Implementing Connected Component Labeling as a User Defined Operator for SciDB

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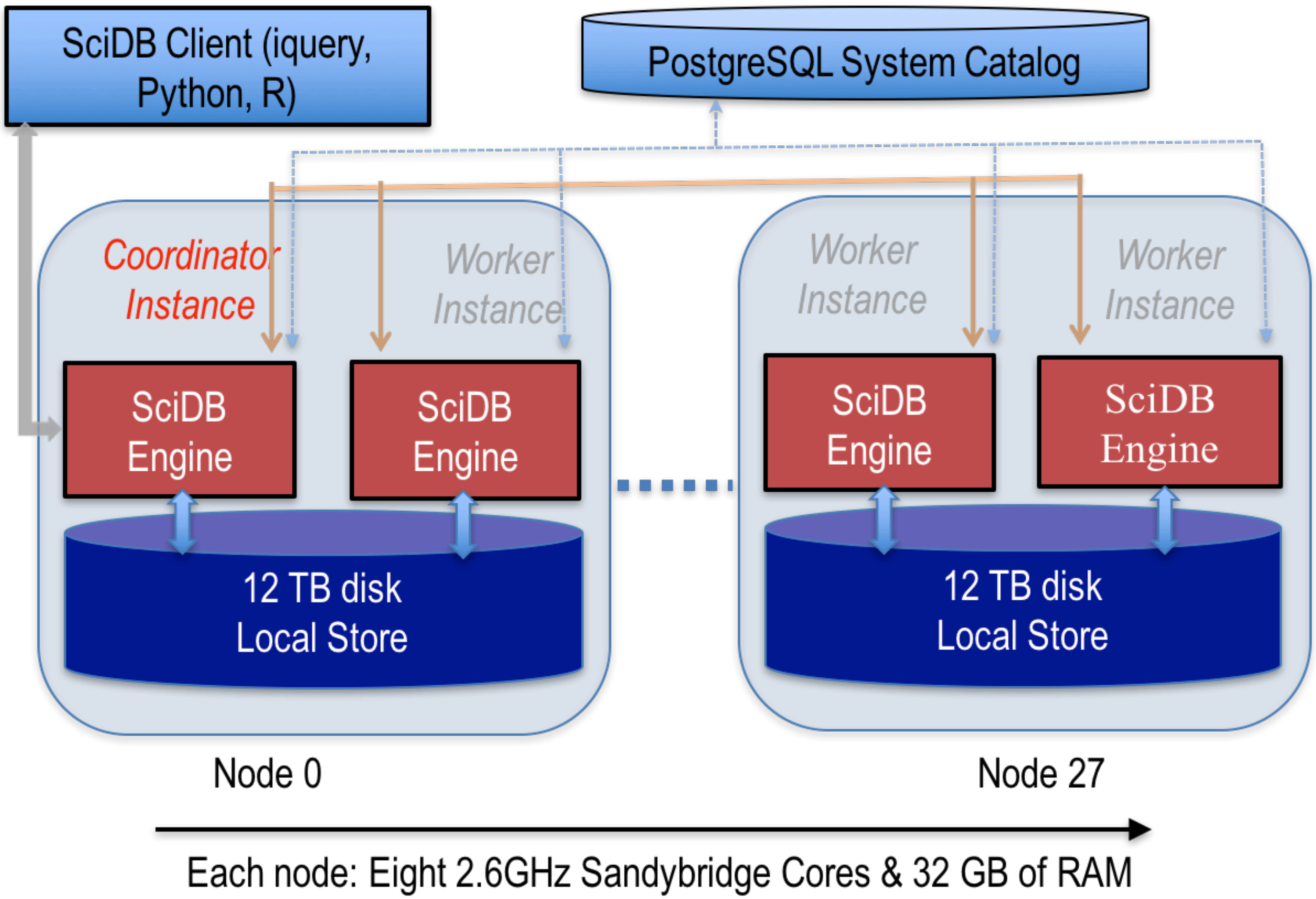
SciDB

SciDB is an all-in-one data management and advanced analytics platform that features:

- Complex analytics inside a next-generation parallel array database, i.e. not row-based or column-based like RDBMS's based on table data model.
    - Supports extensive and flexible algebra operators that can be efficiently "wired" together for more complex operations.
- Based on the "shared nothing architecture" for data parallelism, data versioning and provenance to support science applications.
- Open source.
- A better performer than Hadoop (MapReduce), 2-10 times faster, in almost all benchmarks that we have performed so far.
- Extensible through user-defined types, functions and operators

System Layout



Event Identification needs CCL

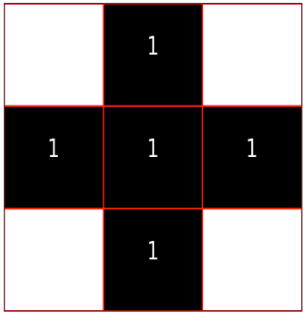
- Our interest: Identifying weather events as connected spatio-temporal regions in large multi-year climate datasets.
    - For example, snowstorm climatology in thirty-plus (30+) years of GEOS-5 MERRA (http://gmao.gsfc.nasa.gov/research/merra/)
    - Thresholding to generate a mask array (foreground & background mesh points).
    - Grouping of (adjacent) foreground mesh points into uniquely labeled connected regions, hence CCL

CCL implementation in SciDB

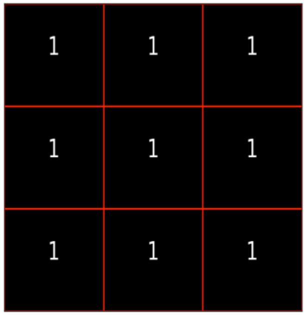
- Requirements:
  - Flexible array dimensionality
  - Flexible connectivity in any of the array dimensions
  - Periodic Boundary Conditions - BCs (due to need to support earth science applications)
- Algorithm - Weighted Quick Union with Half-Path compression (WQU) e.g. as in http://algs4.cs.princeton.edu/15uf/:
  - Efficient
  - Easy implementation considering the requirements.
- SciDB MemArray (data structure for handling larger-than-RAM arrays)
  - Used extensively for efficient indexing and searching throughout.

CCL implementation in SciDB

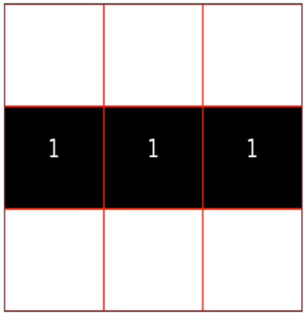
- Flexible connectivity achieved by an auxiliary array of the same dimension as the mask array but length 3 in each dimension e.g. for 2-D



4-connectivity



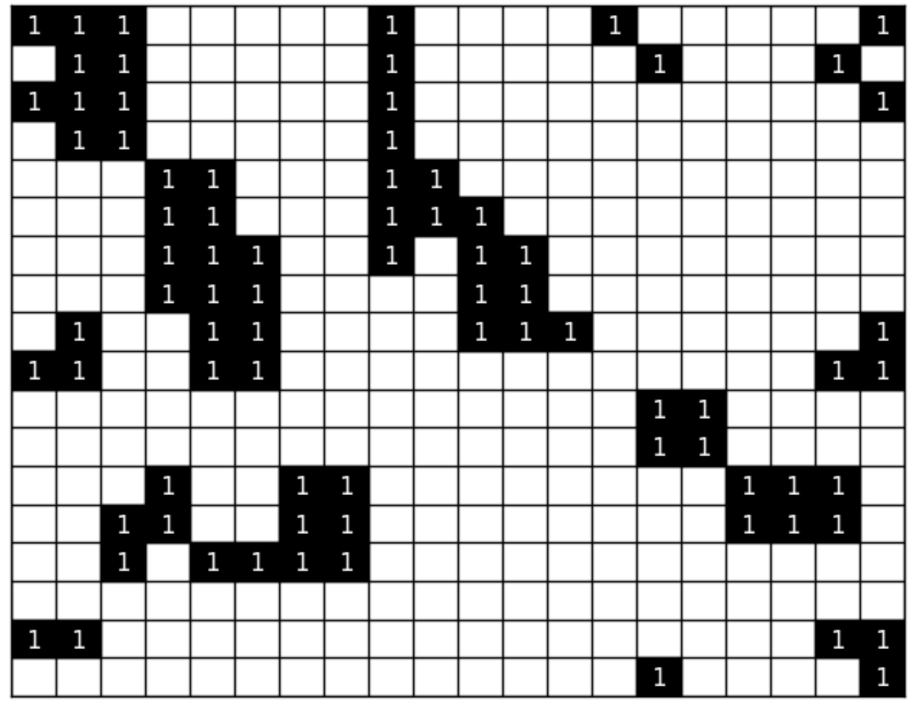
8-connectivity



X-connectivity

Preparation steps

1. Thresholding already done to prepare the mask array



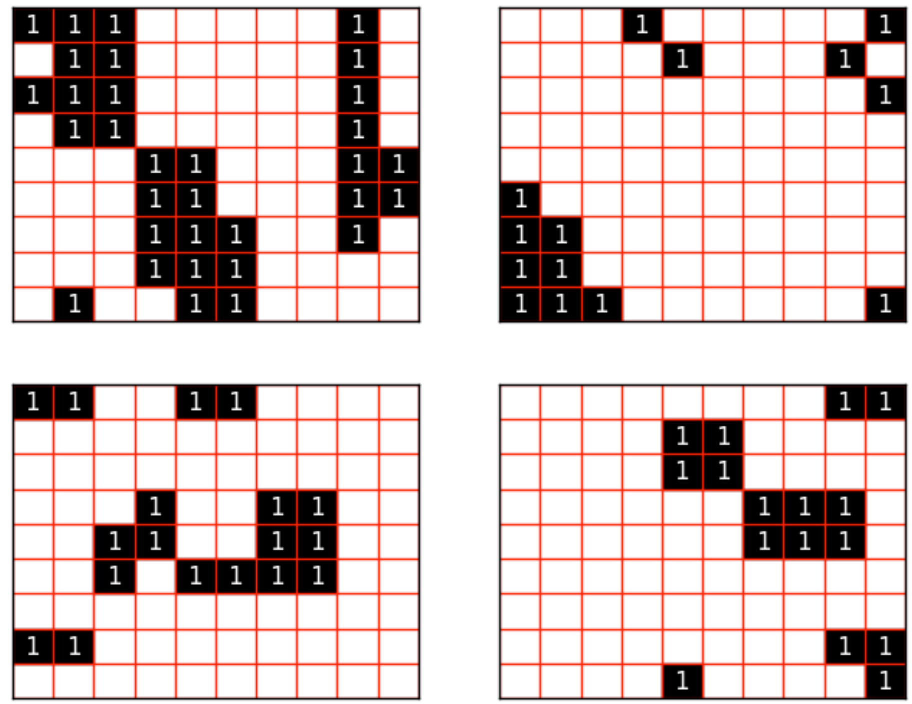
Preparation step

Partition mask array into SciDB chunks

- Schema supplied by the user to set chunk sizes (and overlap if any) e.g.

  <mask:int8> [x=0:17,9,1,y=0:19,10,1]

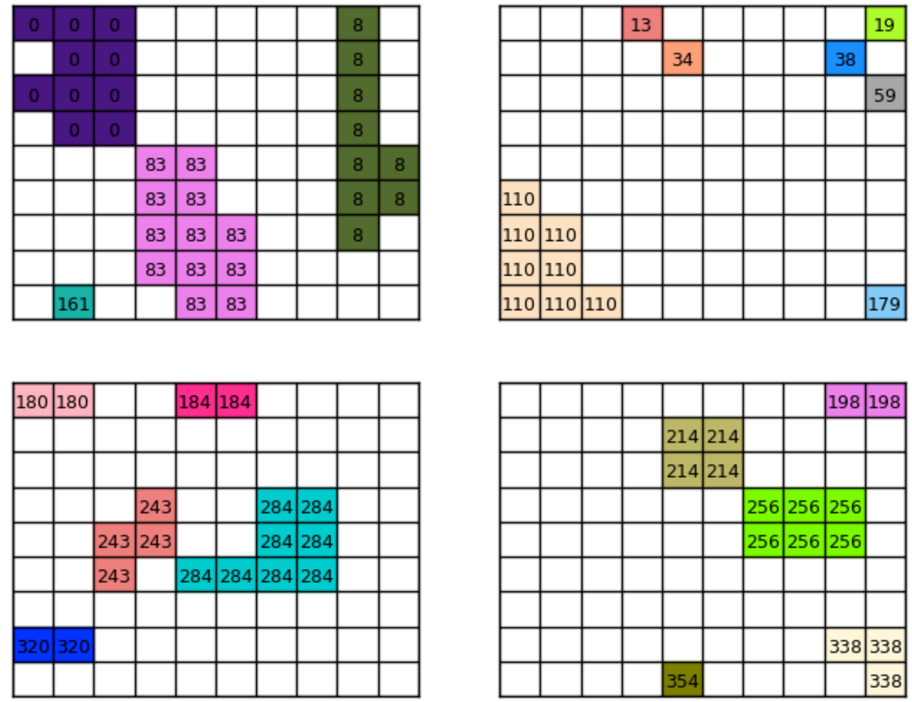
- Chunk assignment to instances is managed by SciDB using a heuristic hash function



Implementation steps

1. Stage 1 - CCL is computed by each instance, one chunk at a time

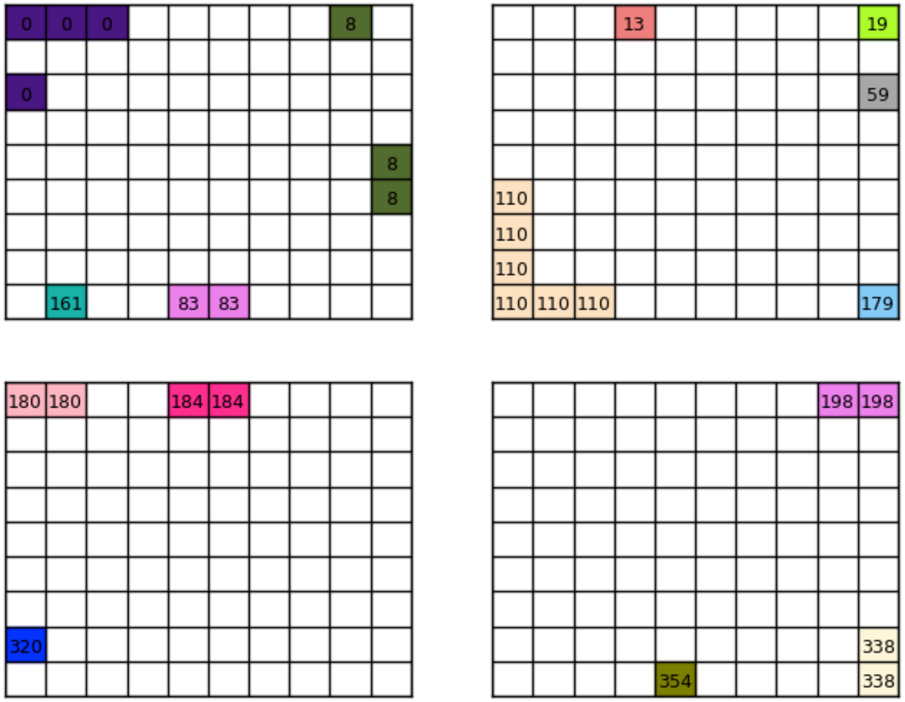
- Apply the auxiliary connectivity array (4-connectivity in this case) to each foreground mask (using “flattened” coordinates) to determine pairs of adjacent cells.
- Eliminate duplicate pairs
- Apply WQU to each pair to determine CCLs for the chunk
- Write chunk CCLs to MemArray



Implementation steps

2. Stage 2a - Equivalency resolution

- Write chunks' boundary labels to MemArray
- Replicate the MemArray on all instances so that each instance now has all boundary labels

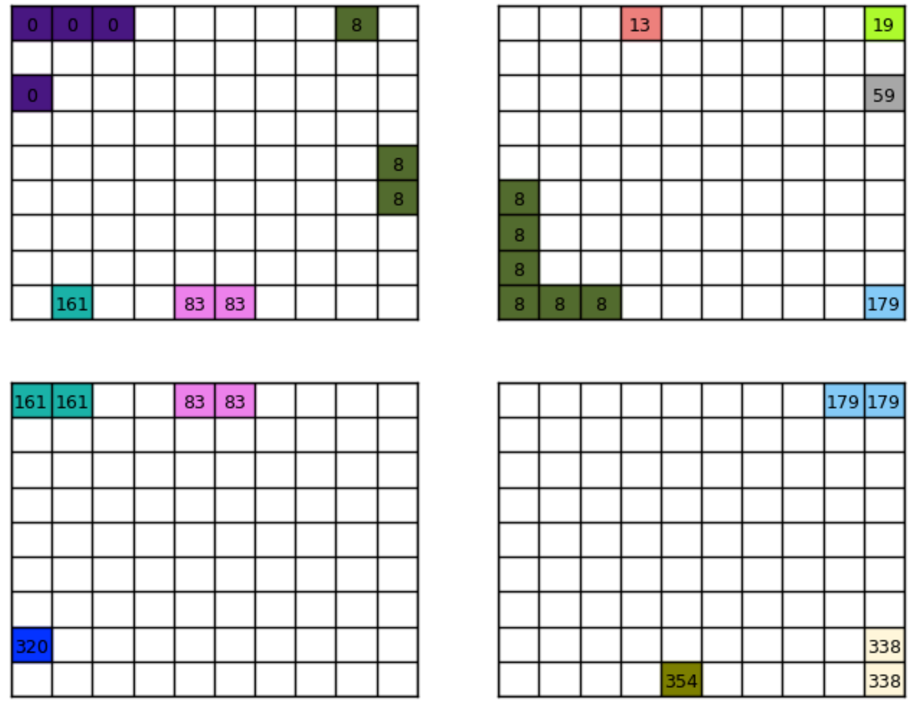


Implementation steps

3. Stage 2b - Equivalency resolution (contn'd)

On each instance

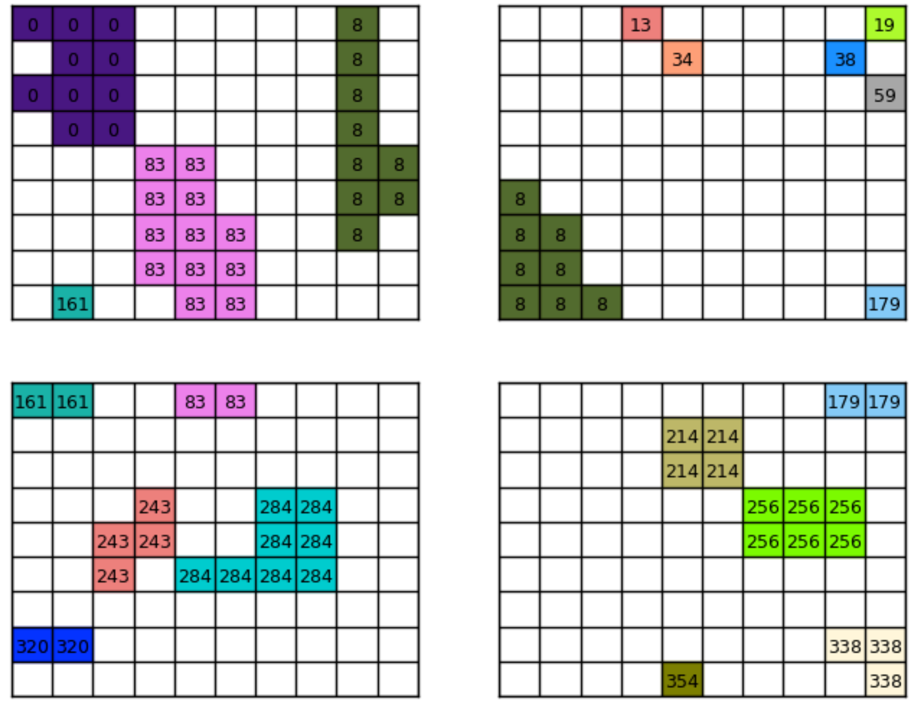
- Set up pairs of adjacent boundary labels
- Apply WQU to each pair to resolve equivalencies
- Write resolved boundary labels into 1-D MemArray using boundary labels from the Stage 1 as index (for later fast access in Stage 3)



Implementation steps

4. Stage 3 - Relabeling of Stage 1 using resolved labels from Stage 2b
   - On each instance, iterate over each chunk and relabel:

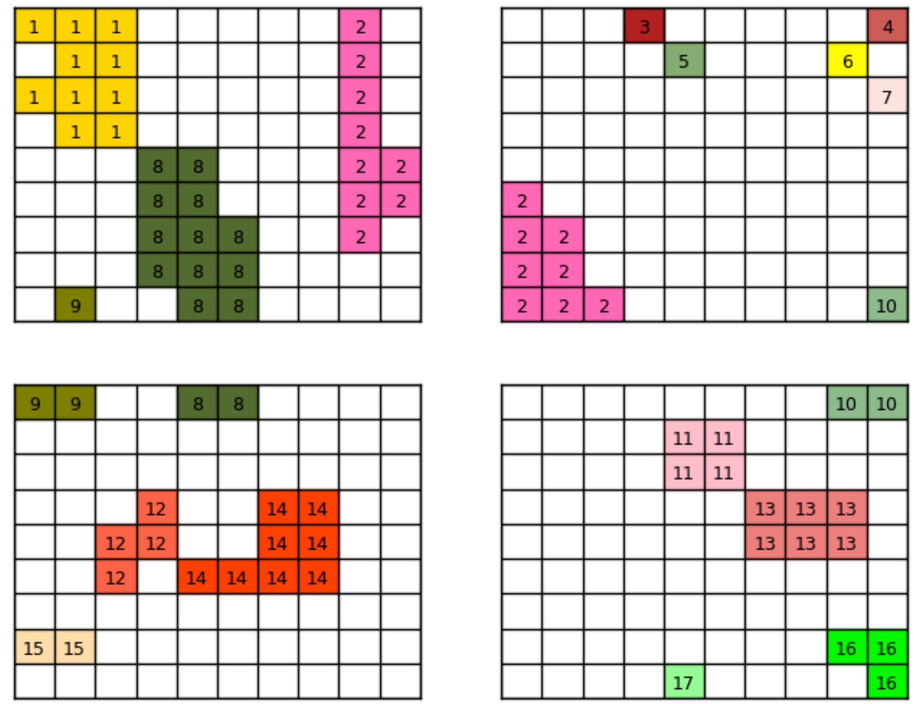
```
if stage2b_array[stage1_label] is not NULL :
        new_label <- stage2b_array[stage1_label]
else :
        new_label <- stage1_label
```



Implementation steps

5. Stage 4 – Final Relabeling

- Replace out-of-order labels from Stage 3 (represented by "flattened" coordinates from the original mask array) with sequential integers for legibility



Operator invocation

The operator is invoked (using the Array Functional Interface - AFL - interface via the iquery client):

```
iquery -anq “store(ccl(mask_array, con_array), ccl_array)”
```

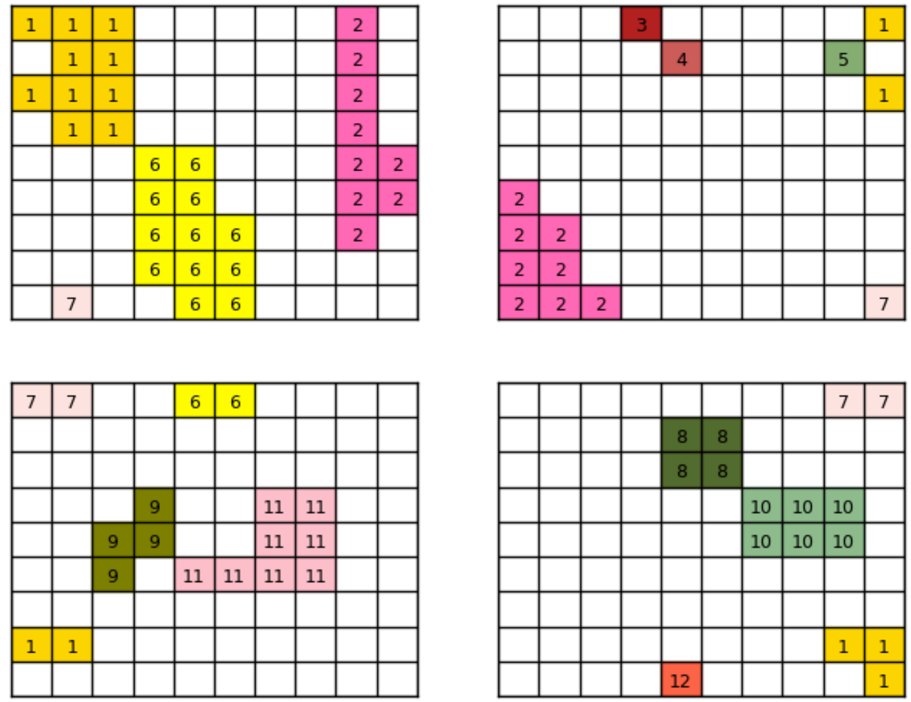
where

- ccl : the new CCL operator
- store : the SciDB native operator to “write” results into an array
- mask_array : the binary mask array
- con_array : the connectivity array
- ccl_array : array into which the resulting labels are written

Operator invocation with periodic BCs

Periodic BCs in both X- and Y-directions for our example:

iquery -aq “store(ccl(mask_array, con_array, 1, 2), ccl_array)”



Real life example

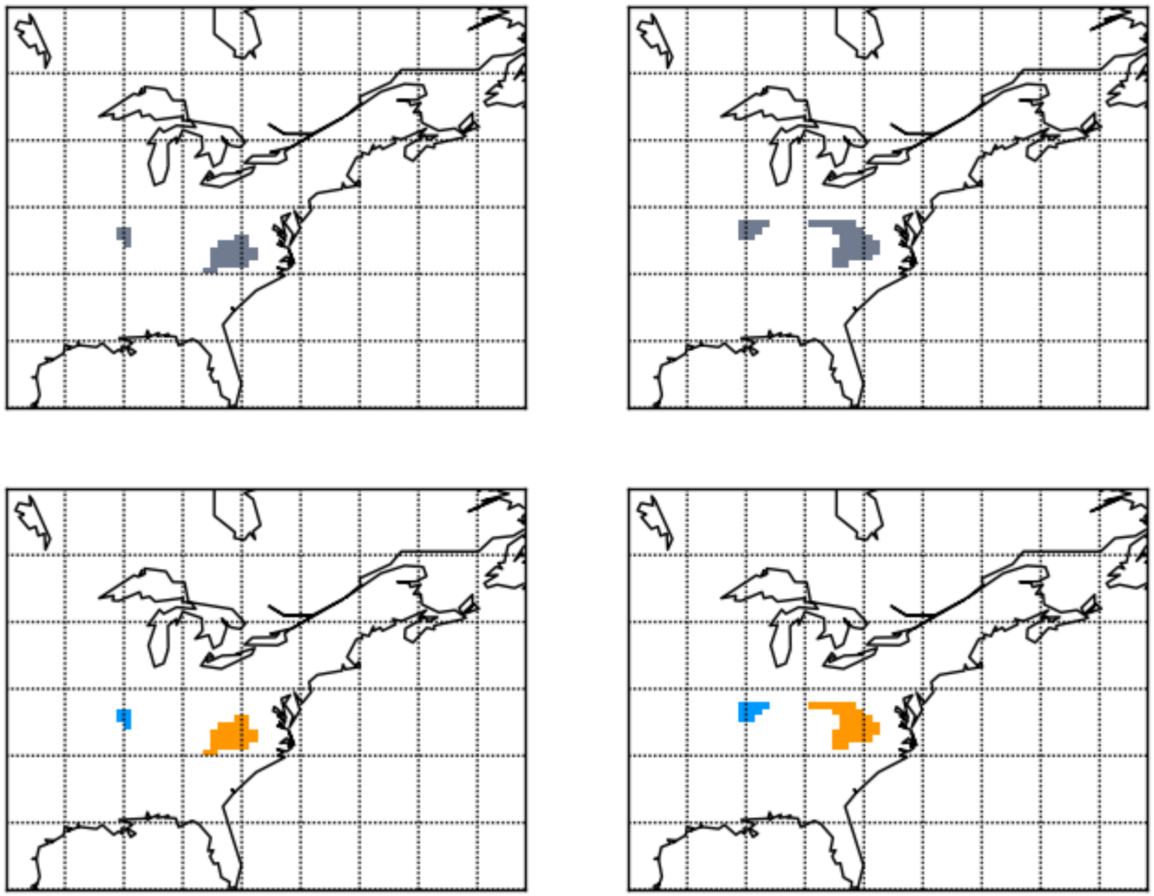
- Thirty-plus (30+) years of potential blizzard conditions on the globe
- Binary mask created by applying thresholds to GEOS-5 MERRA
- Total grid (array) size: $O(10^{11})$
- Foreground cells: $O(10^{8})$
- Spatio-Temporal CCLs (with periodic BCs in longitudinal direction): $O(10^{6})$

Sample results (from Winter 2010 blizzard over Eastern U.S.)

2010-2-5 13:30 | 2010-2-5 14:30

Mask

Connected Components



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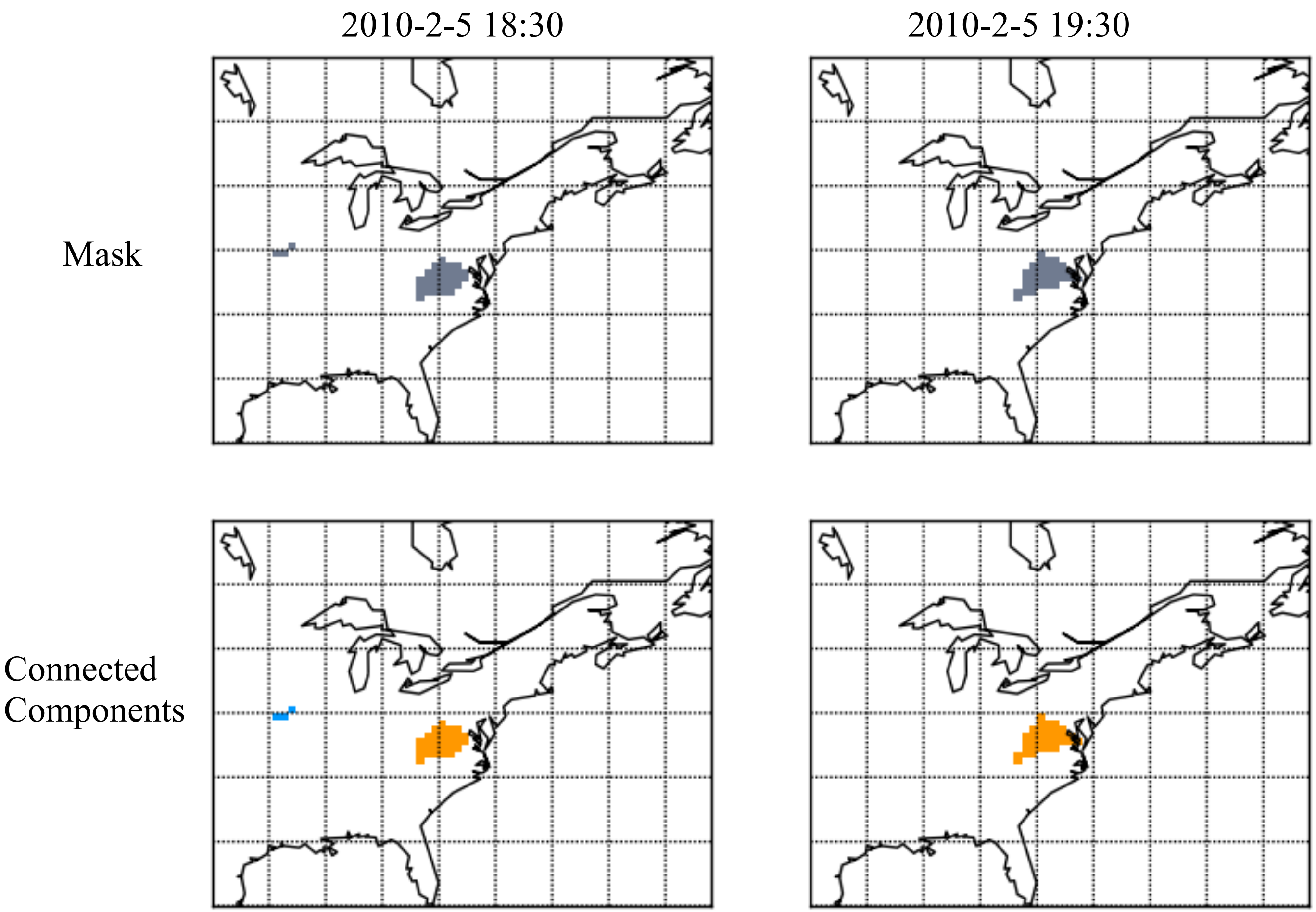

Wall time - seconds min(max)

	84 instances	56 instances	28 instances	14 instances
Stage 1 (local chunk labeling)	12(18)	21(27)	41(54)	88(114)
Stage 2a (replicate)	6(14)	6(12)	7(9)	9(12)
Stage 2b (resolve)	705(975)	705(935)	715(950)	725(940)
Stage 3 (relabeling)	33(55)	85(120)	115(160)	240(320)
Stage 4 (Final sequential labeling)	49(81)	90(125)	180(240)	364(475)

Comments

- Array schema - need to choose with care – significant effect on performance

  <ccl:int64> [t=0:323591,720,0,z=0:0,1,0,y=0:360,91,0,x=0:539,135,0]

- Good scaling for Stages 1, 3 & 4
- Boundary labels replication (Stage 2a) not terrible; dependent on array & schema
- As expected, no scaling for Stage 2b; further work needed to improve efficiency

Concluding remarks

- Array grows as time slices are added
- Expensive to re-compute labels for whole array each time new time slices are added
- Working on incremental implementation so that completed labels are excluded from new computation

Acknowledgement

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