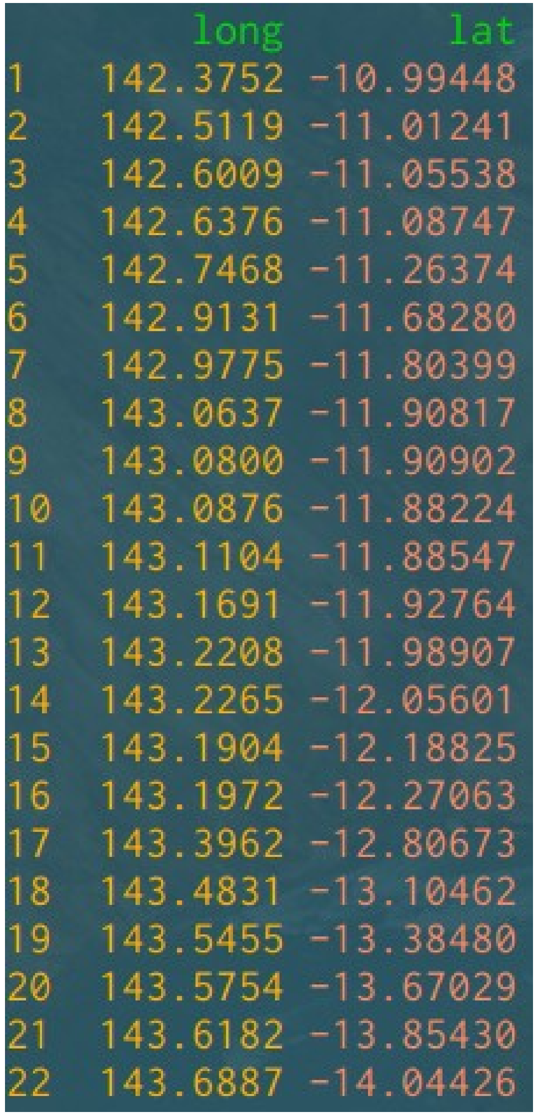
Feature types: Multiple polygons

- Polygons can have holes
- Holes are also polygons that are inside other polygons
- The direction of points defines whether something is a hole or not



Registering complex data in R

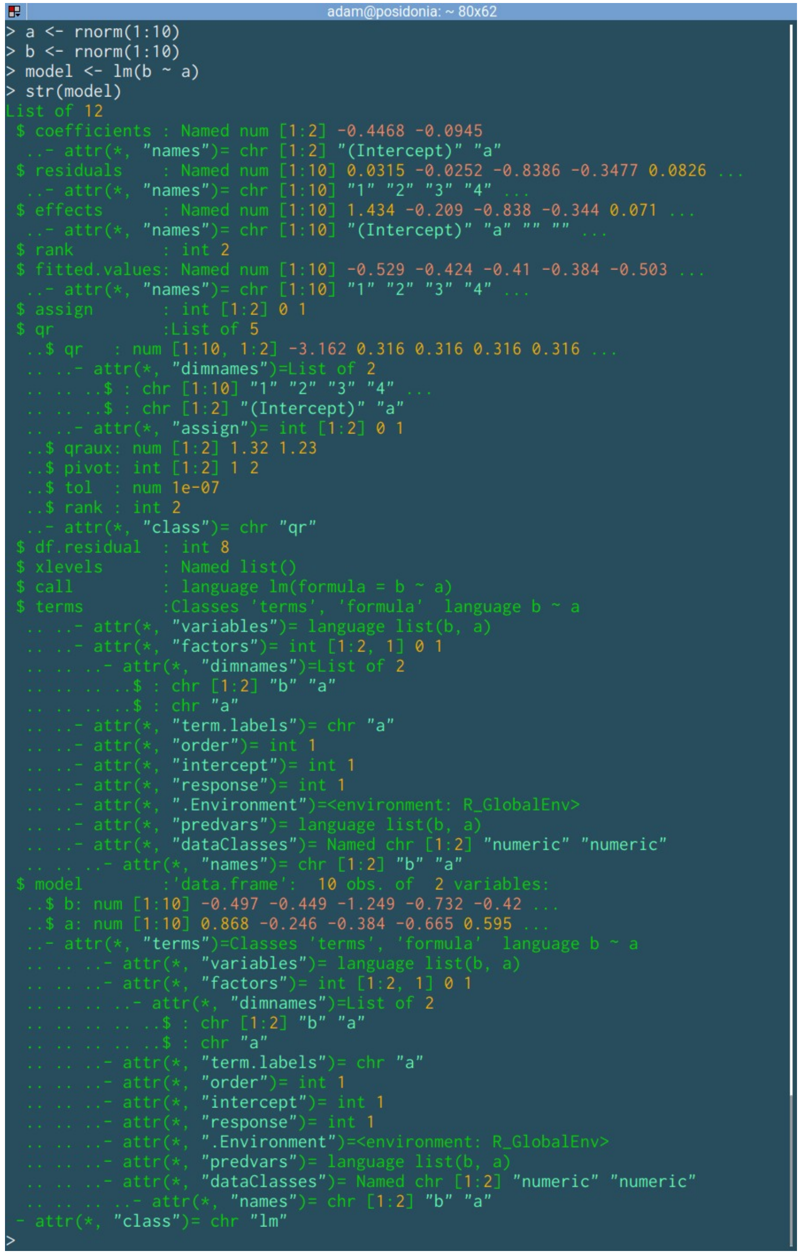
- For GIS, 2 column matrices can do the job for points, lines and polygons
- You can create lists of Polygons and lists of that, but it quickly becomes a mess…
- S3 and S4 classes



```
       long       lat
1  142.3752 -10.99448
2  142.5119 -11.01241
3  142.6009 -11.05538
4  142.6376 -11.08747
5  142.7468 -11.26374
6  142.9131 -11.68280
7  142.9775 -11.80399
8  143.0637 -11.90817
9  143.0800 -11.90902
10 143.0876 -11.88224
11 143.1104 -11.88547
12 143.1691 -11.92764
13 143.2208 -11.98907
14 143.2265 -12.05601
15 143.1904 -12.18825
16 143.1972 -12.27063
17 143.3962 -12.80673
18 143.4831 -13.10462
19 143.5455 -13.38480
20 143.5754 -13.67029
21 143.6182 -13.85430
22 143.6887 -14.04426
```

S3 Objects

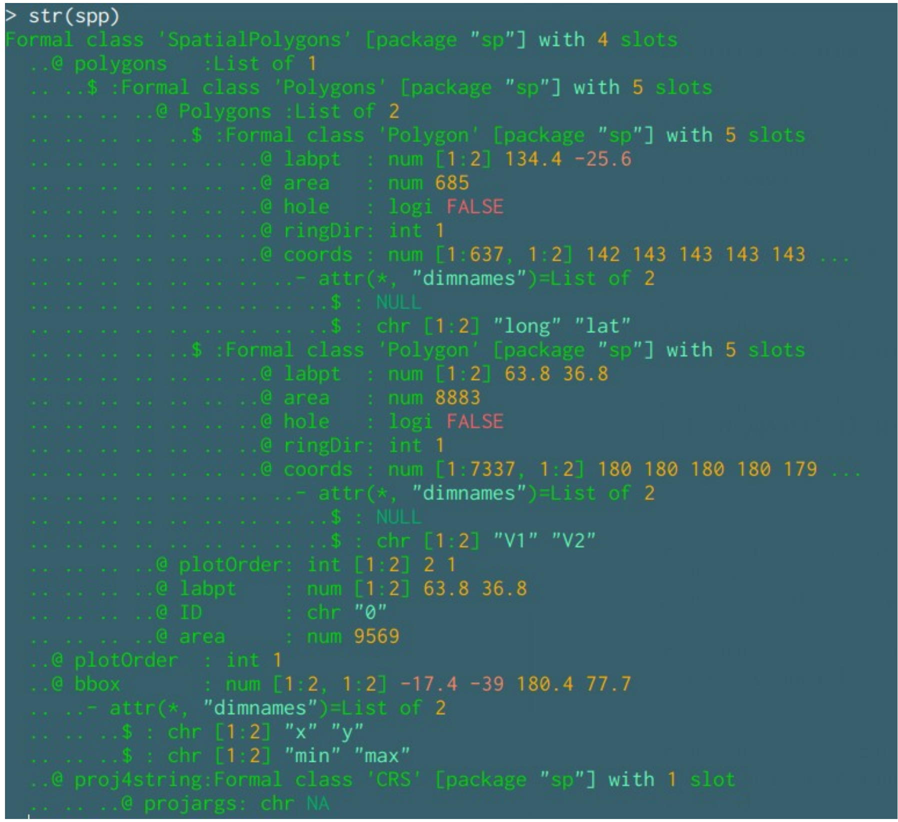
- Informal classes, which is based on a label: the `class` attribute
- They are often just lists: access elements with `$` or `[[]]`
- Example the “`lm`” class produced by `lm()`
- Methods dispatch works based on function names:
  - `predict.lm()` is called when `predict()` is used on an object that comes from this class
- There is no constraint on the object structure!
- Example in spatial: sf



```
> a <- rnorm(1:10)
> b <- rnorm(1:10)
> model <- lm(b ~ a)
> str(model)
List of 12
 $ coefficients : Named num [1:2] -0.4468 -0.0945
  ..- attr(*, "names")= chr [1:2] "(Intercept)" "a"
 $ residuals    : Named num [1:10] 0.0315 -0.0252 -0.8386 -0.3477 0.0826 ...
  ..- attr(*, "names")= chr [1:10] "1" "2" "3" "4" ...
 $ effects      : Named num [1:10] 1.434 -0.209 -0.838 -0.344 0.071 ...
  ..- attr(*, "names")= chr [1:10] "(Intercept)" "a" "" "" ...
 $ rank         : int 2
 $ fitted.values: Named num [1:10] -0.529 -0.424 -0.41 -0.384 -0.503 ...
  ..- attr(*, "names")= chr [1:10] "1" "2" "3" "4" ...
 $ assign       : int [1:2] 0 1
 $ qr           :List of 5
  ..$ qr   : num [1:10, 1:2] -3.162 0.316 0.316 0.316 0.316 ...
  .. ..- attr(*, "dimnames")=List of 2
  .. .. ..$ : chr [1:10] "1" "2" "3" "4" ...
  .. .. ..$ : chr [1:2] "(Intercept)" "a"
  .. ..- attr(*, "assign")= int [1:2] 0 1
  ..$ qraux: num [1:2] 1.32 1.23
  ..$ pivot: int [1:2] 1 2
  ..$ tol  : num 1e-07
  ..$ rank : int 2
  ..- attr(*, "class")= chr "qr"
 $ df.residual  : int 8
 $ xlevels      : Named list()
 $ call         : language lm(formula = b ~ a)
 $ terms        :Classes 'terms', 'formula'  language b ~ a
  .. ..- attr(*, "variables")= language list(b, a)
  .. ..- attr(*, "factors")= int [1:2, 1] 0 1
  .. .. ..- attr(*, "dimnames")=List of 2
  .. .. .. ..$ : chr [1:2] "b" "a"
  .. .. .. ..$ : chr "a"
  .. ..- attr(*, "term.labels")= chr "a"
  .. ..- attr(*, "order")= int 1
  .. ..- attr(*, "intercept")= int 1
  .. ..- attr(*, "response")= int 1
  .. ..- attr(*, ".Environment")=<environment: R_GlobalEnv>
  .. ..- attr(*, "predvars")= language list(b, a)
  .. ..- attr(*, "dataClasses")= Named chr [1:2] "numeric" "numeric"
  .. .. ..- attr(*, "names")= chr [1:2] "b" "a"
 $ model        :'data.frame':  10 obs. of  2 variables:
  ..$ b: num [1:10] -0.497 -0.449 -1.249 -0.732 -0.42 ...
  ..$ a: num [1:10] 0.868 -0.246 -0.384 -0.665 0.595 ...
  ..- attr(*, "terms")=Classes 'terms', 'formula'  language b ~ a
  .. .. ..- attr(*, "variables")= language list(b, a)
  .. .. ..- attr(*, "factors")= int [1:2, 1] 0 1
  .. .. .. ..- attr(*, "dimnames")=List of 2
  .. .. .. .. ..$ : chr [1:2] "b" "a"
  .. .. .. .. ..$ : chr "a"
  .. .. ..- attr(*, "term.labels")= chr "a"
  .. .. ..- attr(*, "order")= int 1
  .. .. ..- attr(*, "intercept")= int 1
  .. .. ..- attr(*, "response")= int 1
  .. .. ..- attr(*, ".Environment")=<environment: R_GlobalEnv>
  .. .. ..- attr(*, "predvars")= language list(b, a)
  .. .. ..- attr(*, "dataClasses")= Named chr [1:2] "numeric" "numeric"
  .. .. .. ..- attr(*, "names")= chr [1:2] "b" "a"
 - attr(*, "class")= chr "lm"
>
```

S4 Objects

- Formal classes, with a pre-defined structure
- The object has slots, that can have only specific types and they must have them!
- Slots can be accessed with the @ operator
- Methods are written more explicitly for the argument classes (with `setMethod()`)
- Most spatial objects use this framework!



```
> str(spp)
Formal class 'SpatialPolygons' [package "sp"] with 4 slots
  ..@ polygons   :List of 1
  .. ..$ :Formal class 'Polygons' [package "sp"] with 5 slots
  .. .. .. ..@ Polygons :List of 2
  .. .. .. .. ..$ :Formal class 'Polygon' [package "sp"] with 5 slots
  .. .. .. .. .. .. ..@ labpt  : num [1:2] 134.4 -25.6
  .. .. .. .. .. .. ..@ area   : num 685
  .. .. .. .. .. .. ..@ hole   : logi FALSE
  .. .. .. .. .. .. ..@ ringDir: int 1
  .. .. .. .. .. .. ..@ coords : num [1:637, 1:2] 142 143 143 143 143 ...
  .. .. .. .. .. .. .. ..- attr(*, "dimnames")=List of 2
  .. .. .. .. .. .. .. .. .. ..$ : NULL
  .. .. .. .. .. .. .. .. .. ..$ : chr [1:2] "long" "lat"
  .. .. .. .. ..$ :Formal class 'Polygon' [package "sp"] with 5 slots
  .. .. .. .. .. .. ..@ labpt  : num [1:2] 63.8 36.8
  .. .. .. .. .. .. ..@ area   : num 8883
  .. .. .. .. .. .. ..@ hole   : logi FALSE
  .. .. .. .. .. .. ..@ ringDir: int 1
  .. .. .. .. .. .. ..@ coords : num [1:7337, 1:2] 180 180 180 180 179 ...
  .. .. .. .. .. .. .. ..- attr(*, "dimnames")=List of 2
  .. .. .. .. .. .. .. .. .. ..$ : NULL
  .. .. .. .. .. .. .. .. .. ..$ : chr [1:2] "V1" "V2"
  .. .. .. ..@ plotOrder: int [1:2] 2 1
  .. .. .. ..@ labpt    : num [1:2] 63.8 36.8
  .. .. .. ..@ ID       : chr "0"
  .. .. .. ..@ area     : num 9569
  ..@ plotOrder  : int 1
  ..@ bbox       : num [1:2, 1:2] -17.4 -39 180.4 77.7
  .. ..- attr(*, "dimnames")=List of 2
  .. .. ..$ : chr [1:2] "x" "y"
  .. .. ..$ : chr [1:2] "min" "max"
  ..@ proj4string:Formal class 'CRS' [package "sp"] with 1 slot
  .. .. ..@ projargs: chr NA
```

An object from the old sp package

Package sp: Classes and Methods for Spatial Data

- Primarily by Edzer Pebesma and Roger Bivand
- From 2005
- The structures to represent the data in R
- S4 classes and how to interact with them
- Primarily used for vector data also some raster
  - `SpatialPoints(DataFrame)`
  - `SpatialLines(DataFrame)`
  - `SpatialPolygons(DataFrame)`

Vector File formats

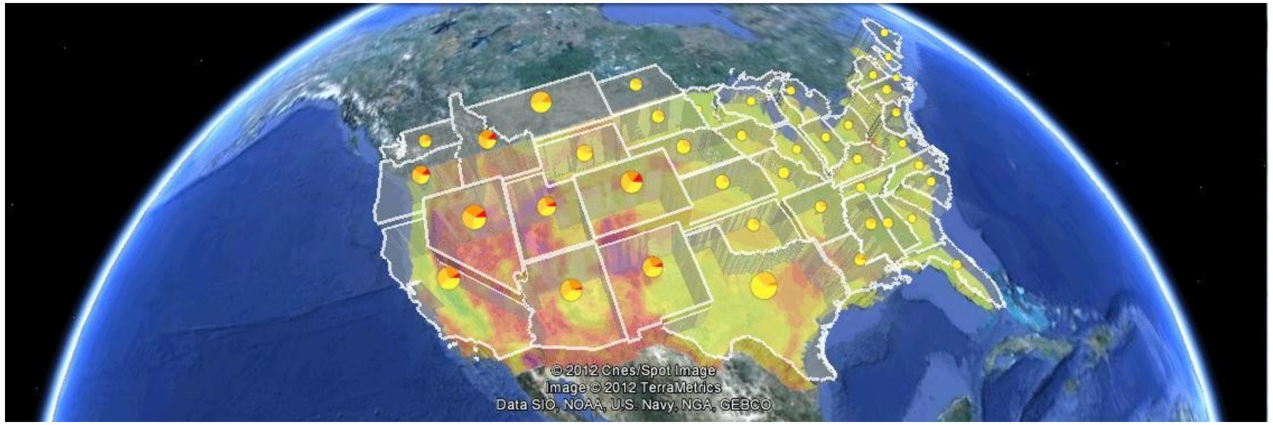
ESRI Shapefiles

- Multiple files represent the data
  - `.shx`: Index file, where is what
  - `.shp`: Main file, geometries
  - `.dbf`: Attribute information (dBASE)
  - `.prj`, `.sbn`, etc..

Vector File formats

Keyhole Markup Language

- `.kml` or `.kmz` file (z for zipped)
- Standard for the web



© 2012 Cnes/Spot Image
Image © 2012 TerraMetrics
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

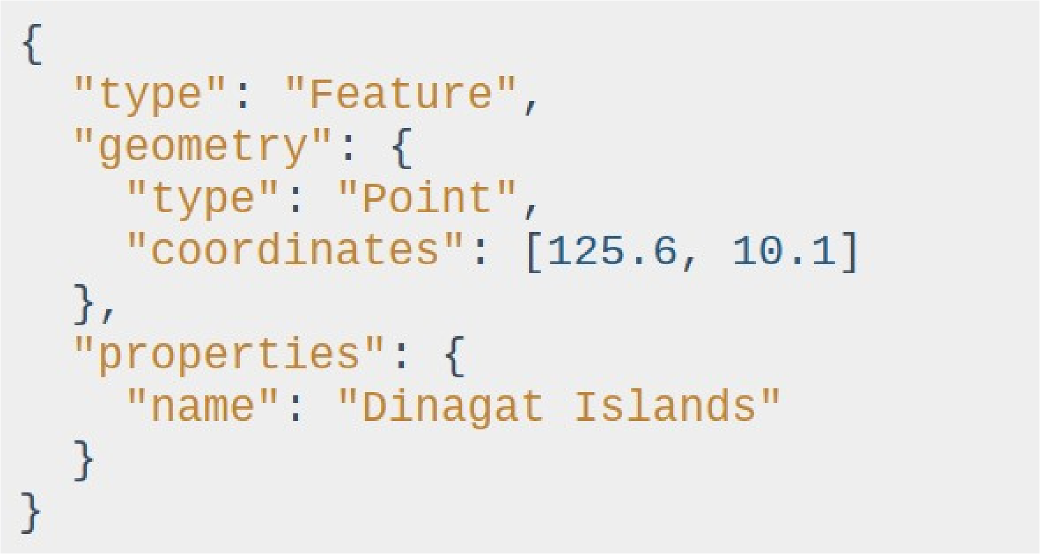
Google Earth uses .kml

Open
Geospatial
Consortium

Vector File formats

GeoJSON

- `.js .json` also for the web
- Human readable



```
{
  "type": "Feature",
  "geometry": {
    "type": "Point",
    "coordinates": [125.6, 10.1]
  },
  "properties": {
    "name": "Dinagat Islands"
  }
}
```

PostGIS

- Database-oriented (PostgreSQL)

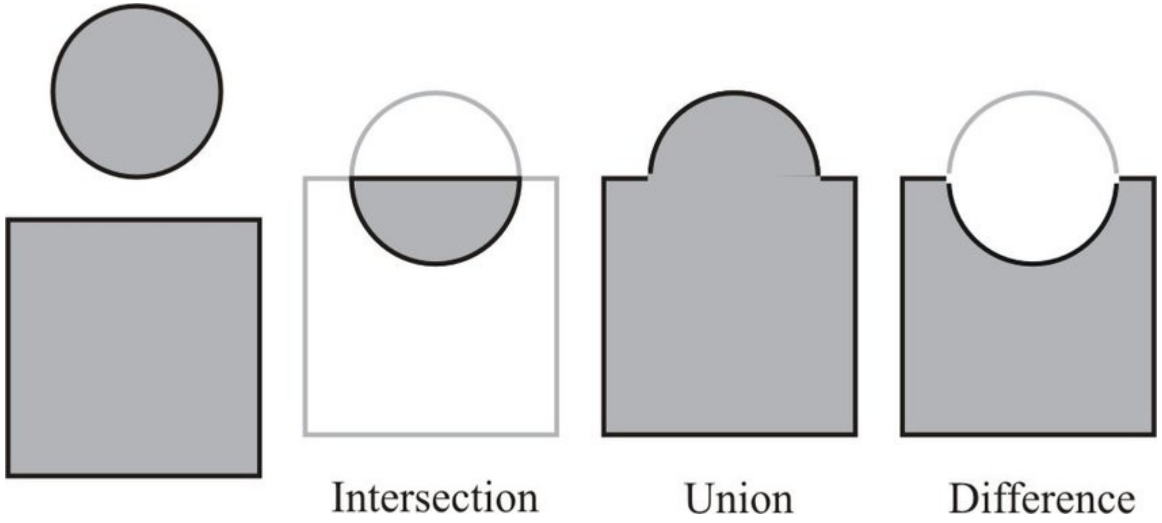
Package rgdal: Bindings for the 'Geospatial' Data Abstraction Library

- Primarily by Roger Bivand
- Interface to GDAL and PROJ<6
- Accessing data (I/O) and executing projections

OLD

Package rgeos: Interface to Geometry Engine - Open Source ('GEOS')

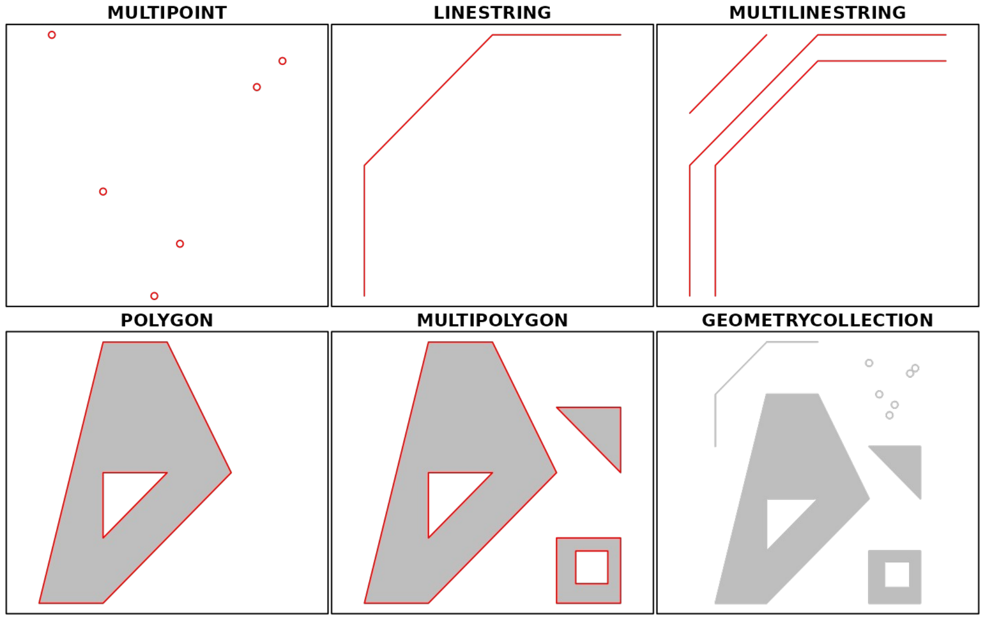
- Primarily by Roger Bivand
- Interface to GEOS
- Geometric calculations in the same CRS (e.g. Area)
- Boolean operations with shapes



OLD

Package sf: Simple Features for R

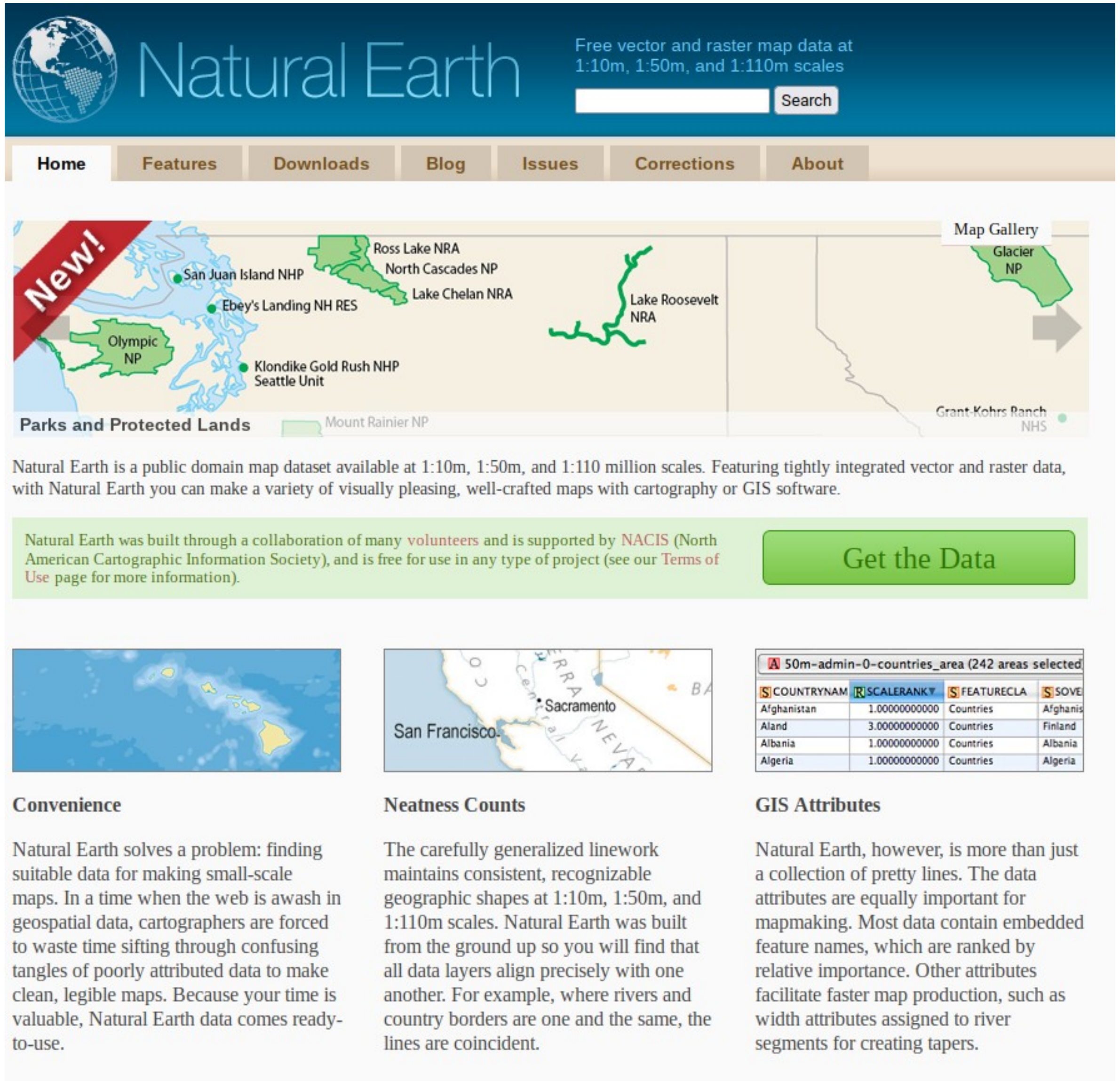
- Primarily by Edzer Pebesma
- From 2017
- Integrates with GDAL, GEOS and PROJ
- Uses the **simple feature** standard
- Good tidyverse integration



NEW

Example 1

- Coastlines Natural Earth
- Plotting a world map!



Natural Earth is a public domain map dataset available at 1:10m, 1:50m, and 1:110 million scales. Featuring tightly integrated vector and raster data, with Natural Earth you can make a variety of visually pleasing, well-crafted maps with cartography or GIS software.

Natural Earth was built through a collaboration of many volunteers and is supported by NACIS (North American Cartographic Information Society), and is free for use in any type of project (see our Terms of Use page for more information).

50m-admin-0-countries_area (242 areas selected

COUNTRYNAM	SCALERANK	FEATURECLA	SOVE
Afghanistan	1.00000000000	Countries	Afghanis
Aland	3.00000000000	Countries	Finland
Albania	1.00000000000	Countries	Albania
Algeria	1.00000000000	Countries	Algeria

Convenience

Natural Earth solves a problem: finding suitable data for making small-scale maps. In a time when the web is awash in geospatial data, cartographers are forced to waste time sifting through confusing tangles of poorly attributed data to make clean, legible maps. Because your time is valuable, Natural Earth data comes ready-to-use.

Neatness Counts

The carefully generalized linework maintains consistent, recognizable geographic shapes at 1:10m, 1:50m, and 1:110m scales. Natural Earth was built from the ground up so you will find that all data layers align precisely with one another. For example, where rivers and country borders are one and the same, the lines are coincident.

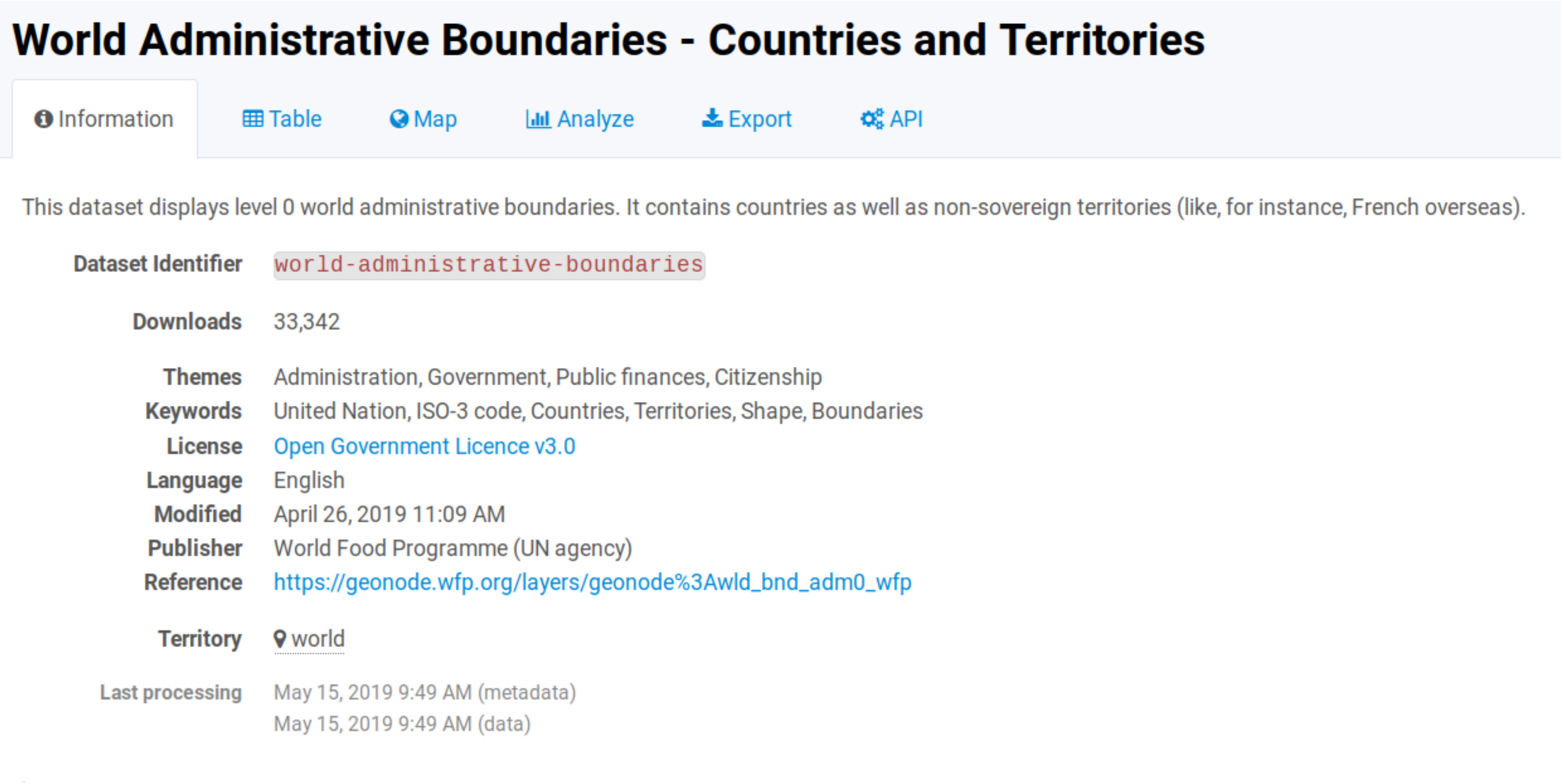
GIS Attributes

Natural Earth, however, is more than just a collection of pretty lines. The data attributes are equally important for mapmaking. Most data contain embedded feature names, which are ranked by relative importance. Other attributes facilitate faster map production, such as width attributes assigned to river segments for creating tapers.

https://www.naturalearthdata.com/downloads/110m-physical-vectors/

Example 2

- World Administrative Boundaries



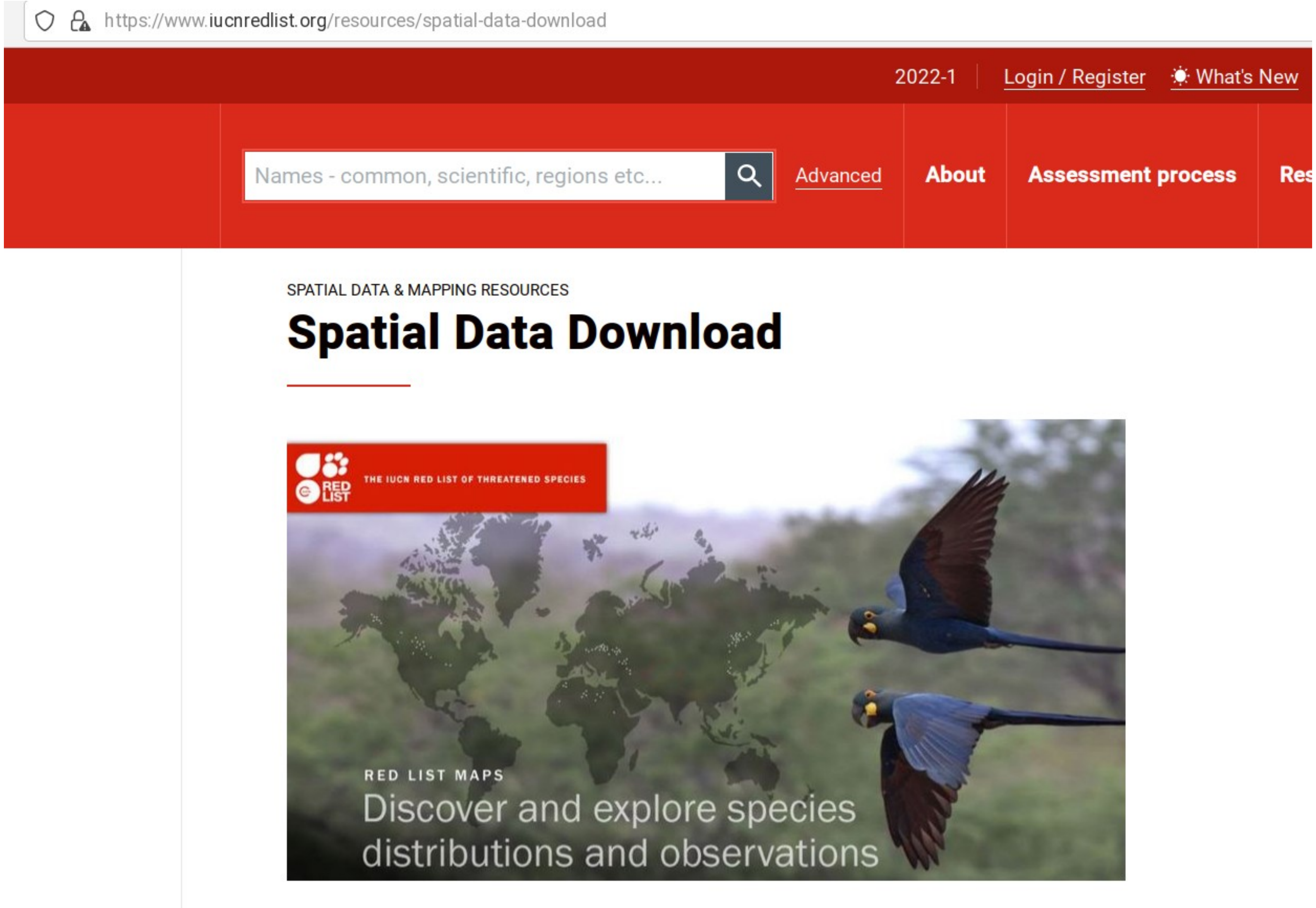
World Administrative Boundaries - Countries and Territories

This dataset displays level 0 world administrative boundaries. It contains countries as well as non-sovereign territories (like, for instance, French overseas).

Dataset Identifier	`world-administrative-boundaries`
Downloads	33,342
Themes	Administration, Government, Public finances, Citizenship
Keywords	United Nation, ISO-3 code, Countries, Territories, Shape, Boundaries
License	Open Government Licence v3.0
Language	English
Modified	April 26, 2019 11:09 AM
Publisher	World Food Programme (UN agency)
Reference	https://geonode.wfp.org/layers/geonode%3Awld_bnd_adm0_wfp
Territory	world
Last processing	May 15, 2019 9:49 AM (metadata) May 15, 2019 9:49 AM (data)

Example 3

- Range data from the IUCN
- Freely available for academic use



https://www.iucnredlist.org/resources/spatial-data-download

2022-1
Login / Register
What's New
Names - common, scientific, regions etc...
Advanced
About
Assessment process
Res

SPATIAL DATA & MAPPING RESOURCES

Spatial Data Download

RED LIST
THE IUCN RED LIST OF THREATENED SPECIES

RED LIST MAPS

Discover and explore species distributions and observations

Raster data

With terra (and raster)

Package raster: Geographic Data Analysis and Modeling

- Primarily by Robert Hijmans
- Since 2010
- Standard for raster processing for a long time
- Most ecological packages depend on this
- Integration of WorldClim data

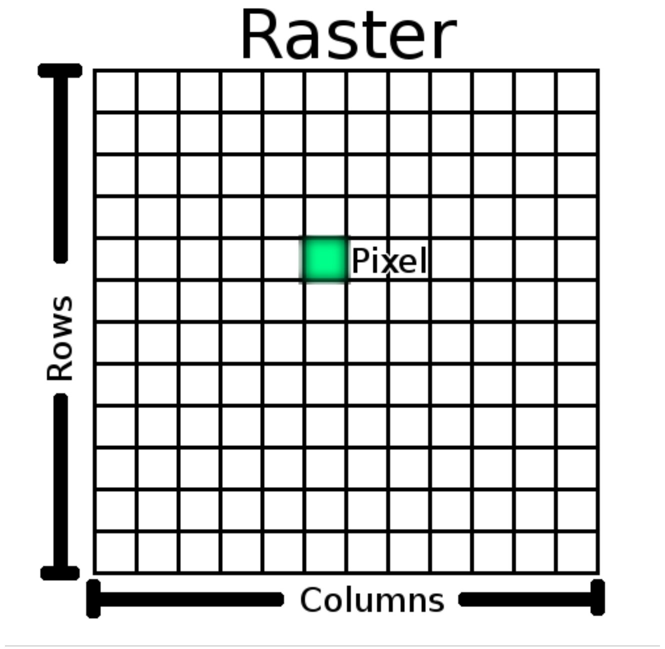
OLD

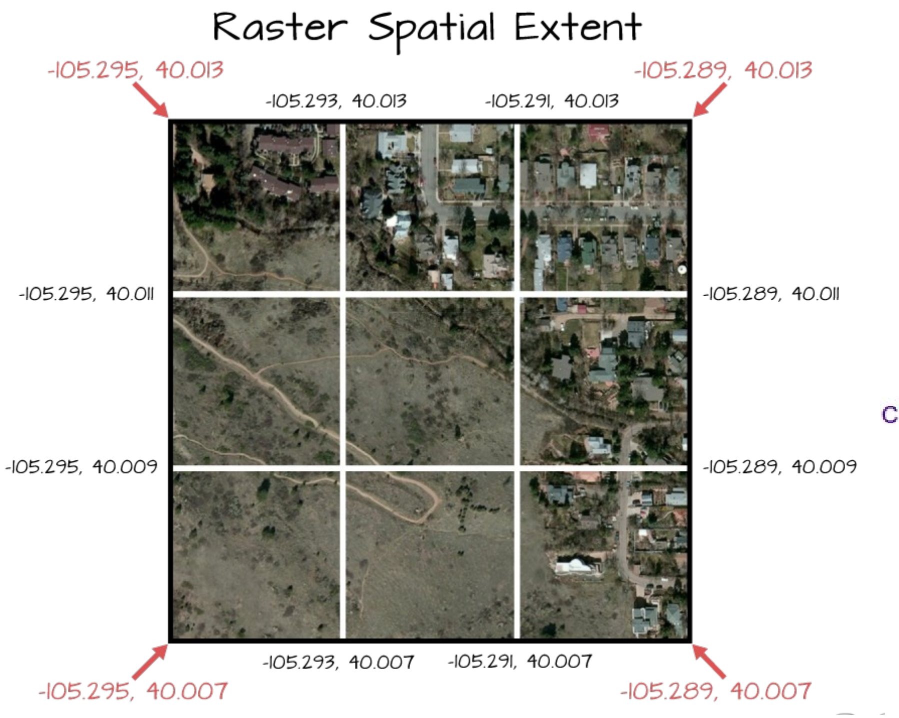
Package terra: Spatial Data Analysis

- Primarily by Robert Hijmans
- Interface to GEOS
- Almost the same as raster, this is the easier transition.

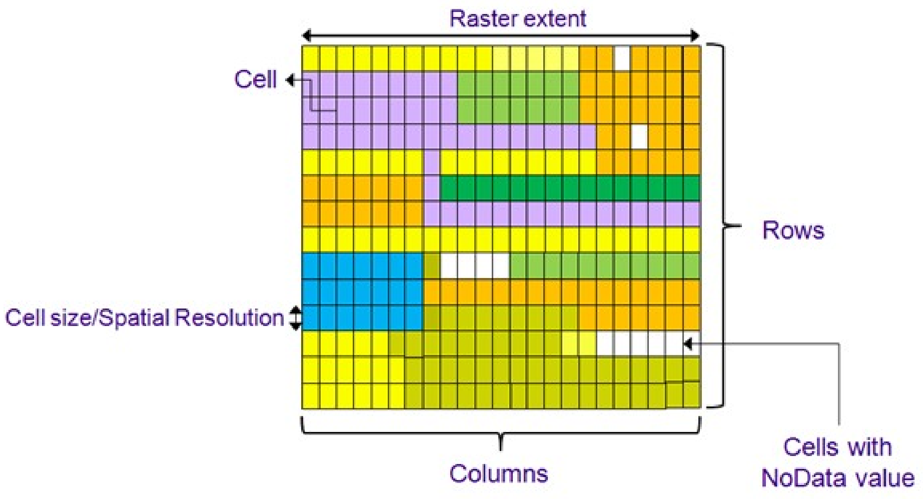
NEW

Raster properties



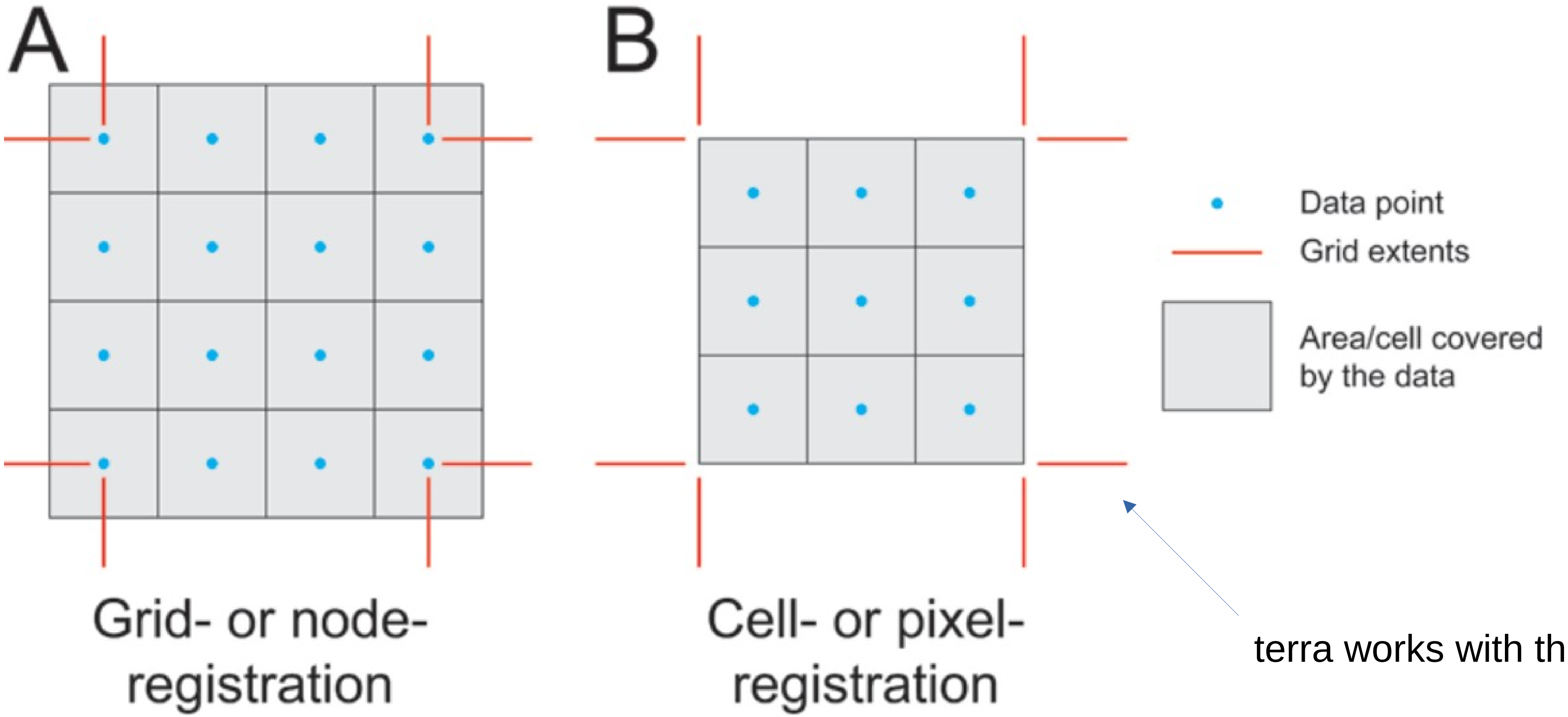


https://www.neonscience.org/resources/learning-hub/tutorials/raster-res-extent-pixels-r



https://sites.google.com/a/ncsu.edu/gis-520-portfolio-yujia-zhai/7-spatial-analysis-with-raster-data/1-basics-of-raster-data

Grid vs. cell registered rasters


A
B
Data point
Grid extents
Area/cell covered by the data
Grid- or node-registration
Cell- or pixel-registration

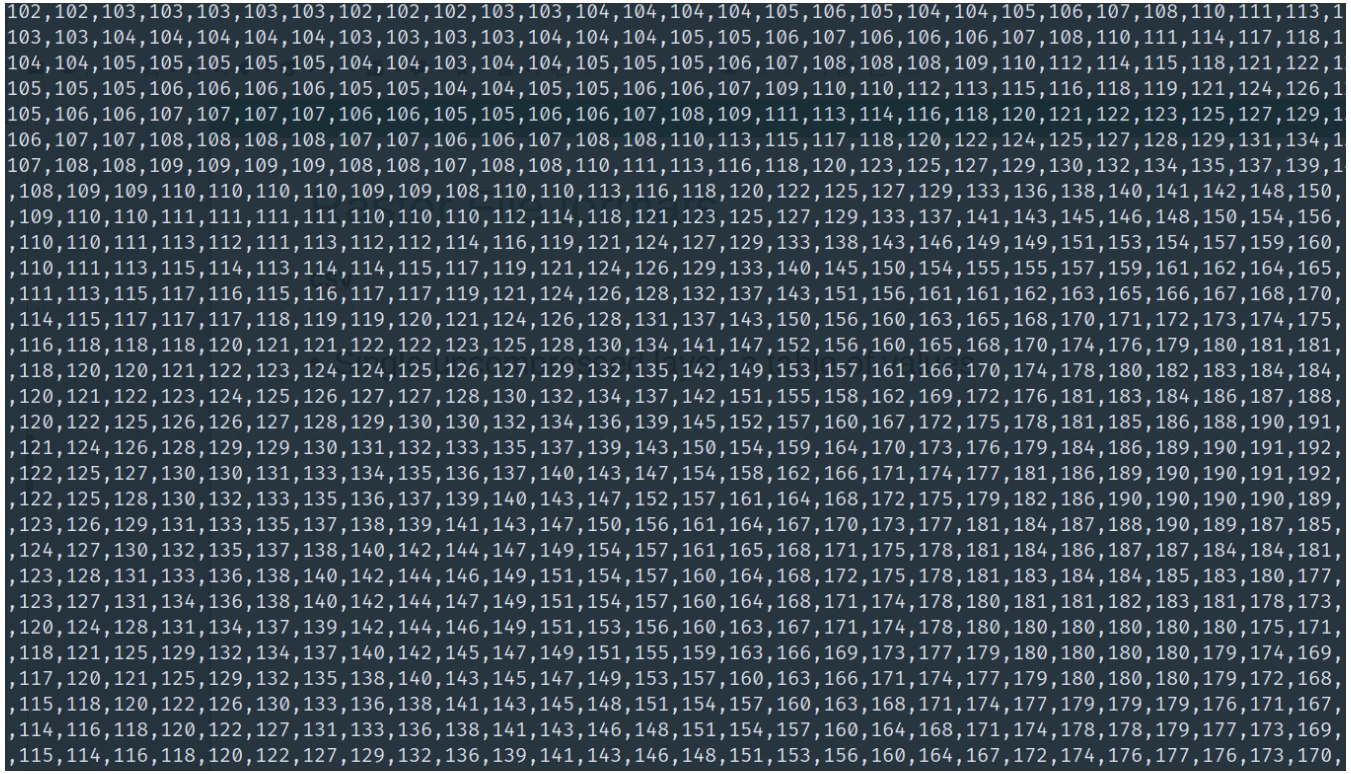
terra works with these

https://www.ncei.noaa.gov/products/grid-cell-registration

Raster File formats

csv

- Single uncompressed layer, a table of values
- Not properly georeferenced
- Column and row names might help



```
102,102,103,103,103,103,103,102,102,102,103,103,104,104,104,104,105,106,105,104,104,105,106,107,108,110,111,113,1
103,103,104,104,104,104,104,103,103,103,103,104,104,104,105,105,106,107,106,106,106,107,108,110,111,114,117,118,1
104,104,105,105,105,105,105,104,104,103,104,104,105,105,105,106,107,108,108,108,109,110,112,114,115,118,121,122,1
105,105,105,106,106,106,106,105,105,104,104,105,105,106,106,107,109,110,110,112,113,115,116,118,119,121,124,126,1
105,106,106,107,107,107,107,106,106,105,105,106,106,107,108,109,111,113,114,116,118,120,121,122,123,125,127,129,1
106,107,107,108,108,108,108,107,107,106,106,107,108,108,110,113,115,117,118,120,122,124,125,127,128,129,131,134,1
107,108,108,109,109,109,109,108,108,107,108,108,110,111,113,116,118,120,123,125,127,129,130,132,134,135,137,139,1
,108,109,109,110,110,110,110,109,109,108,110,110,113,116,118,120,122,125,127,129,133,136,138,140,141,142,148,150,
,109,110,110,111,111,111,111,110,110,110,112,114,118,121,123,125,127,129,133,137,141,143,145,146,148,150,154,156,
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,110,111,113,115,114,113,114,114,115,117,119,121,124,126,129,133,140,145,150,154,155,155,157,159,161,162,164,165,
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,118,120,120,121,122,123,124,124,125,126,127,129,132,135,142,149,153,157,161,166,170,174,178,180,182,183,184,184,
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,120,122,125,126,126,127,128,129,130,130,132,134,136,139,145,152,157,160,167,172,175,178,181,185,186,188,190,191,
,121,124,126,128,129,129,130,131,132,133,135,137,139,143,150,154,159,164,170,173,176,179,184,186,189,190,191,192,
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,123,126,129,131,133,135,137,138,139,141,143,147,150,156,161,164,167,170,173,177,181,184,187,188,190,189,187,185,
,124,127,130,132,135,137,138,140,142,144,147,149,154,157,161,165,168,171,175,178,181,184,186,187,187,184,184,181,
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,123,127,131,134,136,138,140,142,144,147,149,151,154,157,160,164,168,171,174,178,180,181,181,182,183,181,178,173,
,120,124,128,131,134,137,139,142,144,146,149,151,153,156,160,163,167,171,174,178,180,180,180,180,180,180,175,171,
,118,121,125,129,132,134,137,140,142,145,147,149,151,155,159,163,166,169,173,177,179,180,180,180,180,179,174,169,
,117,120,121,125,129,132,135,138,140,143,145,147,149,153,157,160,163,166,171,174,177,179,180,180,180,179,172,168,
,115,118,120,122,126,130,133,136,138,141,143,145,148,151,154,157,160,163,168,171,174,177,179,179,179,176,171,167,
,114,116,118,120,122,127,131,133,136,138,141,143,146,148,151,154,157,160,164,168,171,174,178,178,179,177,173,169,
,115,114,116,118,120,122,127,129,132,136,139,141,143,146,148,151,153,156,160,164,167,172,174,176,177,176,173,170,
```
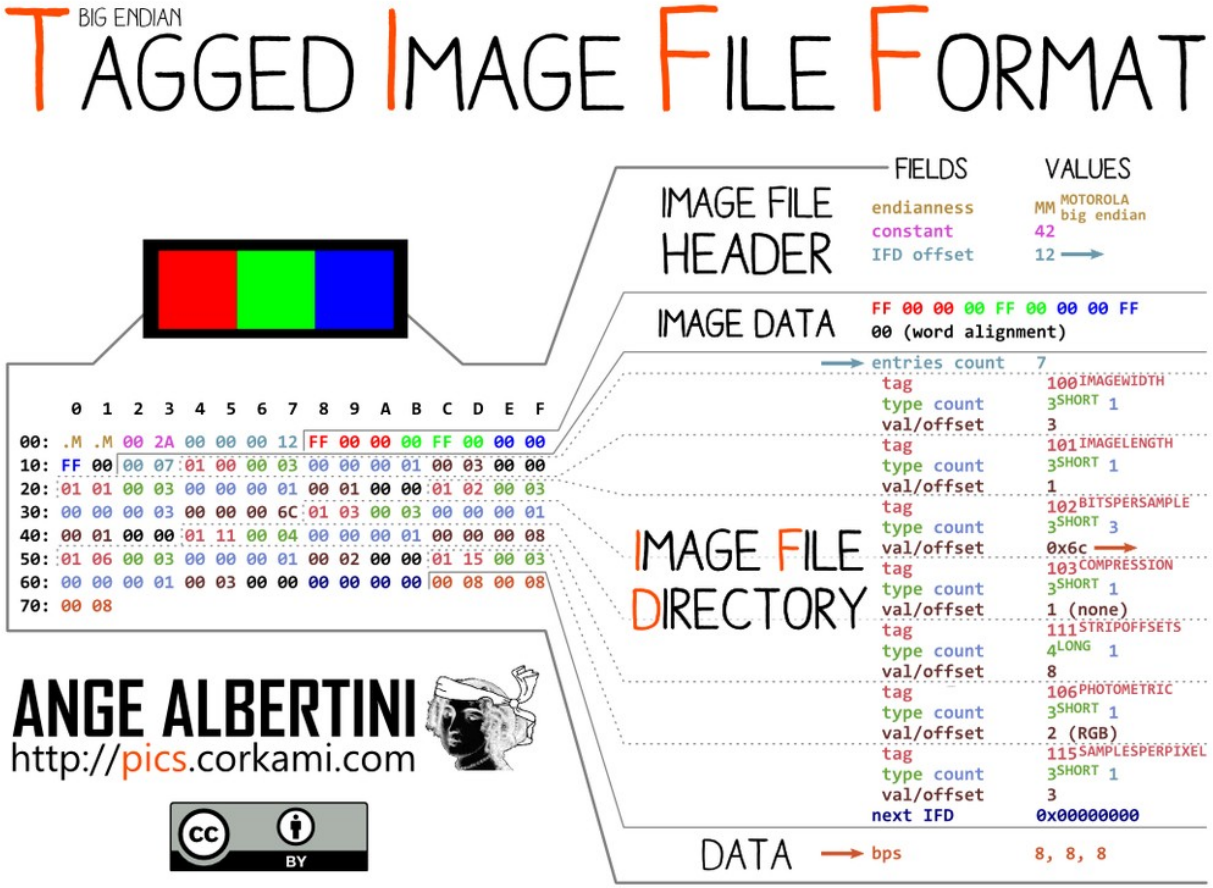

Raster File formats

GeoTIFF

- Single uncompressed layer
- Completely open source
- TIFF image + georeferencing



BIG ENDIAN TAGGED IMAGE FILE FORMAT

```
      0  1  2  3  4  5  6  7  8  9  A  B  C  D  E  F
00:  .M .M 00 2A 00 00 00 12 FF 00 00 00 FF 00 00 00
10:  FF 00 00 07 01 00 00 03 00 00 00 01 00 03 00 00
20:  01 01 00 03 00 00 00 01 00 01 00 00 01 02 00 03
30:  00 00 00 03 00 00 00 6C 01 03 00 03 00 00 00 01
40:  00 01 00 00 01 11 00 04 00 00 00 01 00 00 00 08
50:  01 06 00 03 00 00 00 01 00 02 00 00 01 15 00 03
60:  00 00 00 01 00 03 00 00 00 00 00 00 00 08 00 08
70:  00 08
```

```
                          FIELDS            VALUES
IMAGE FILE HEADER         endianness        MM MOTOROLA big endian
                          constant          42
                          IFD offset        12 →
IMAGE DATA                FF 00 00 00 FF 00 00 00 FF
                          00 (word alignment)
                       →  entries count     7
IMAGE FILE DIRECTORY       tag              100 IMAGEWIDTH
                           type count       3 SHORT 1
                           val/offset       3
                           tag              101 IMAGELENGTH
                           type count       3 SHORT 1
                           val/offset       1
                           tag              102 BITSPERSAMPLE
                           type count       3 SHORT 3
                           val/offset       0x6c →
                           tag              103 COMPRESSION
                           type count       3 SHORT 1
                           val/offset       1 (none)
                           tag              111 STRIPOFFSETS
                           type count       4 LONG  1
                           val/offset       8
                           tag              106 PHOTOMETRIC
                           type count       3 SHORT 1
                           val/offset       2 (RGB)
                           tag              115 SAMPLESPERPIXEL
                           type count       3 SHORT 1
                           val/offset       3
                          next IFD          0x00000000
DATA                   →  bps               8, 8, 8
```

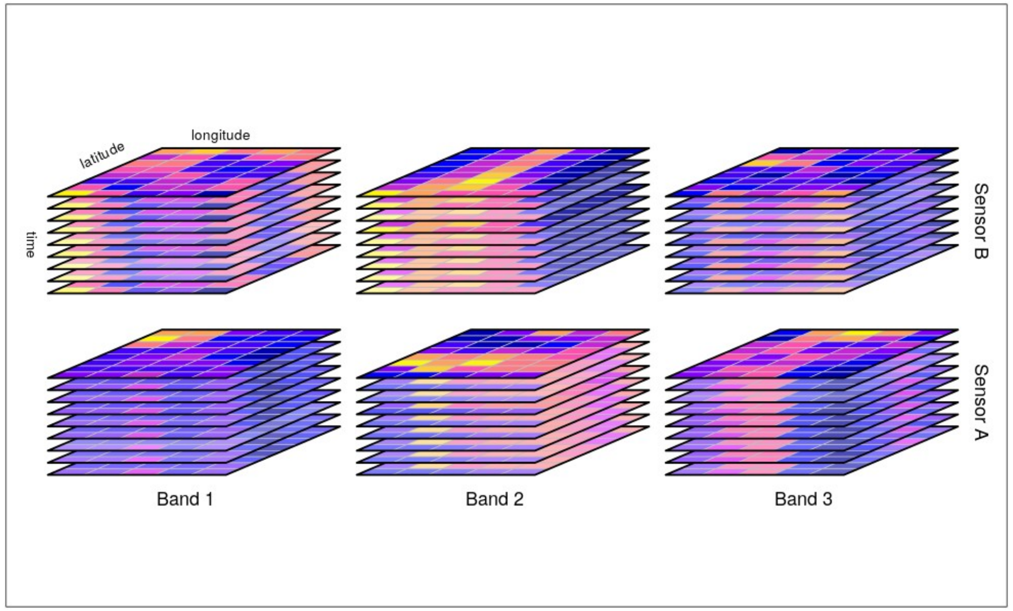
ANGE ALBERTINI
http://pics.corkami.com

CC BY

Raster File formats

NetCDF

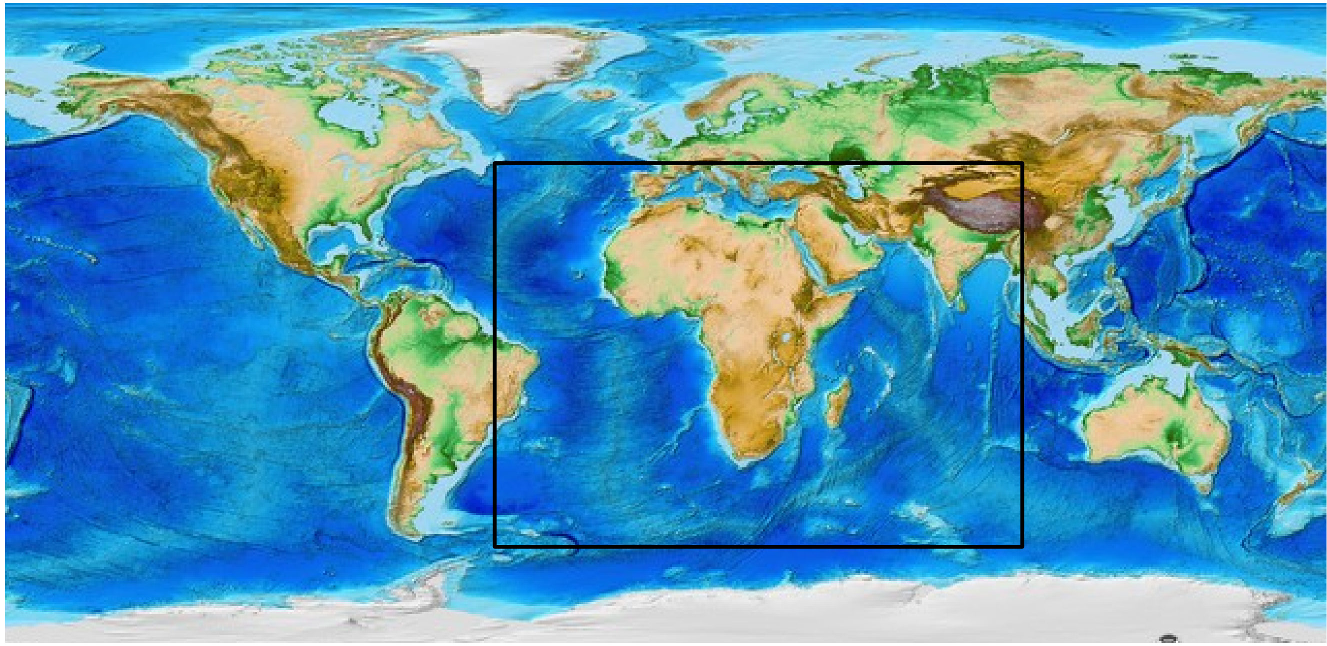
- Binary data cubes, lots of dimensions can be included
- Data registered in bands
- Requires the presence of `ncdf4` in R!



Operations on Rasters

Cropping

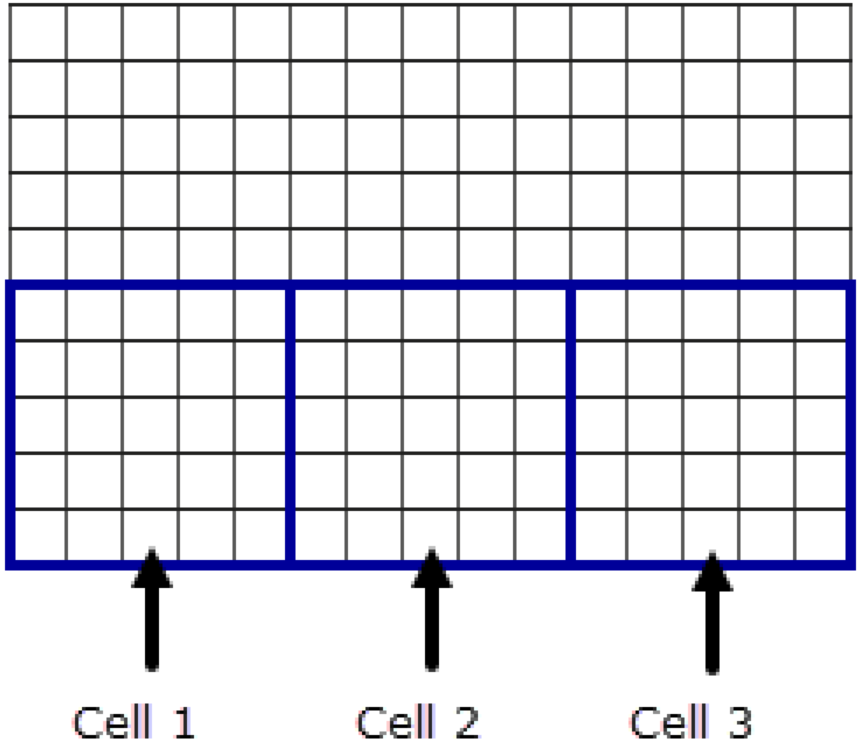
- Changes the extent of a raster



Operations on Rasters

Aggregation / Disaggregation

- Change resolution without changing cell boundaries
- Iteration of a function for data that belongs in a new cell

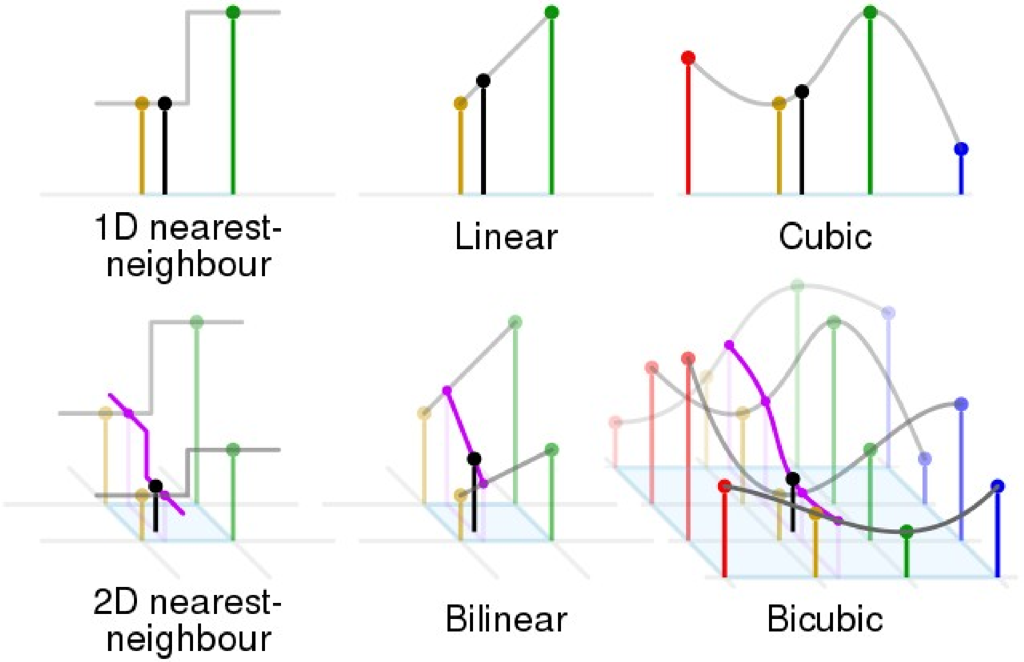


https://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/how-aggregate-works.htm

Operations on Rasters

Resampling

- Change resolution to any resolution
- Often relies on interpolation

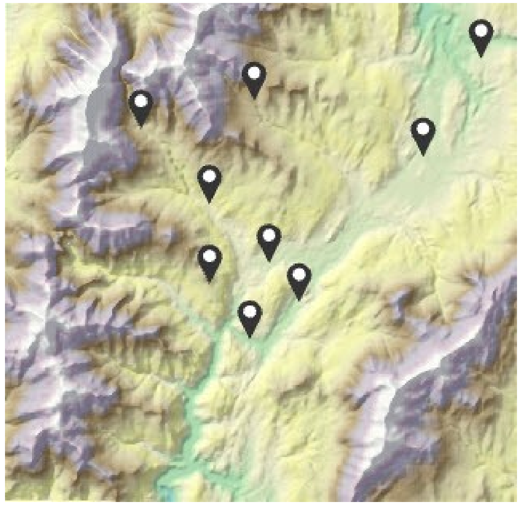


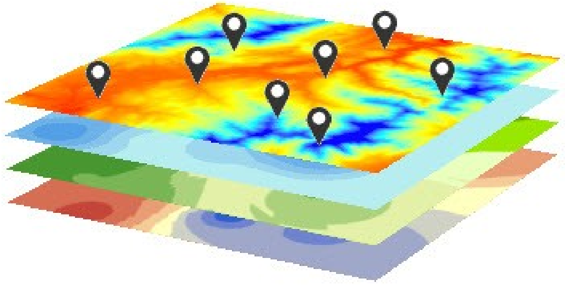
https://www.wikiwand.com/en/Bicubic_interpolation

Operations on Rasters

Extraction

- Getting data out of a raster at given coordinates/locations
- Basic operation for species distribution modelling

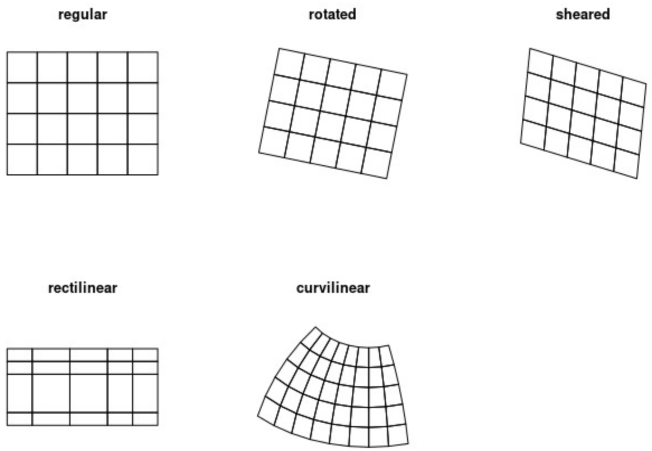




esri.com

Package stars: Spatiotemporal Arrays, Raster and Vector Data Cubes

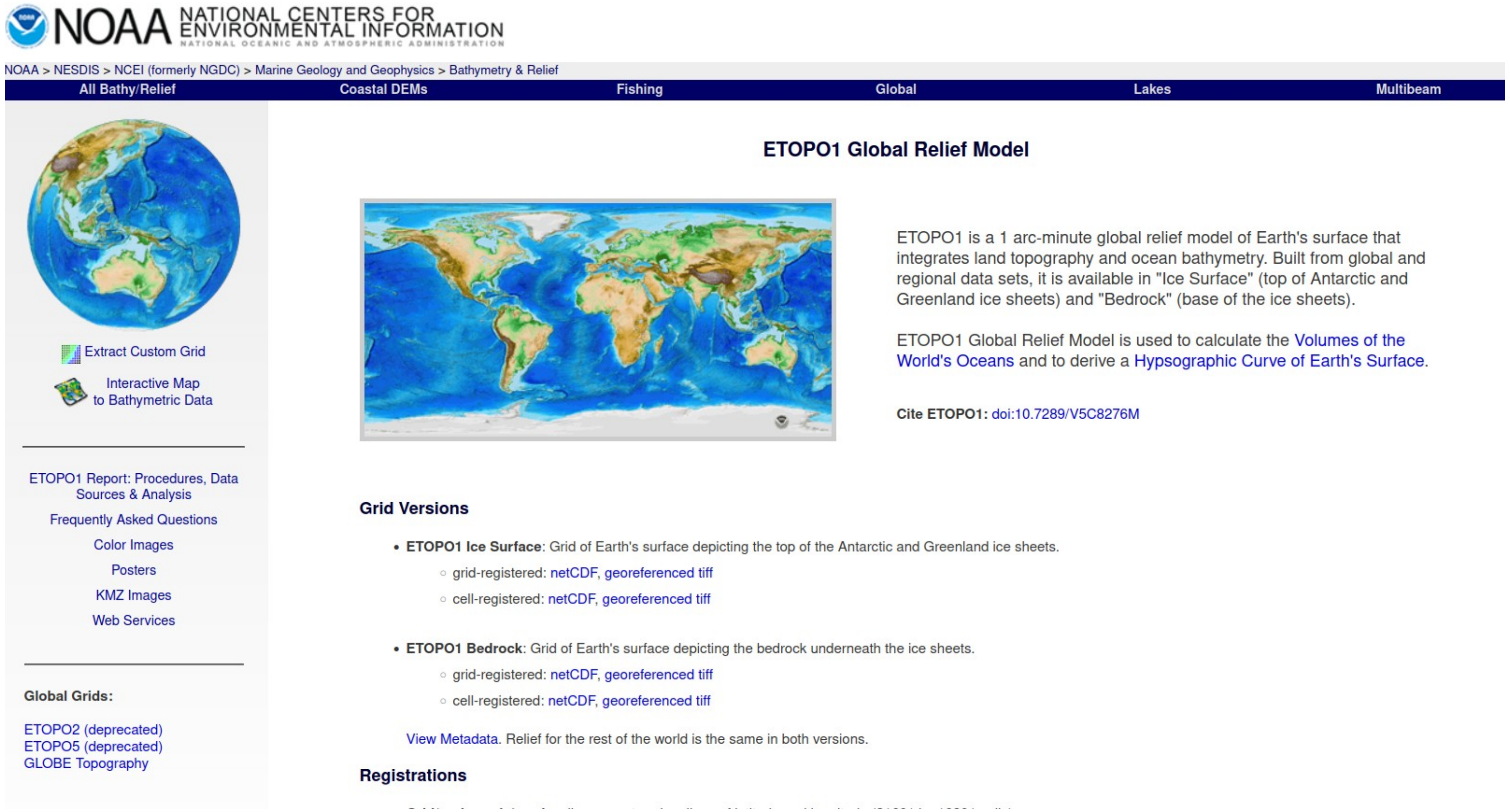
- Primarily by Edzer Pebesma
- Somewhat more complex than terra



NEW

Example 1

- The ETOPO1 Topography (1° by 1°)



NOAA NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

NOAA > NESDIS > NCEI (formerly NGDC) > Marine Geology and Geophysics > Bathymetry & Relief

Extract Custom Grid

Interactive Map to Bathymetric Data

ETOPO1 Report: Procedures, Data Sources & Analysis

Frequently Asked Questions

Color Images

Posters

KMZ Images

Web Services

Global Grids:

ETOPO2 (deprecated)
ETOPO5 (deprecated)
GLOBE Topography

ETOPO1 Global Relief Model

ETOPO1 is a 1 arc-minute global relief model of Earth's surface that integrates land topography and ocean bathymetry. Built from global and regional data sets, it is available in "Ice Surface" (top of Antarctic and Greenland ice sheets) and "Bedrock" (base of the ice sheets).

ETOPO1 Global Relief Model is used to calculate the Volumes of the World's Oceans and to derive a Hypsographic Curve of Earth's Surface.

Cite ETOPO1: doi:10.7289/V5C8276M

Grid Versions

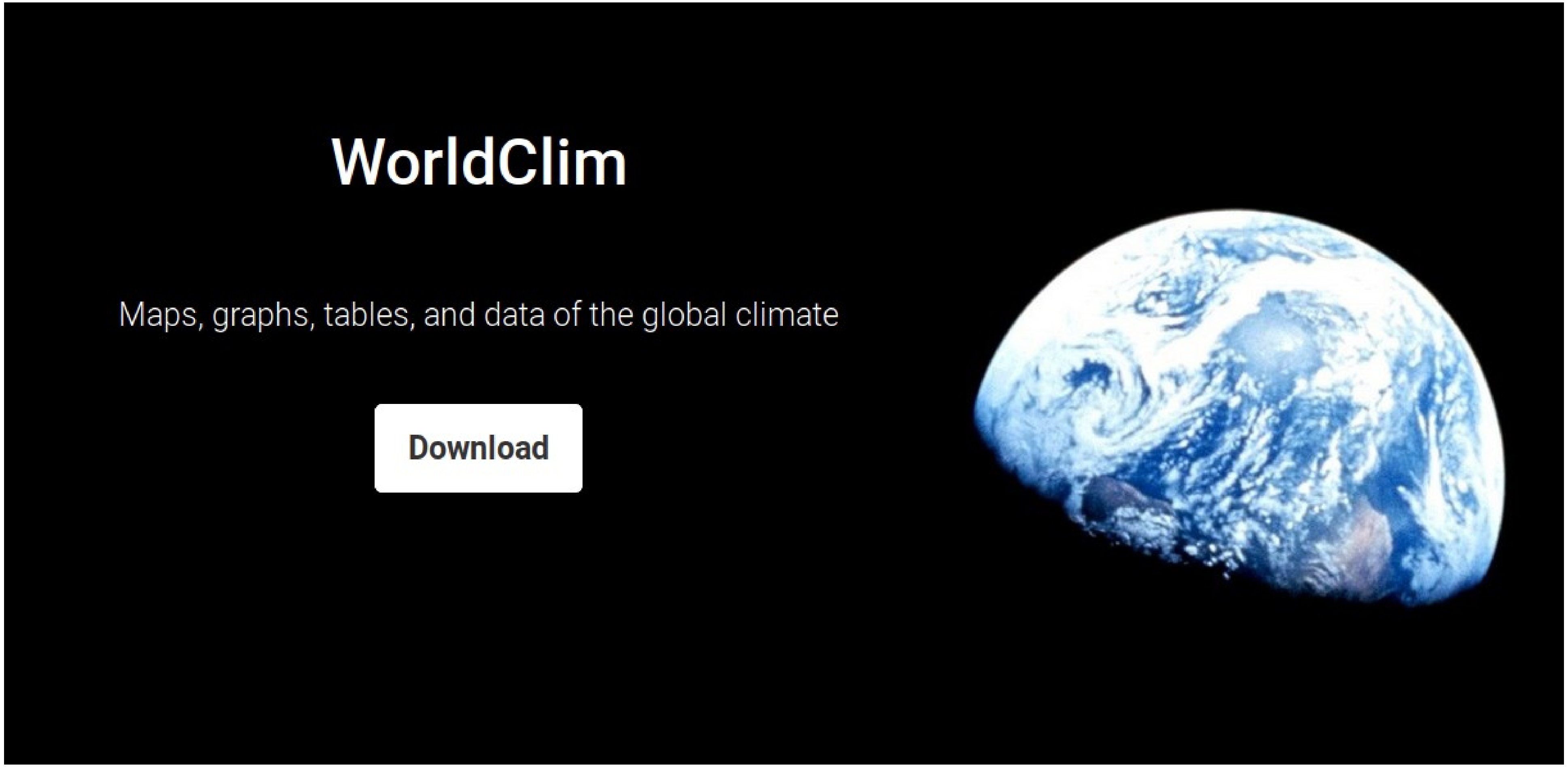
- **ETOPO1 Ice Surface**: Grid of Earth's surface depicting the top of the Antarctic and Greenland ice sheets.
  - grid-registered: netCDF, georeferenced tiff
  - cell-registered: netCDF, georeferenced tiff
- **ETOPO1 Bedrock**: Grid of Earth's surface depicting the bedrock underneath the ice sheets.
  - grid-registered: netCDF, georeferenced tiff
  - cell-registered: netCDF, georeferenced tiff

View Metadata. Relief for the rest of the world is the same in both versions.

Registrations

Example 2

- WorldClim

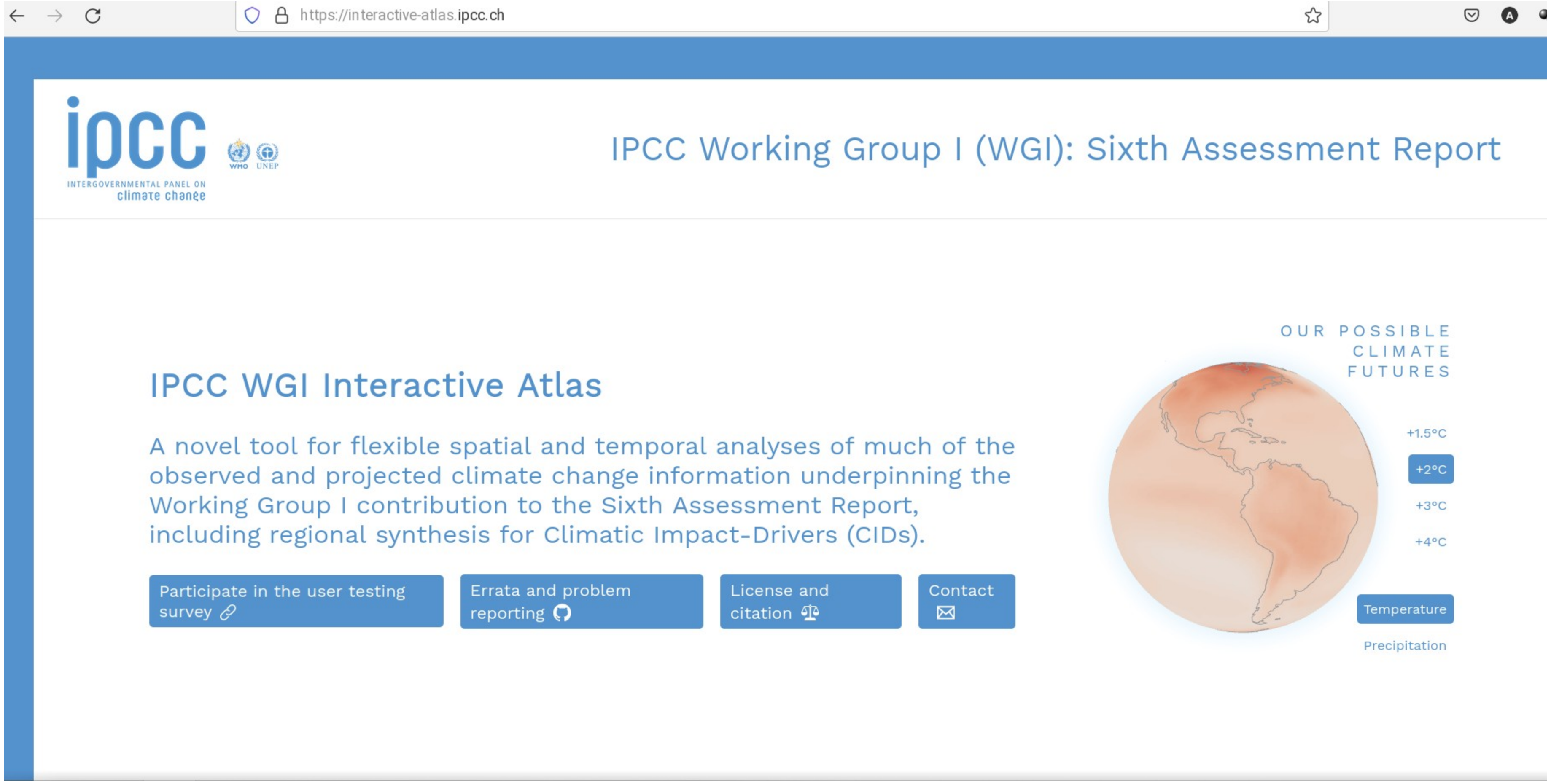


WorldClim

Maps, graphs, tables, and data of the global climate

Example +

- IPCC AR6 Atlas



https://interactive-atlas.ipcc.ch

IPCC Working Group I (WGI): Sixth Assessment Report

IPCC WGI Interactive Atlas

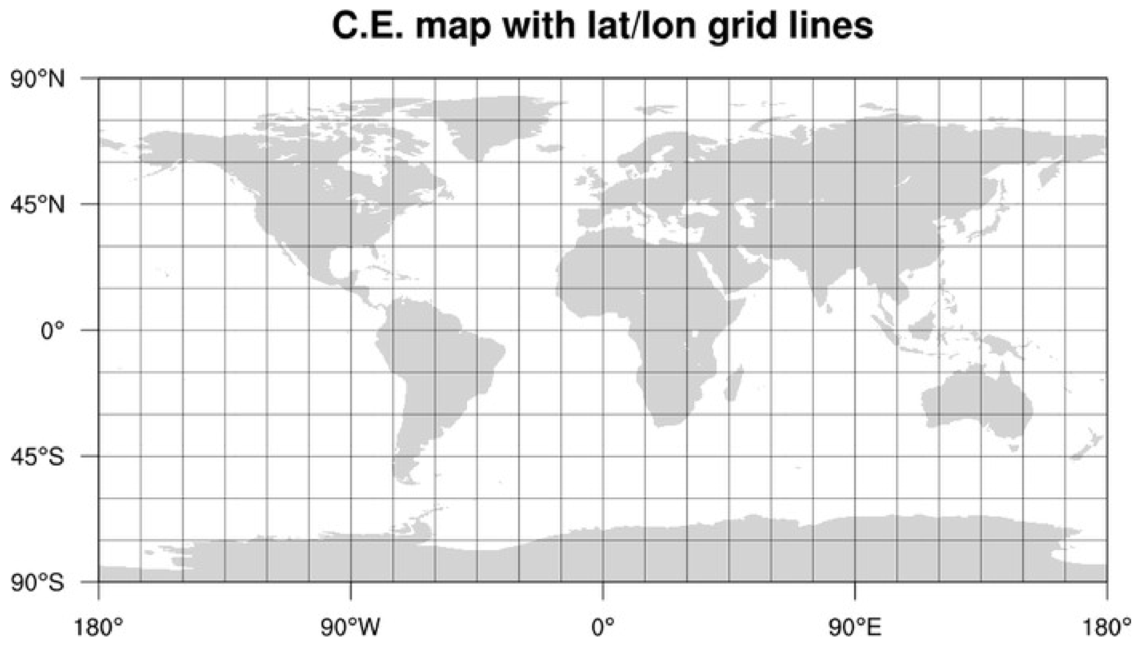
A novel tool for flexible spatial and temporal analyses of much of the observed and projected climate change information underpinning the Working Group I contribution to the Sixth Assessment Report, including regional synthesis for Climatic Impact-Drivers (CIDs).

ipcc
INTERGOVERNMENTAL PANEL ON climate change
WMO
UNEP
Participate in the user testing survey
Errata and problem reporting
License and citation
Contact
OUR POSSIBLE CLIMATE FUTURES
+1.5°C
+2°C
+3°C
+4°C
Temperature
Precipitation

Non-rectangular raster grids

The advantage of rectangles

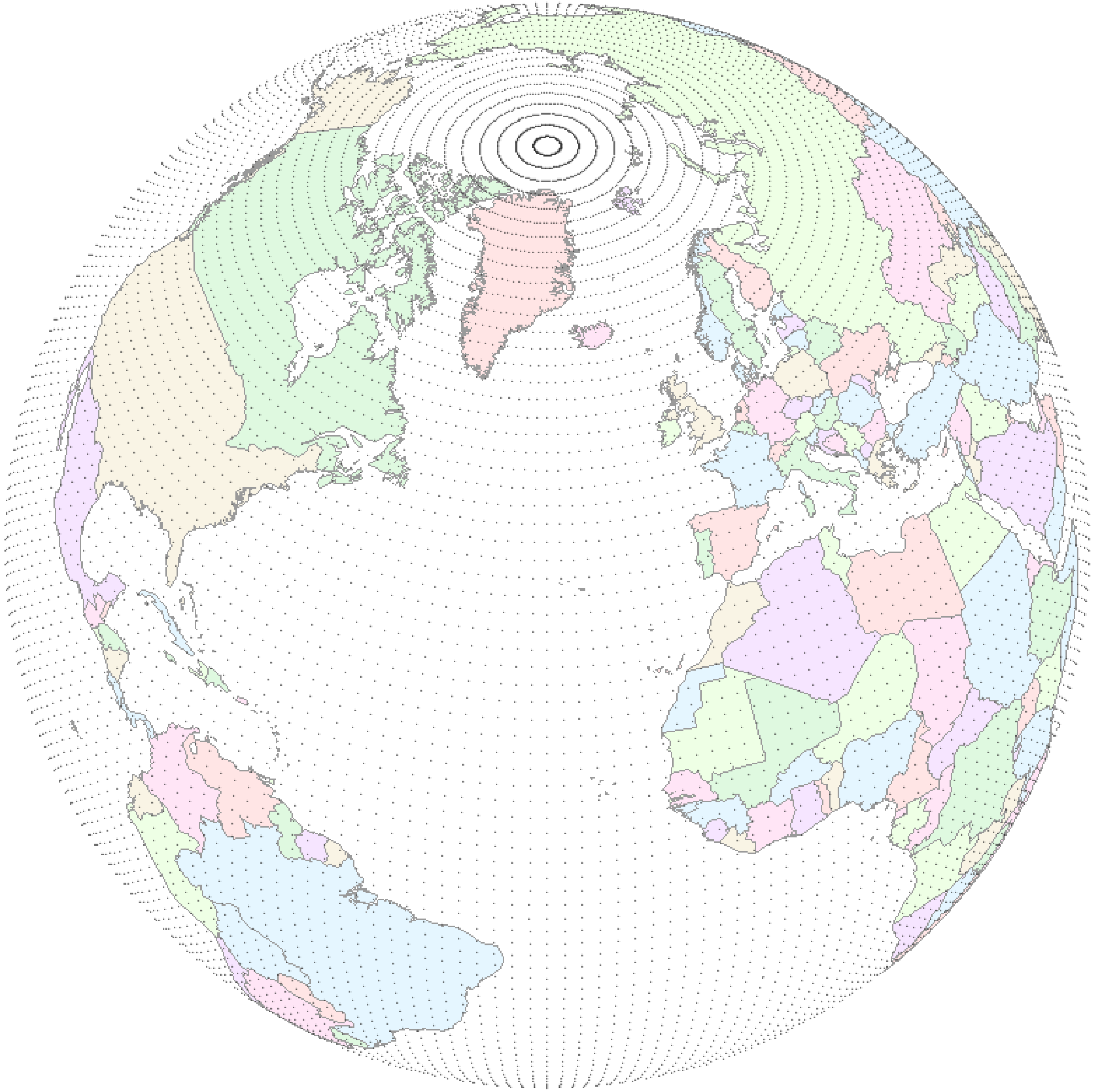
- Structure is easy to define
- Very easy to store in the memory
- Look natural in projections



Non-rectangular raster grids

The disadvantage

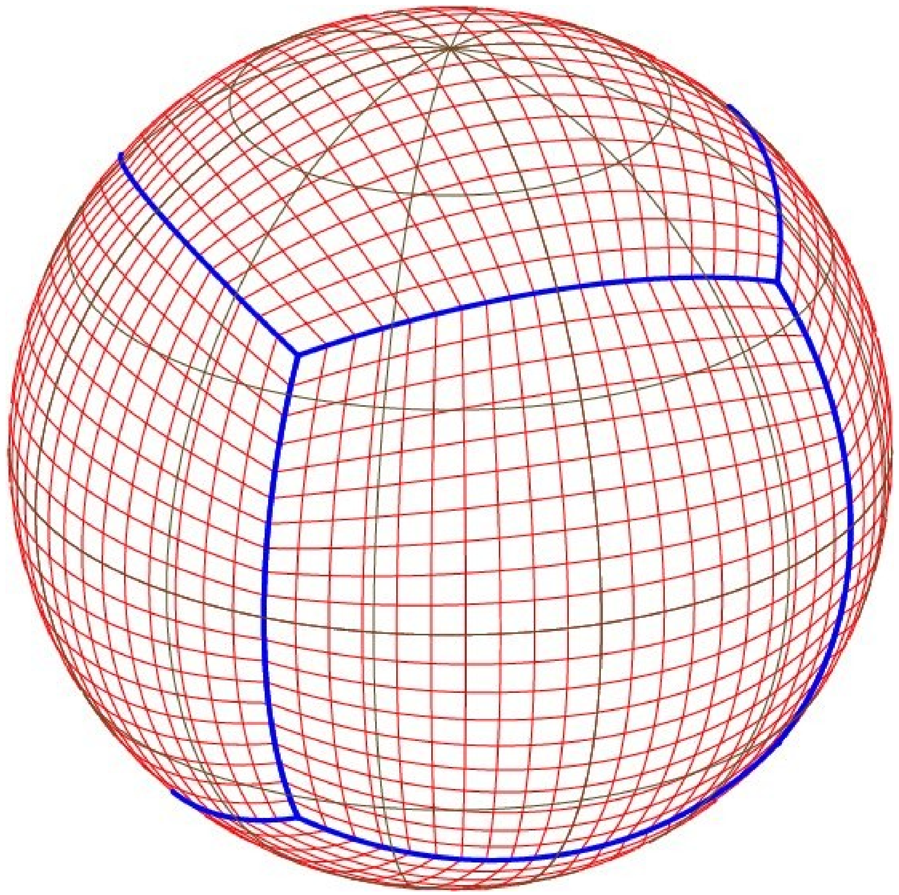
- long-lat grids are Gaussian
- Non-uniform on a sphere
  - Increased density towards the poles
  - Cell sizes decrease towards the poles
- Spatial binning will be biased!



Non-rectangular raster grids

Common solution: cubed-sphere grid

- Still quadrilateral
- Some climate models rely on this

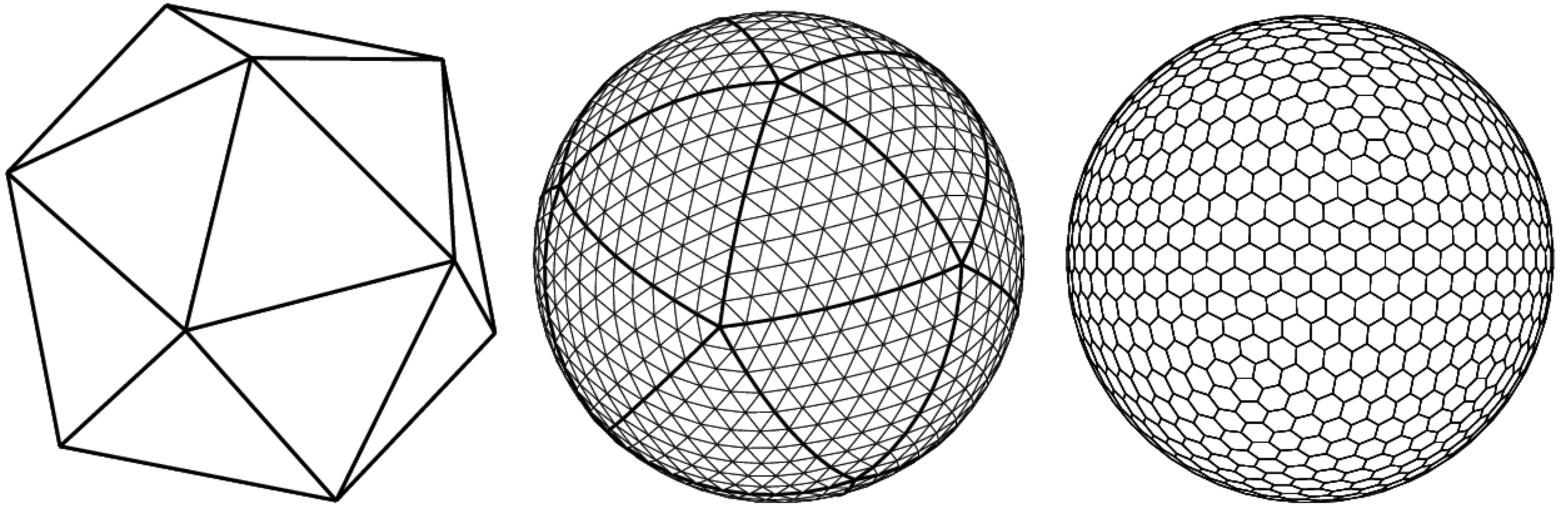


Purser and Tong, 2017

Non-rectangular raster grids

Most common solution: polyhedra

- Trianglular or Penta-Hexagonal grids
- Also in some climate models



(a) Regular icosahedron

(b) N=10

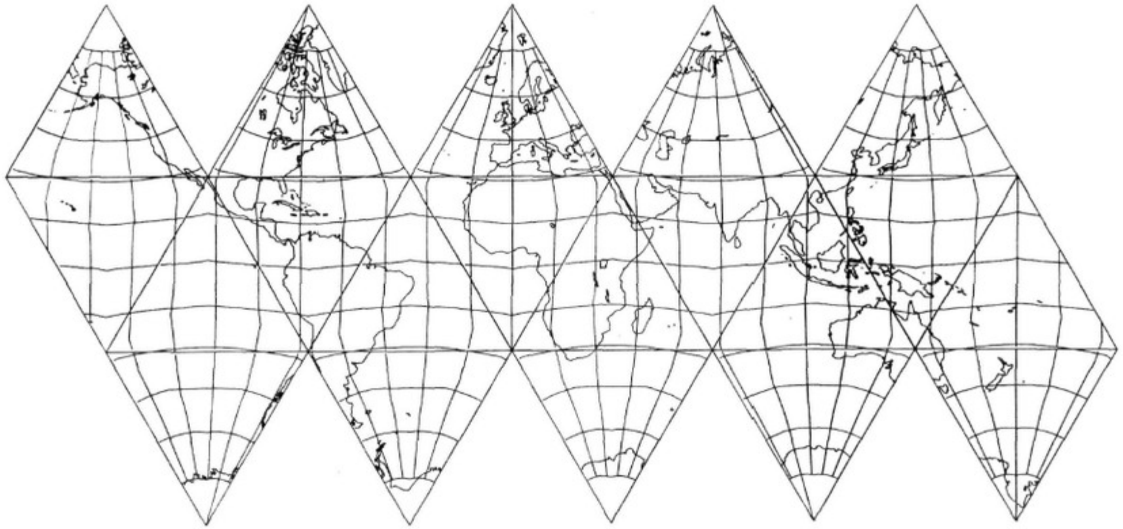
(c) N=10

Fig. 7. The gradual refinement of the icosahedral geodesic grids.

Chen et al. 2014

Package ddgridR: Discrete Global Grids for R

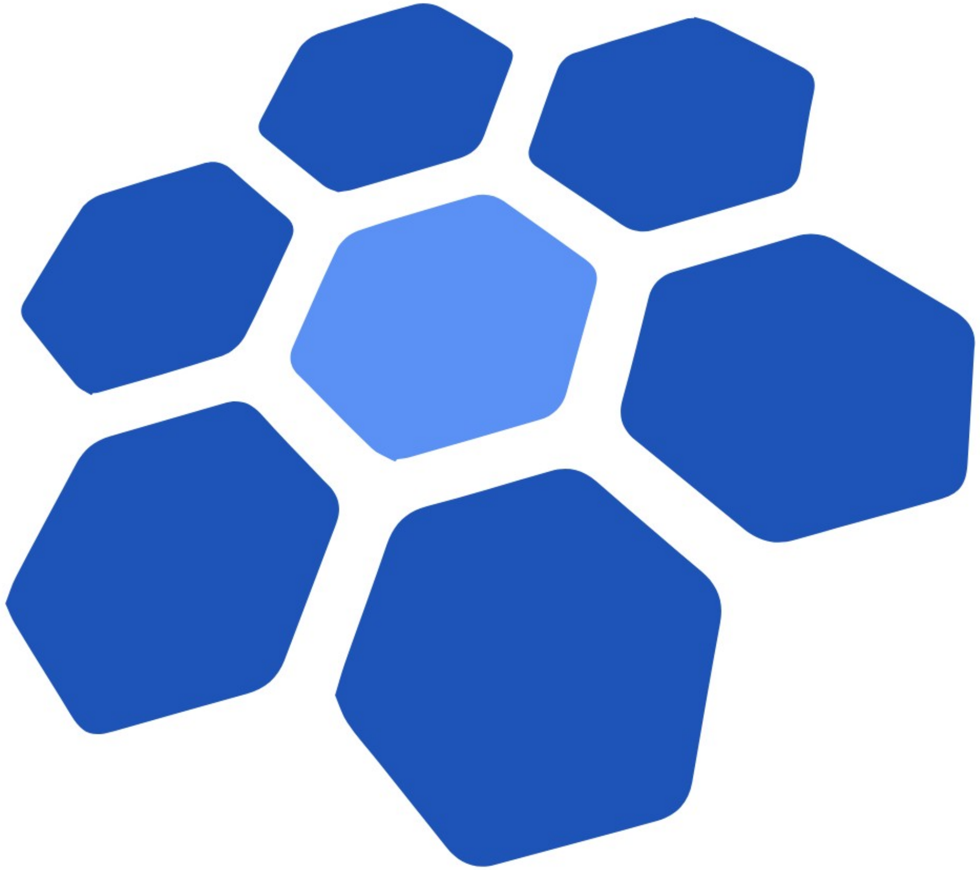
- by Richard Barnes
- Based on an program by Kevin Sahr
- Not on CRAN! https://github.com/r-barnes/dggridR
- Based on a Snyder projection
- Very high resolution, and well-known mathematical properties



Package h3jsr: Access to H3 (via javascript)

R library for the H3 system (https://h3geo.org/)

- Developed For Uber
- Hierarchical system (fine scale)
- https://cran.r-project.org/package=h3js



Package icosa: Coarse grids based on tessellated icosahedra

- Adam wrote this (first package)
- More scalable for global scale
- Interface to sf
- 3D model
- The mathematical properties are partially explored
- https://adamkocsis.github.io/icosa/