Empowering Data Management, Diagnosis, and Visualization of Cloud-Resolving Models (CRM) by Cloud Library upon Spark and Hadoop

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Goals

- Make Cloud Resolving Model output more usable by science community
  - Accelerate visualization of output.
  - Inter-compare large volumes of output from high-resolution simulations.
  - Diagnose key processes for cloud-precipitation.

- Demonstrate the value to distribute, visualize, analyze and inter-compare Cloud Resolving Model output and data with GCE and NU-WRF

GCE: Goddard Cumulus Ensemble model (1982 - )
NU-WRF: NASA Unified Weather Research Forecast (2010 - )
Approach

• Develop Super Cloud Library (SCL) supporting Cloud Resolving Model Data Analyses using Spark on Hadoop.
  • *Create cloud data files*;
  • *Develop data model and Hadoop format transformer*;
  • *Develop a dynamic Hadoop reader tool*;
  • *Develop subsetting and visualization APIs (Application Programming Interfaces)*;
  • *Develop a Web User Interface*.

• Conduct Demo of GCE and NU-WRF diagnoses on NCCS.
Super Cloud Library (SCL)

Hadoop Distribution File System (HDFS)

MapReduce

YARN

Spark

Spatial temporal index

Diagnosis

Query

Animation

IDL

Python + R

IBM’s Hadoop (FPO)

IBM GPFS -Hadoop Connector

Dynamic Hadoop Reader

GCE, NU-WRF simulation

NCCS Hadoop road map
Outline

• Cloud-Model Data (Real Cases);
• Hadoop Format Translator;
• Subsetting/Visualization via Hadoop-IDL, Hardoop-R and Model Inter-Comparison/Diagnoses;
• Hadoop Dynamic Reader: GPFS and HIVE Interface;
• SCL Web Design;
• Future Work.
# NU-WRF Real Cases

## Long-Term Case
- **Grid (9km):** 600x400x50
- **Date:** West African Monsoon (June-July-August in 2006)
- **Output frequency:** 3hr
- **Data Sizes:** 0.34TB

## Semi-Giga Cases
- **Grid (2km):** 2500x2500x50
- **Date:** Tornado Outbreak (6days), Tropical Storm Bill (6days)
- **Output frequency:** 1hr
- **Data Sizes:** 145 files x 2, 1.73TB x 2
NU-WRF Semi-Giga Cases ($\Delta=2$km)

-2014 Tornado Outbreak vs Hurrrinca Bill-

Total grid points (3D) is 0.312 Giga points

2500x2500x50

2014 Tornado Outbreak

2015 Tropical Storm Bill
## GCE Real Cases

### Long-Term MJO Case
- **Grid (1km):** 1024x1024x45
- **Case & Date:** DYNAMO (Nov. 1~Dec. 10, 2011)
- **Output frequency:** 3hr
- **Data Sizes:** 0.832TB

### Giga Case
- **Grid (250m):** 4096x4096x106
- **Case & Date:** DYNAMO (Nov. 23~Nov. 29, 2011)
- **Output frequency:** 1hr
- **Data Sizes:** 15 TB

1.8 Billion 3D grids
GCE Giga Case ($\Delta=0.25\text{km}$)
DYNAMO simulated vertical velocity details

4096x4096x106 grid points

vertical velocit at level 20 (m/s)
Summary: Data Model

<table>
<thead>
<tr>
<th>Case Tag</th>
<th>GCE</th>
<th>NU-WRF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long-Term (DYNAMO)</td>
<td>Long-Term (AMMA)</td>
</tr>
<tr>
<td></td>
<td>Giga Scale (DYNAMO)</td>
<td>Semi-Giga scale (Tornado 2014)</td>
</tr>
<tr>
<td></td>
<td>Semi-Giga Scale (Tropical Storm Bill 2015)</td>
<td></td>
</tr>
<tr>
<td>Grid points (i-j-k)</td>
<td>1024x1024x45</td>
<td>4096x4096x106</td>
</tr>
<tr>
<td></td>
<td>600x400x50</td>
<td>2500x2500x50</td>
</tr>
<tr>
<td>Horizontal Grid</td>
<td>1km</td>
<td>0.25km</td>
</tr>
<tr>
<td></td>
<td>9km</td>
<td>2km</td>
</tr>
<tr>
<td></td>
<td>06/01/2006 - 09/01/2006</td>
<td>04/27/2014 - 05/03/2014</td>
</tr>
<tr>
<td></td>
<td>06/15/2015 – 06/21/2015</td>
<td></td>
</tr>
<tr>
<td>Model Integration (Output freq.)</td>
<td>5 weeks (3hr)</td>
<td>6 days (1hr)</td>
</tr>
<tr>
<td>Total native output size</td>
<td>0.832TB</td>
<td>15TB</td>
</tr>
<tr>
<td>Status of Porting HDFS</td>
<td>Yes</td>
<td>No¹</td>
</tr>
</tbody>
</table>

Summary of SCL data model, including simulations of Goddard Cumulus Ensemble (GCE) model and NASA-Unified Weather Research and Forecasting (NU-WRF) model. 1. Our current quota of HDFS is not enough of porting Giga-scale GCE output into NCCS’s HDFS yet, but in progress.
Hadoop Format Translator
CSV Data-Size Reduction

CSV format (V1.0)
• Original CSV: each files has time-geolocation information and single geophysical parameter..

CSV format (V2.1)
• Geolocation information is stored in single separate file per case.
• Parameter files contains several parameters.
• **Parallel gzip program** compress CSV files quickly (4days $\rightarrow$ 7min).
• Hadoop reads the geolocation file and parameter files simultaneously.

Geolocation+Parameter File x 27
ID, time, lev, lat, lon, param

<table>
<thead>
<tr>
<th>ID</th>
<th>time</th>
<th>lev</th>
<th>lat</th>
<th>lon</th>
<th>param</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2820</td>
<td>1,1.45085</td>
<td>75.82308</td>
<td>0.10038067E+04</td>
<td>2,2820,1,1.45090,75.83212,0.10038067E+04</td>
<td>3,2820,1,1.45095,75.84116,0.10038067E+04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Geolocation files
ID, i, j, lev, lat, lon

<table>
<thead>
<tr>
<th>ID</th>
<th>i</th>
<th>j</th>
<th>lev</th>
<th>lat</th>
<th>lon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2820</td>
<td>1</td>
<td>1</td>
<td>1.45085</td>
<td>75.82308</td>
<td>0.10038067E+04</td>
</tr>
<tr>
<td>2,2820</td>
<td>1</td>
<td>1.45090</td>
<td>75.83212</td>
<td>0.10038067E+04</td>
<td></td>
</tr>
<tr>
<td>3,2820</td>
<td>1</td>
<td>1.45095</td>
<td>75.84116</td>
<td>0.10038067E+04</td>
<td></td>
</tr>
<tr>
<td>4,2820</td>
<td>1</td>
<td>1.45100</td>
<td>75.85021</td>
<td>0.10038067E+04</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Parameter files x 3
ID, time, param1, param2...

<table>
<thead>
<tr>
<th>ID</th>
<th>time</th>
<th>param1</th>
<th>param2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,0</td>
<td>1.0038067E+04</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>2,0</td>
<td>1.0038067E+04</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>3,0</td>
<td>1.0038067E+04</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>4,0</td>
<td>1.0038067E+04</td>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>

PGZIP.sh

This method is close to what NetCDF reader does.
CFMC CSV Data Size

Single Time Frame of NU-WRF Semi-Giga Case

V1.0: Original format
V1.2: Separate Geolocation from parameter files
V2.0: Bundle multiple parameters
V2.1: Only single Geolocation file for each case.

Note. Data size reduction also improved conversion process time (linearly in size).
Subset/Visualization via Hadoop-IDL, Hadoop-R

Model Inter-comparison (Diagnosis)
Visualization with **IDL+Hadoop** and Subsetting with Impala: GCE 1024x1024x45 Updraft Simulation

Four examples for subsetting at different times
Red color indicating the strongest updraft cores
Impala Subset Can Overlay Multiple Variables and Study Their Relations

GCE Simulation
1024 x 1024 x 45 Grid

Subset domain
(40x40x20km)

Simulation domain

Red: updraft core
Blue: rain shaft

1024 km

1024 km
WRF Semi-giga Scale (2500x2500) Simulation

Surface Rainfall Rate with Impala Subsetting of Maximum \( w \) in Red Box
3-D animation of subset data

Cloud ice + Rain

Downdraft + Updraft
Spark-Python CRM Diagnostic Module

Model Inter-comparisons

Surface Rainfall PDF

3D solid: dx=0.25km
2D hatched: dx=1km

Scientific Diagnoses

Height (km MSL)

Mass fraction of hail in air [g/kg]

Mass fraction of cloud ice in air [g/kg]

Air temperature [K]

Upward air velocity (m/s)
Summary

• Different approaches for data subsetting and visualization have been experimented: e.g., Hadoop/Hive + IDL, Hadoop/Impala + IDL, Hadoop + R;

• Lesson learned:
  – Subsetting with Impala is much faster than Hive;

• Spark – Python is the current choice of model diagnoses and inter-comparisons.
Dynamic Hadoop Reader and Visualization with R, Hadoop, Spark and Adaptive Subsetting of Earth Science Data in HDFS
Super Cloud Library (SCL)

Hadoop Distribution File System (HDFS)

MapReduce
Spark
YARN

IBM’s Hadoop (FPO)
IBM GPFS-Hadoop Connector
Dynamic Hadoop Reader
GCE, NU-WRF simulation

Spatial temporal index

NCCS Hadoop road map
PortHadoop Overview

GPFS (IBM Spectrum Scale 4.2.0.1)
PortHadoop (based on Cloudera Hadoop 5.3.3)
Adaptively Subsetting: Data Flow

Using multiple tables saves storage as well as be flexible. Combining tables is compute-intensive.
Visualization and Diagnosis via MapReduce

Submitted to The 6th IEEE International Conference on Big Data and Cloud Computing (BDCloud 2016)
Visualization of NU WRF 1250x1250 Rain Simulation with R+Hadoop and Spark R

An image with a highlighted area for an interested event (the heaviest rainfall)

Animation (From 9 AM, 2014-04-28 to 12 AM, 2014-04-29)
Performance with Spark R

Image Plotting

Data: NU-WRF model with a 1250×1250×50 grid (4km resolution) and 48-hour simulation time. Each time frame has ~3GB data. An image is created for each layer.

Testbed: 9 nodes (1 master + 8 slaves). Each node has 48 cores and 128 GB memory.

Method: Spark R
Query and Adaptively Subsetting

TABLE II: Simple SQL query statements

<table>
<thead>
<tr>
<th>Labels in Figure 10</th>
<th>SQL statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top 1</td>
<td>select * from dataframe where value == (select max(value) from dataframe) limit 1</td>
</tr>
<tr>
<td>Top 10</td>
<td>select * from dataframe desc order by value limit 10</td>
</tr>
<tr>
<td>Condition</td>
<td>select * from dataframe where value &gt; 0.005</td>
</tr>
</tbody>
</table>

- **Query and Plot (Top 1)**
- **Query and Plot (Top 10)**
- **Query and Plot (Condition)**
- **Query Only (Top 1)**
- **Query Only (Top 10)**
- **Query Only (Condition)**
- **Image Plotting**

Elapsed Time (Seconds)

Number of Files

[Bar chart showing elapsed time for different query types and number of files]
SCL Web Design
## SCL Users Defined

### SCL User Hierarchy

<table>
<thead>
<tr>
<th>Level I</th>
<th>User Level</th>
<th>Upload new data</th>
<th>Visualization</th>
<th>Statistics</th>
<th>Subset</th>
<th>Download data</th>
<th>Add new statistical function</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIST Team</td>
<td>Level I (~5+)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level II</th>
<th>User Level</th>
<th>Upload new data</th>
<th>Visualization</th>
<th>Statistics</th>
<th>Subset</th>
<th>Download data</th>
<th>Add new statistical function</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Users (with NCCS account)</td>
<td>Level II (~40)</td>
<td>Yes, upon request to NCCS&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level III</th>
<th>User Level</th>
<th>Upload new data</th>
<th>Visualization</th>
<th>Statistics</th>
<th>Subset</th>
<th>Download data</th>
<th>Add new statistical function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public Users (w/o NCCS account)</td>
<td>Level III (~1000)</td>
<td>N/A</td>
<td>Yes&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Yes&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Yes&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Yes</td>
<td>N/A</td>
</tr>
</tbody>
</table>

<sup>1</sup> after discussion with Dan Duffy@NCCS.

<sup>2</sup> This depends on Hadoop resource and NASA security.
Summary/ Future Work

- Develop Super Cloud Library (SCL) supporting Cloud Resolving Model Data Analyses using Spark on Hadoop.
  - Create cloud data files: *Model inter-comparison*
  - Develop data model and Hadoop format transformer: *Improvement for performance*
  - Develop a dynamic Hadoop reader tool: *NCCS*
  - Develop subset and visualization APIs (Application Programming Interfaces): *Tested and need work on diagnosis analyses*
  - Develop a Web User Interface: *Proposed SCL website*
  - Conduct **Demo** of GCE and NU-WRF diagnoses on NCCS: *By February 2017*