A System for Storing and Analyzing a Massive Climatological Database of Modeled Air Mass Trajectories

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Arctic Black Carbon Study (ABCS)

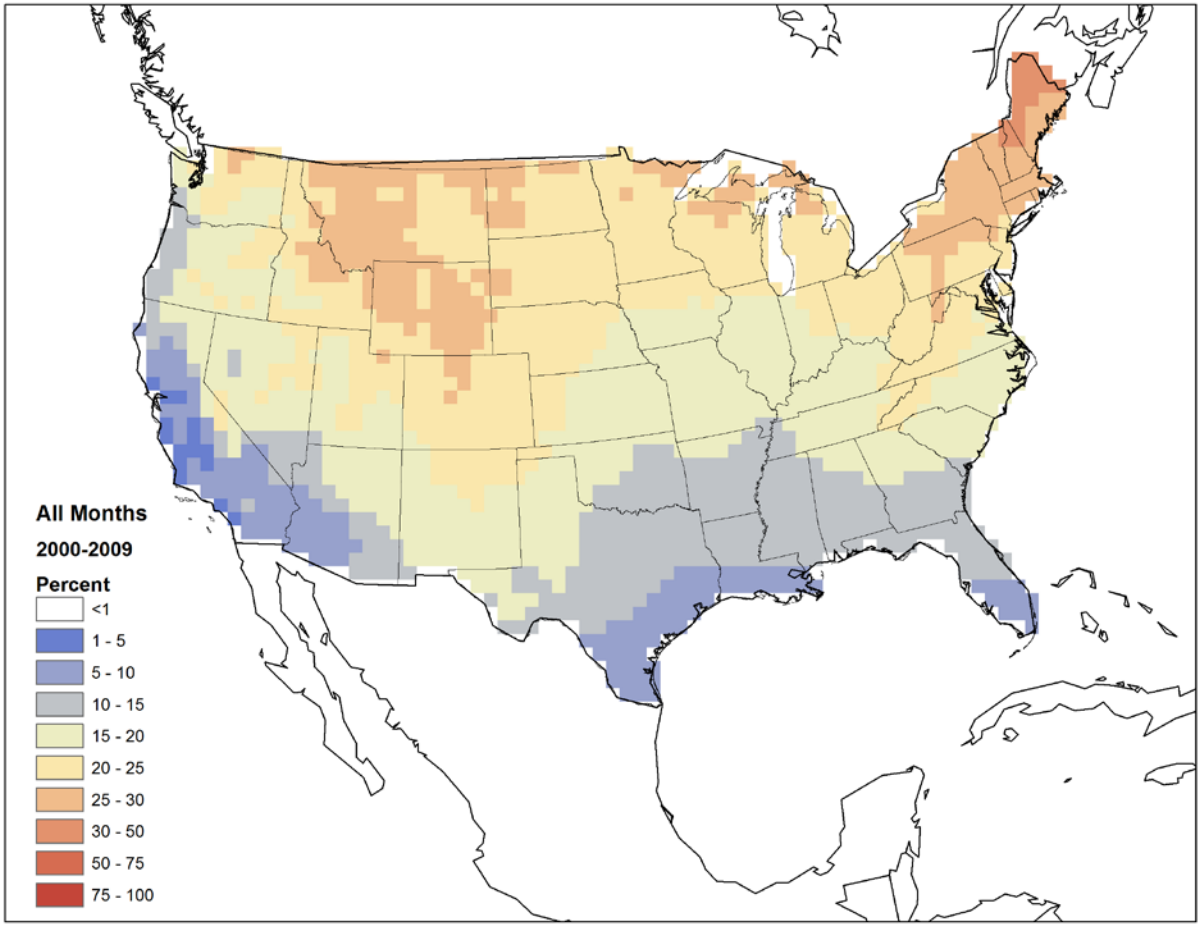
- Goal was to study patterns of transport of black carbon (BC) to the Arctic
- Can biomass burning (prescribed fire) affect climate change?
- Large-scale analysis using NOAA's HYSPLIT model
  - 30 years of data (1979-2008)

(Credit: NASA)

Large-Scale Data

- Modeled nearly **6×10^{8}** individual trajectories
- Final data set contained **1.4×10^{11}** points

- **How did we do it, and what did we learn?**



4.7×10^{10} data points went into this image.

Packed File Format for Trajectories (PFFT)

- HYSPLIT model produces results
  - Text format
  - Each waypoint on its own line
  - Each model initialization produces its own file
- We wanted
  - Compact binary format
  - Fast to read or write
  - Efficient for either full scan or random access
  - Multiple model initialization time steps in a file
- Solution: **Packed File Format for Trajectories (PFFT)**

Runner, Spawner, and Reaper

Goals

- Perform tens of thousands of separate runs of the HYSPLIT model
- Efficiently use many processors in parallel
- Collect results of many HYSPLIT runs into a single file

Modeled 30 years of trajectories in about 3 weeks with 24 cores

A three-part solution

- Runner.py
  - Command-line script; sets up date ranges and configuration
- Spawner.py
  - Launches `hymodelt` processes
  - When model executions finish, adds them to Reaper's work queue
- Reaper.py
  - Reads in HYSPLIT output and writes PFFT

How Do You Analyze 1.4×10^{11} Points?

- Only interested in aggregate results
  - At a minimum, aggregate per day
  - Usually, aggregates per month or year
- Want results on a map
  - Individual waypoints projected to grid cells
  - Value for a particular grid cell is an aggregate of values for all the trajectories that pass through that cell

Functional Programming

- Queries are implemented by defining functions
- Basic form is three functions: `filter()`, `map()`, and `reduce()`
- Processing takes the general form of a **left fold**, so aggregation queries can be performed in O(n) time with O(1) storage

```
filter_func = lambda traj: return True/False (predicate)
projection_func = lambda traj: return x, y, t
map_func = lambda traj: return object (initial grid-cell value)
reduce_func = lambda a, b: combine two grid-cell values
simplify_func = lambda value: return simplified value in correct type
```

Command-line Usage

- Through the magic of `eval()` we can define functions on the command line

```
make_grid.py
    -f FILTER_FUNC
    -m MAP_FUNC
    -r REDUCE_FUNC
    -s SIMPLIFY_FUNC
    -d DATA_TYPE
```

- Typical command line:

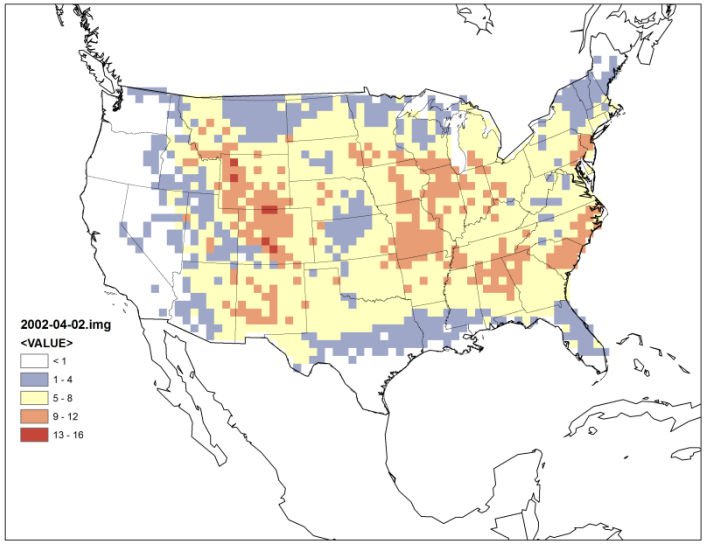
```
./make_grid.py -m "lambda traj: 1" -r "lambda a,
b: a + b" output_dir 2006010100 2006053118
/data/HYSPLIT/pfft/2006.pfft
```

Examples (1 of 2)

Count of trajectories per grid cell

```
# Here we count 1 for each trajectory in a grid cell,
# and we reduce by adding the counts together.

map_func = lambda traj: 1
reduce_func = lambda a, b: a + b
```



Examples (2 of 2)

Mean heights of trajectories

```
# This one is a bit more tricky.  We map each trajectory
# to a 2-tuple of (count_trajs, total_height).  Then the
# reduce_func can reduce them together by just adding
# the counts and the totals.  But we need a final step,
# in the simplify_func, to simplify our 2-tuple into an
# actual output value, by dividing the total by the count
# to come up with an actual average value.

map_func = lambda traj: (1, traj.height)
reduce_func = lambda a, b: (a[0] + b[0], a[1] + b[1])
simplify_func = lambda value: float(value[1]) / float(value[0])
```

Results

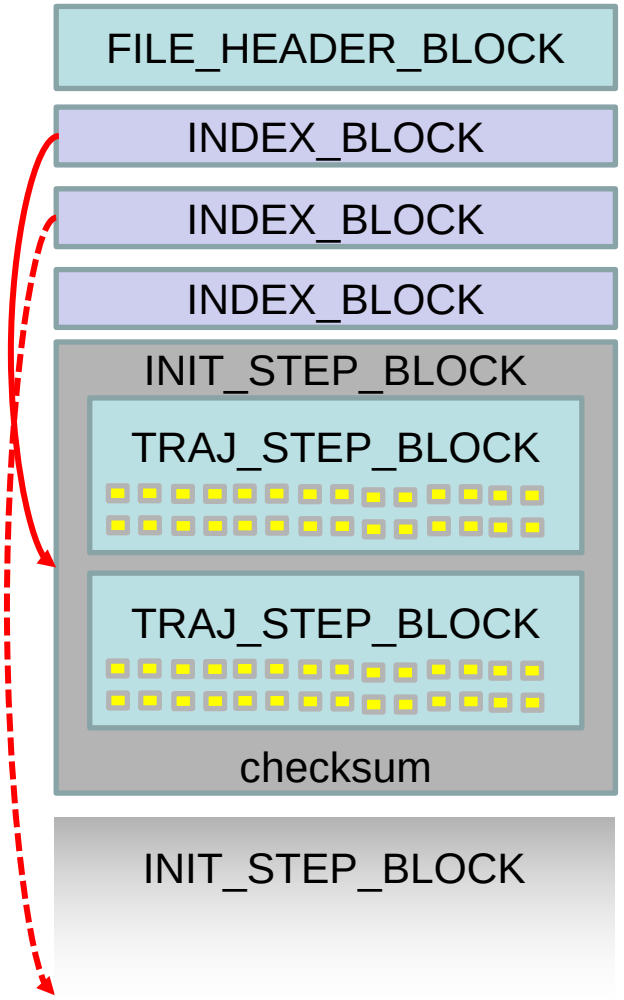
- What is the likelihood of transport from the United States to the Arctic? How does this likelihood vary regionally?
  - *Transport is possible (up to 42% in winter) at altitudes typical of prescribed fire injection (< 2,000 meters)*
  - *Transport is more likely at northern latitudes (varies regionally)*
- Is transport more likely during certain seasons or months?
  - *Transport is more likely during spring, fall, and winter*
  - *Seasonal, monthly, and daily variability due to synoptic patterns*

Conclusion

- Wrapping a command-line model with a Python class is a useful technique enabling large-scale use.
- Higher-order functions and functional programming techniques are a powerful way of constructing analyses on large data sets.

Additional Material: PFFT Structure

- Block sizes defined by header
- Values (latitude, longitude, height, etc.) stored as 32-bit floats
- Reserved spaces for future extensions
- Timestamps and file offsets are 64-bit
- Adler-32 checksums



Additional Material: PFFT Implementation

Implementation

- Uses Python's `struct` module to read and write values
- Adler-32 checksum implementation courtesy of the `zlib` module
- Lazy reading using generator functions (`yield` keyword)

Usage

```
import sys
from pfft import PfftFile

pfft = PfftFile(sys.argv[1])

print "  num_init_steps:", pfft.num_init_steps
print "  num_traj_steps:", pfft.num_traj_steps
print "  num_traj_points:", pfft.num_traj_points
print "  extra variables:", pfft.extra_variable_names

for init_step in pfft:
    print "InitStepBlock:",
    print init_step.initialization_time.strftime("%Y-%m-%d %H:%M")

    for traj_step in init_step:
        print "  TrajStepBlock",
        print traj_step.date_time.strftime("%Y-%m-%d %H:%M")
        for traj in traj_step:
            print "    %s: (%s, %s, %s)" % (
                traj.trajectory_number,
                traj.latitude,
                traj.longitude,
                traj.height,
                )
            for var in pfft.extra_variable_names:
                print "      %s: %s" % (var, traj[var])
```

Running HYSPLIT: hysplit.py

- Internal library used on several projects
- Wrapped command-line `hymodelt` executable using `subprocess` module
- `DataLocation` class and subclasses determine the locations of meteorological data to provide to HYSPLIT, given a desired date/time range

General Form (Pseudocode)

```
# Process through PFFT data
for init_step in pfft_data.iter_steps():
    for traj_step in init_step.iter_traj_steps():
        for traj in traj_step.iter_trajs():
            if filter_func(traj):
                x, y, t = projection_func(traj)
                existing_value = data_cube[x, y, t]
                value = map_func(traj)
                if existing_value is not None:
                    value = reduce_func(existing_value, value)
                data_cube[x, y, t] = value

# Process data cube objects into numeric values
variable = new NetCDFVariable(x_size, y_size, t_size) # etc.
for x in range(data_cube.x_size):
    for y in range(data_cube.y_size):
        for t in range(data_cube.t_size):
            variable[x, y, t] = simplify_func(data_cube[x, y, t])
```