SMART CFD PROXY

REPLICATING CFD RESULTS ACCURATELY & AT HIGH SPEED

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Outline

- Smart Proxy
  - Engineering Application of Big Data Analytics
- Original Application in Reservoir Modeling
  - Tracking Pressure & Saturation Changes at the Grid Block Level
- Application to CFD
  - Multi-Phase Fluidized Bed (Proof of Concept)

Computational Science

- Numerical solution to complex, multi-physic, non-linear, partial differential equation emerged, when
  - Engineering models became too complex to be solved analytically,
  - High speed computers became widely available.

Computational Footprint

- Our models soon increased in size such that use of super computers and CPU clusters became a necessity to solve serious problems.

- Proxy models are used to address the extensive computational cost of the numerical simulation models.

Proxy Models

- Proxy models attempt to behave like the original models but with lower computational cost.
- The current paradigm for developing proxy models is to simplify the original model.
- Existing proxy models are either:
  - Statistics-based (response surfaces – curve fit at specific locations)
  - Physics-based (Reduced Physics)
  - Coarse Models (low resolution)

Paradigm Shift in Proxy Modeling

- In this new paradigm of developing proxy models,
  - The proxy model represents the entire system.
  - Physics of the model is ***<u>NOT</u>*** simplified.
  - Model resolution is ***<u>NOT</u>*** reduced.

- In this new paradigm, data (generated by CFD), and not the physics, will be the basis for the proxy model.

Paradigm Shift in Proxy Modeling

- Smart Proxy uses the pattern recognition capabilities of Artificial Intelligence and Data Mining (Big Data Analytics) to ***LEARN*** and then ***MIMIC*** the behavior of the original CFD.

- Smart Proxy is trained using massive amount of data that is generated from (only a handful of) CFD models runs and validated using blind CFD runs.

Paradigm Shift in Proxy Modeling

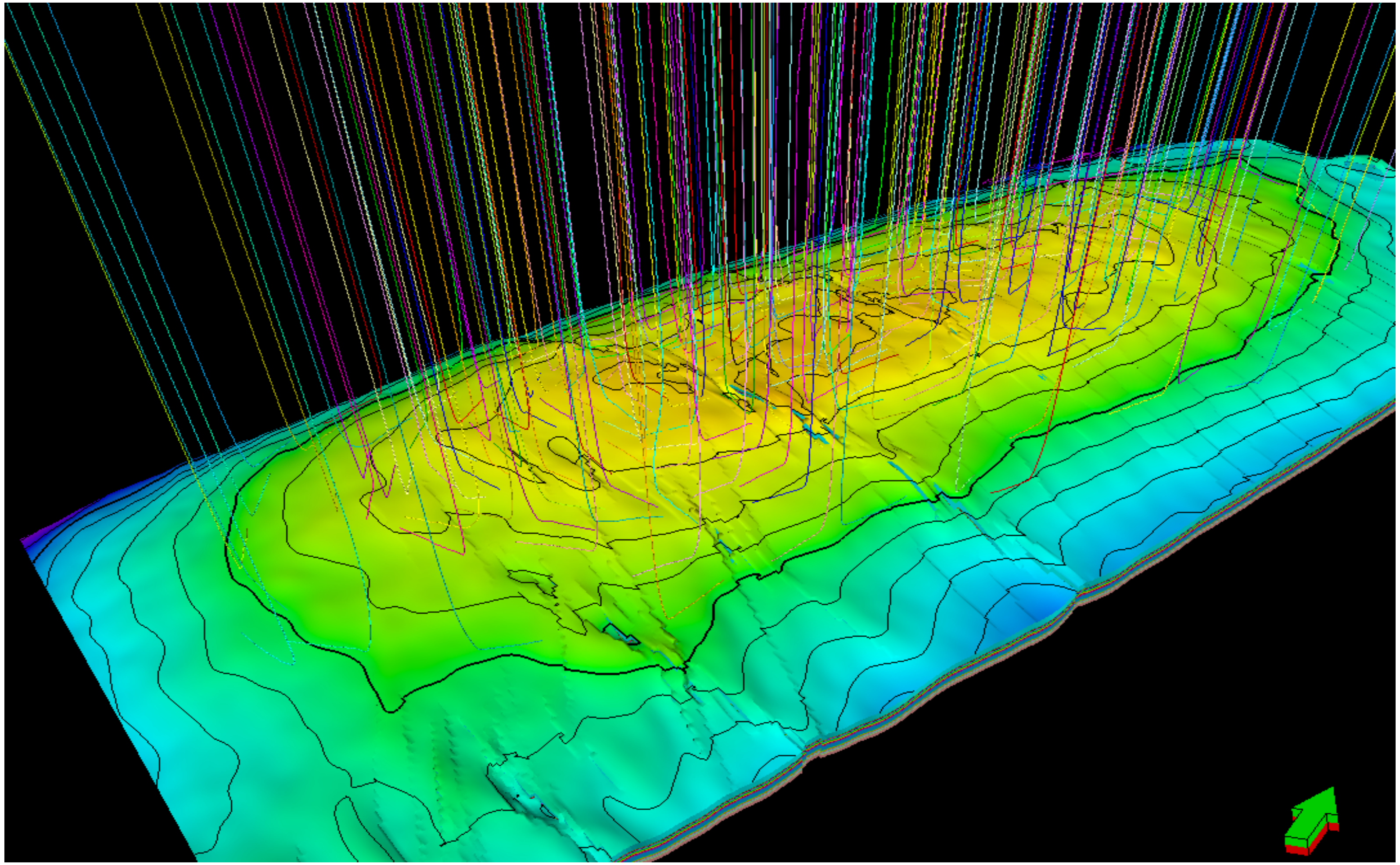
- A single run of the original model is treated as a treasure trove of data and information that can be used to train and calibrate a new, smart model.

- This technology is the manifestation of ***"BIG DATA ANALYTICS"*** in engineering problem solving, specifically, in the numerical modeling arena.

Surrogate Reservoir Modeling - SRM

Smart Proxy Model for high Speed Replication of the Results of Numerical Reservoir Simulator

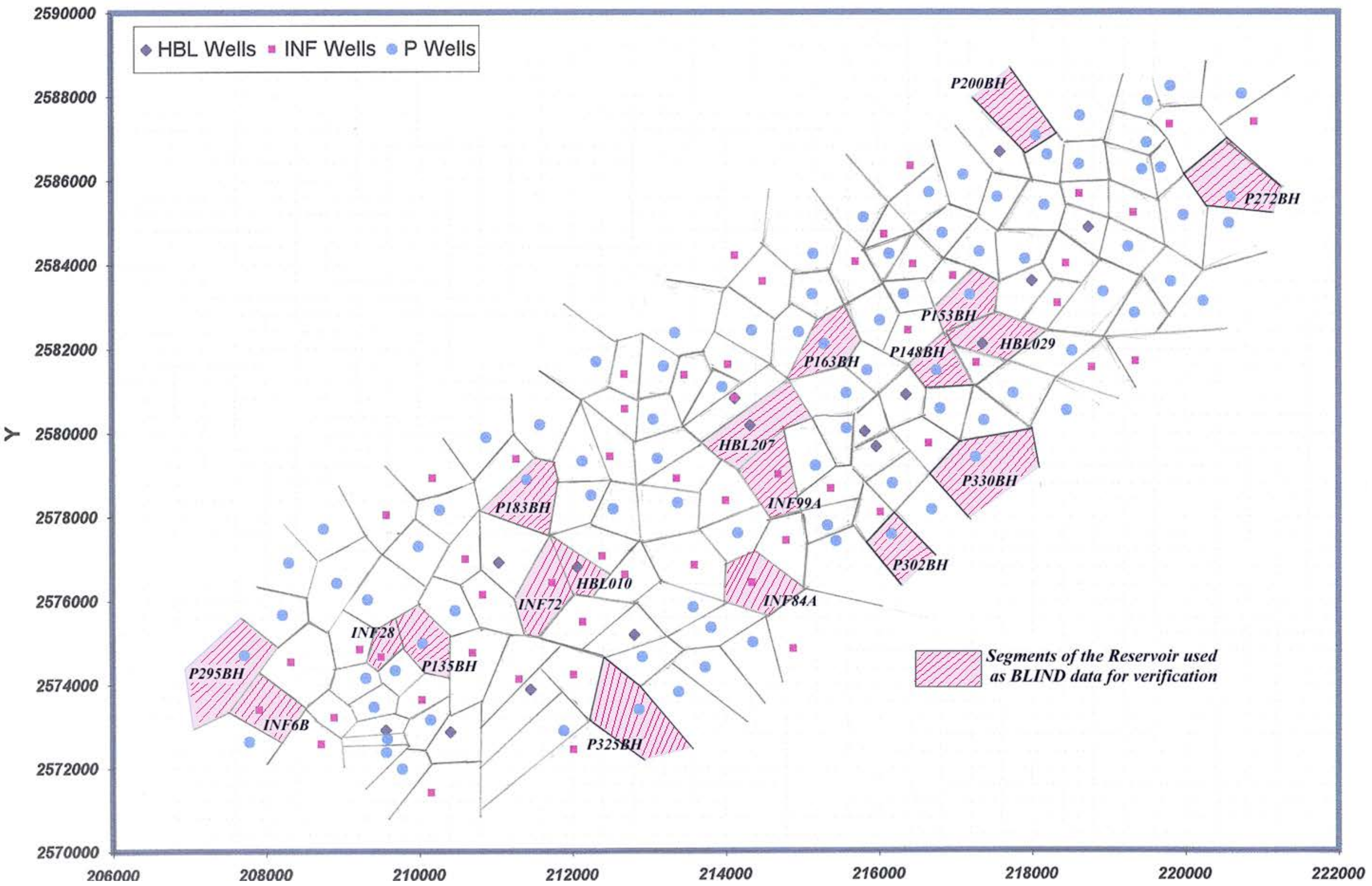
Numerical Model Characteristics



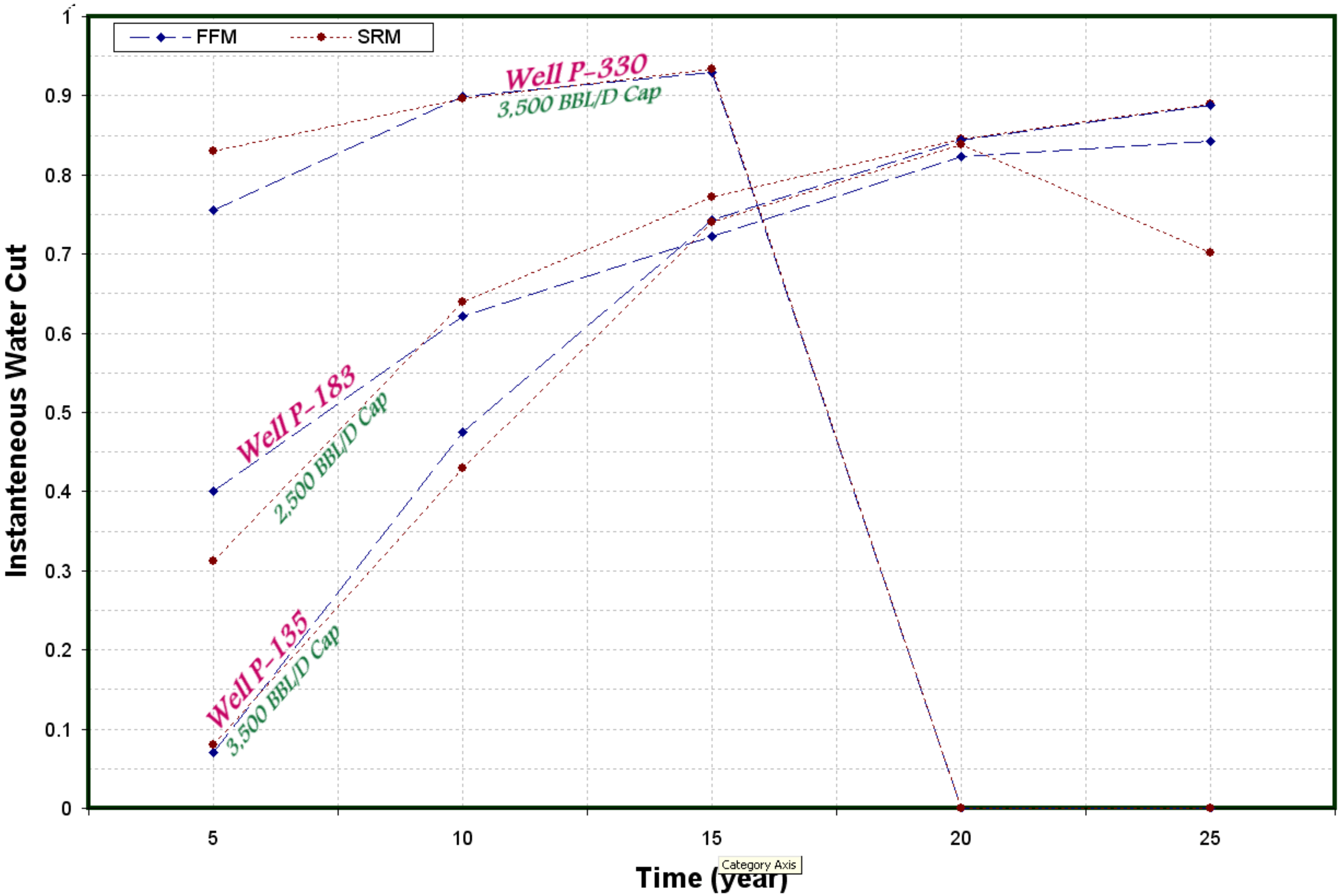
Study Completed	**2005**
Implemented	**2006**
Field Results Published *(SPE 170664)*	**2014**

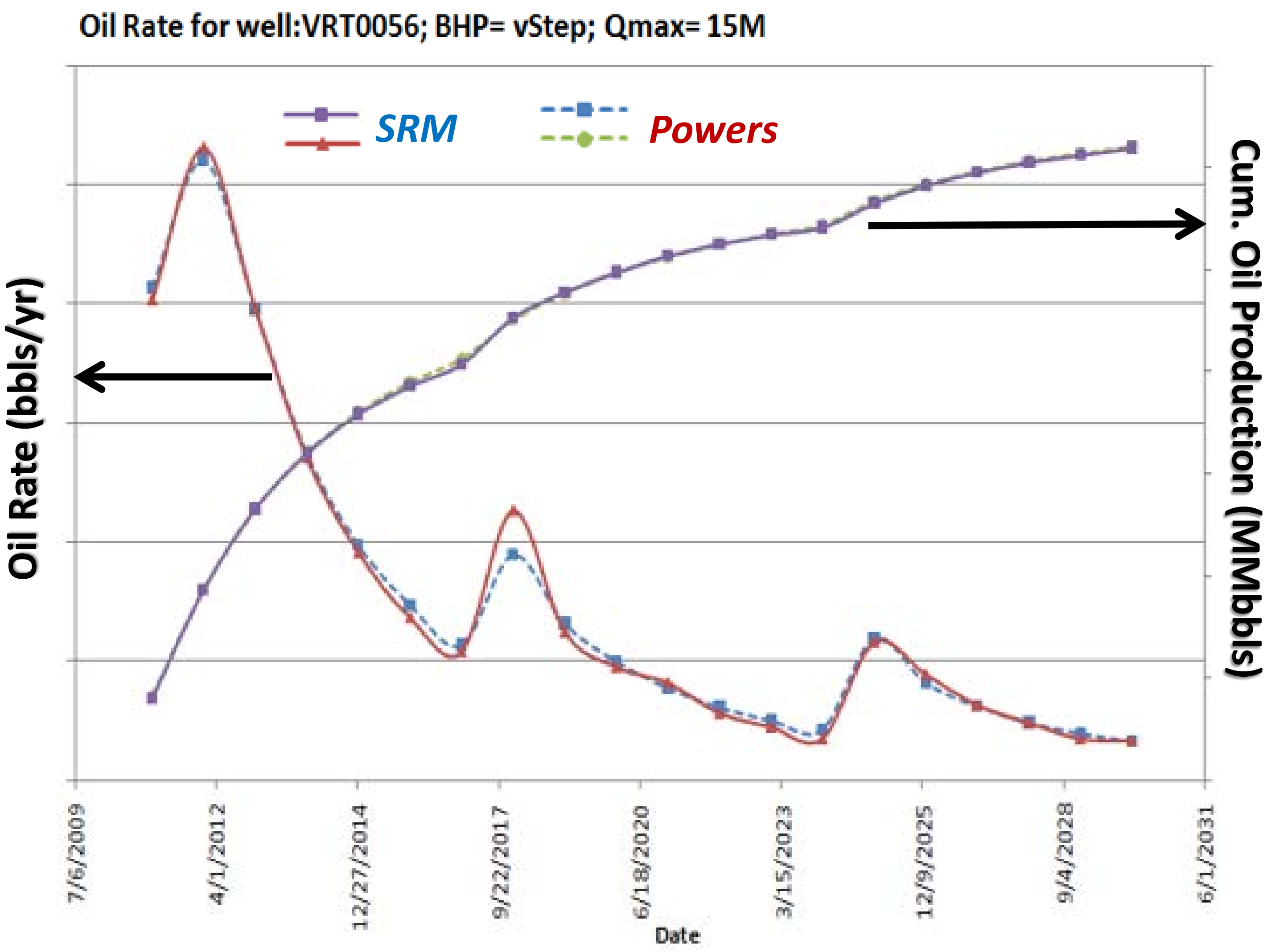
Size of the Full Field Model	**1MM Grid Blocks**
Formation Type	**Naturally Fractured Carbonate**
Number of Wells	**167 (Horizontal)**
Simulation Run	***10 Hours on 12 parallel CPU***

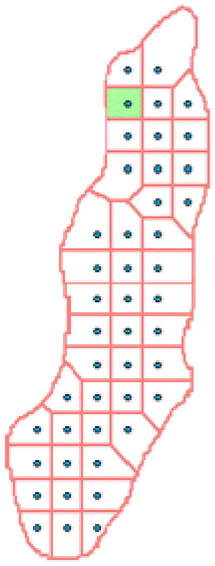
Field Production Optimization Study



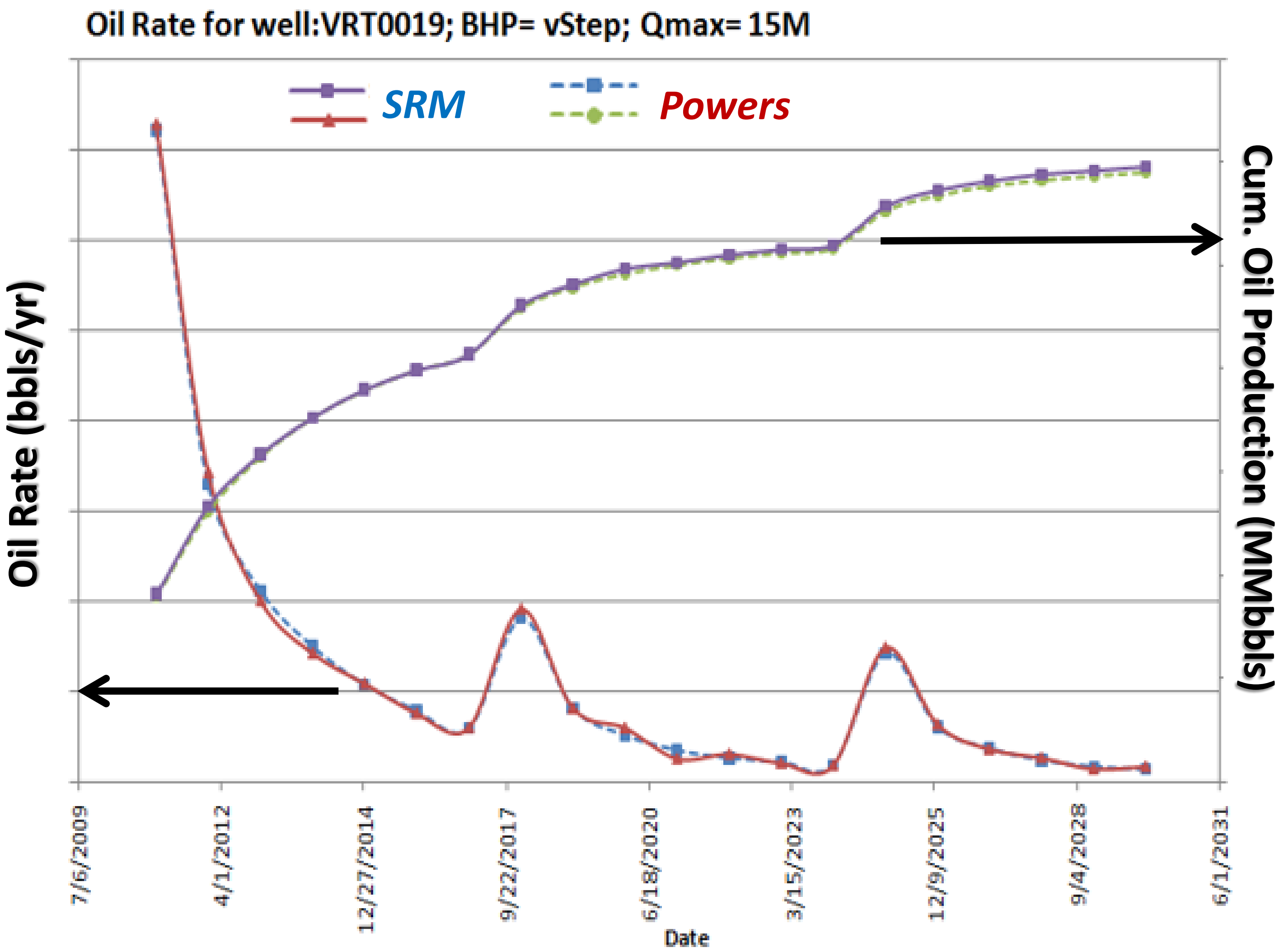
Field Production Optimization Study

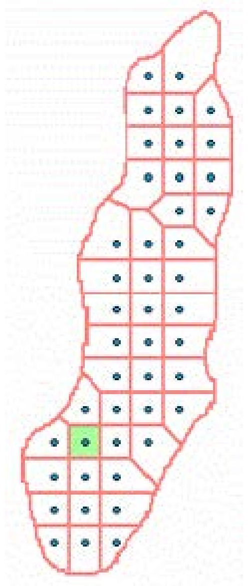






Black Oil Simulation
Green Field
6.5 MM Grid Blocks



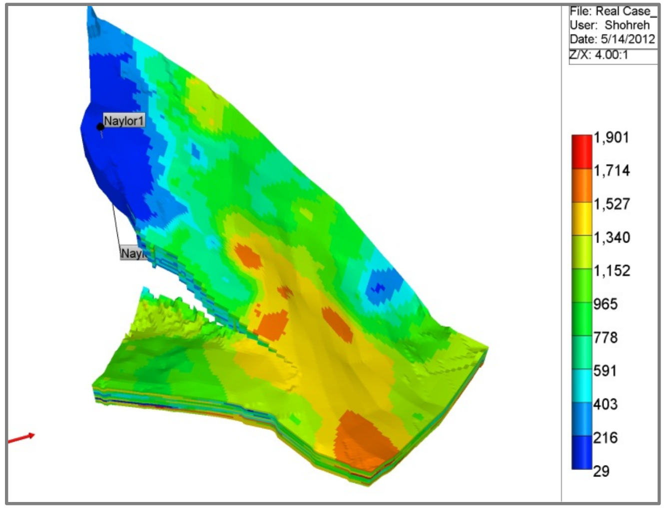


Black Oil Simulation
Green Field
6.5 MM Grid Blocks

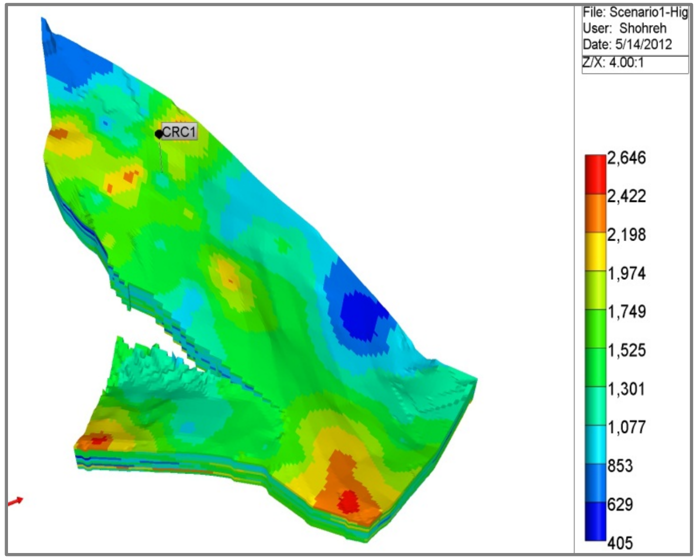
Otway CO_2 Seq. Project, Australia

Permeability Maps

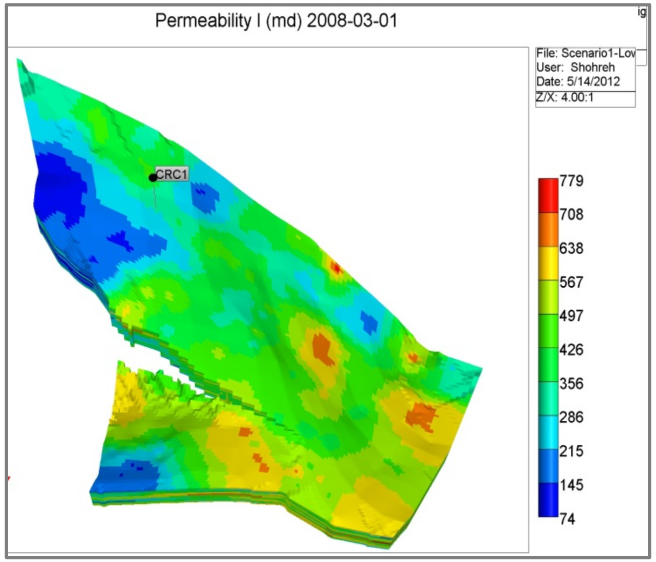
History Matched Perm



High perm



Low perm



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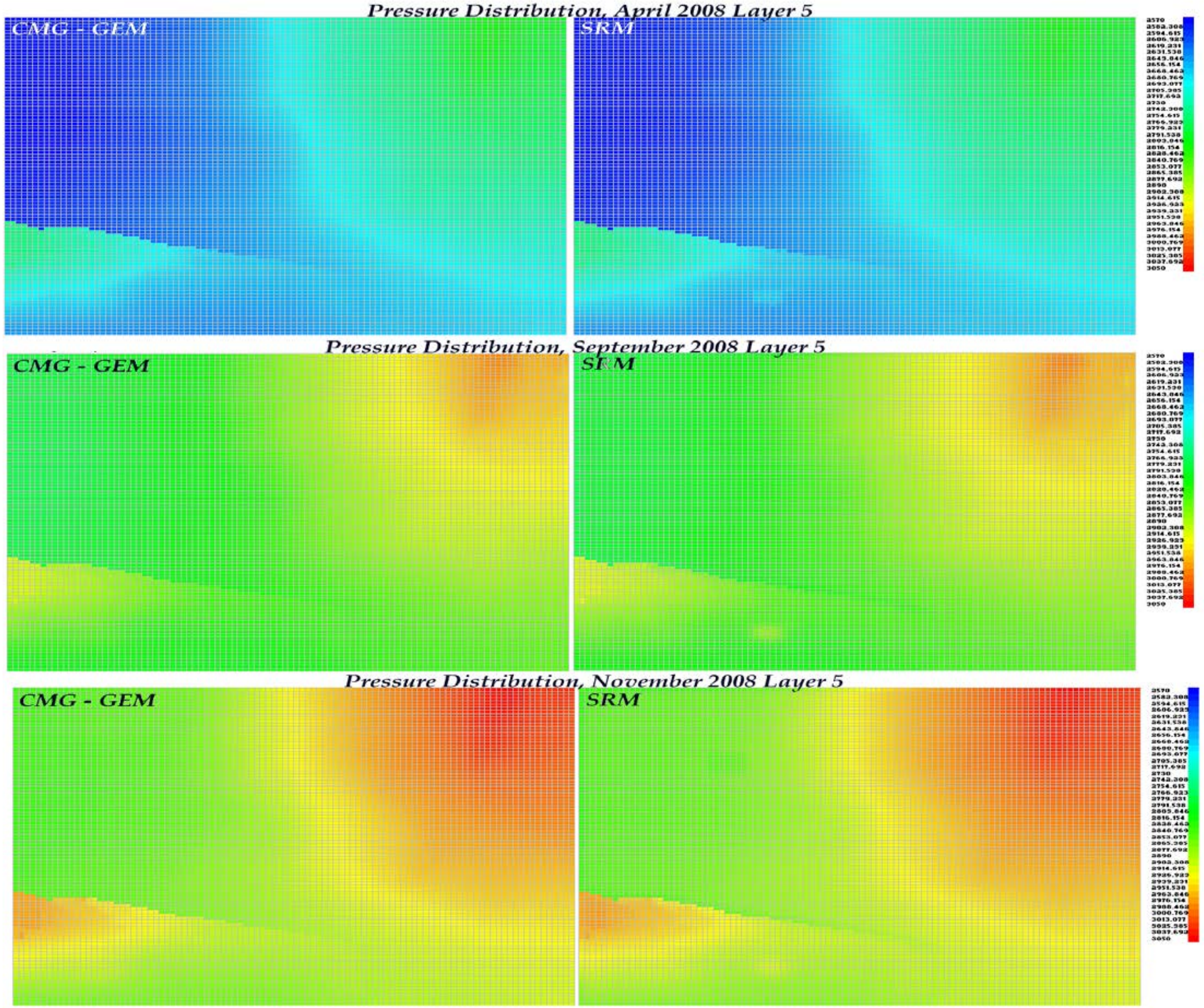
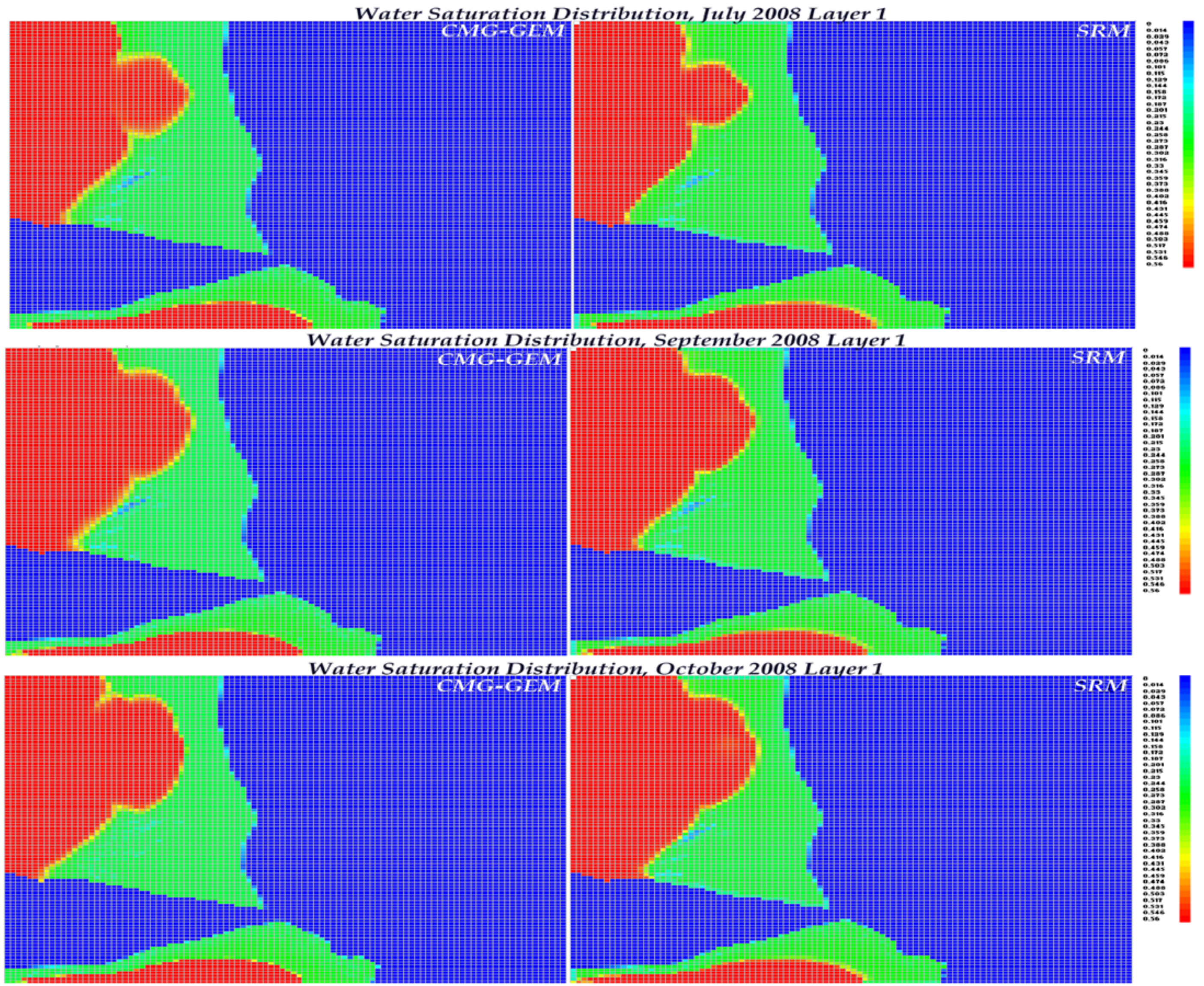
Pressure Distribution



Otway CO_2 Seq. Project, Australia

Water Saturation Distribution



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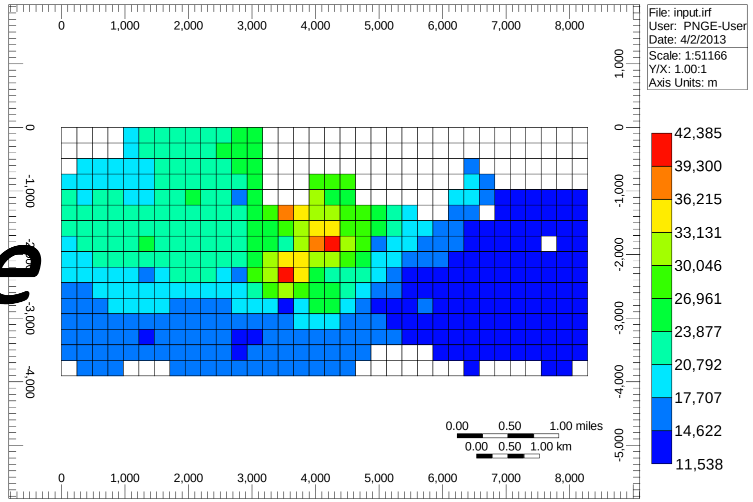
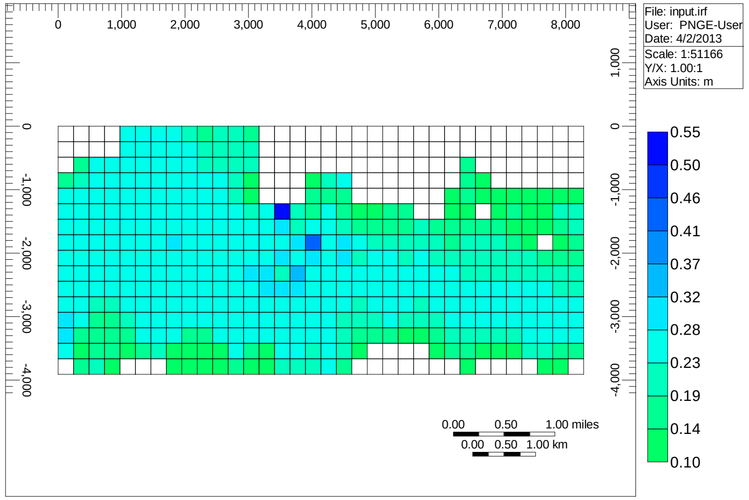
The Coarse Reservoir Model

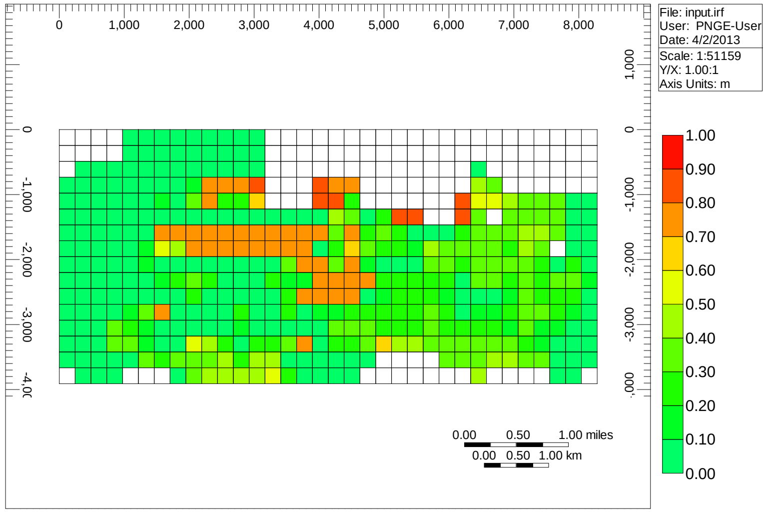
Pressure (kPa) 2172-01-01 K layer: 18



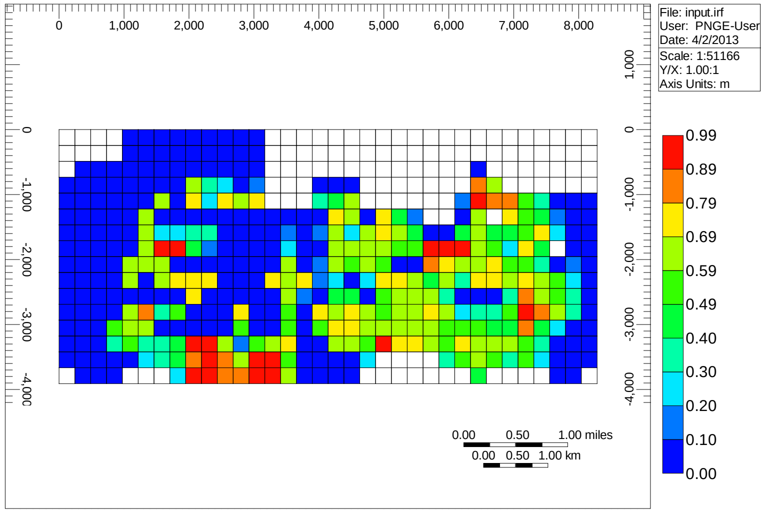
Water Saturation 2172-01-01 K layer: 18



Gas Saturation 2172-01-01 K layer: 18



Gas Mole Fraction(CO2) 2172-01-01 K layer: 18



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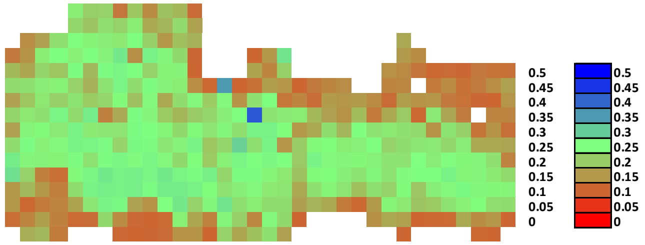
Water Saturation Distribution

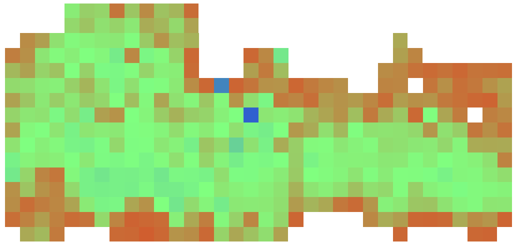
Simulator (CMG) Results

SRM Results

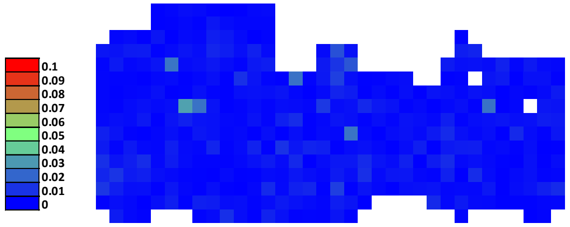
% Relative Error



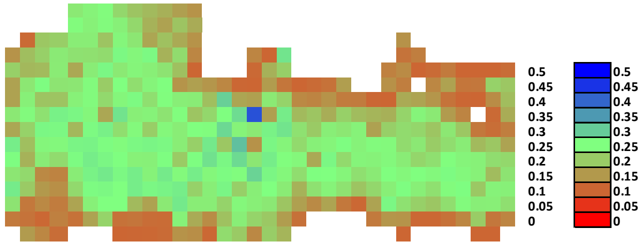
Actual Data: Realization # 1, Layer= 18, 100 years after Injection, Feature= SW %



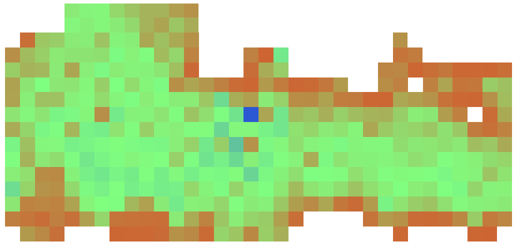
SRM Data: Realization # 1, Layer= 18, 100 years after Injection, Feature= SW %



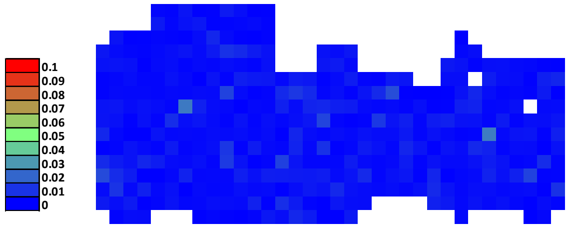
Realization # 1, Layer= 18, 100 years after Injection, Feature= Absolute Error of SW %



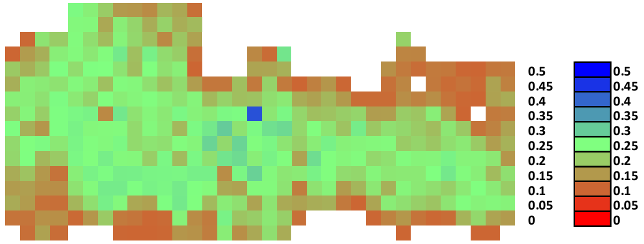
Actual Data: Realization # 11, Layer= 18, 100 years after Injection, Feature= SW %



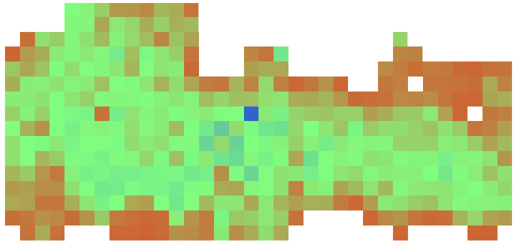
SRM Data: Realization # 11, Layer= 18, 100 years after Injection, Feature= SW %



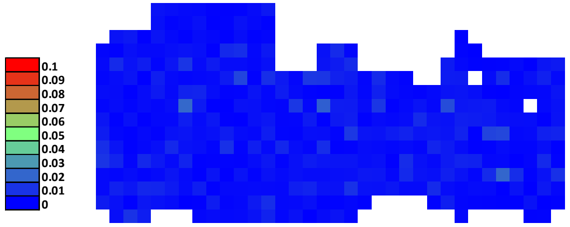
Realization # 11, Layer= 18, 100 years after Injection, Feature= Absolute Error of SW %



Actual Data: Realization # 12, Layer= 18, 100 years after Injection, Feature= SW %



SRM Data: Realization # 12, Layer= 18, 100 years after Injection, Feature= SW %



Realization # 12, Layer= 18, 100 years after Injection, Feature= Absolute Error of SW %

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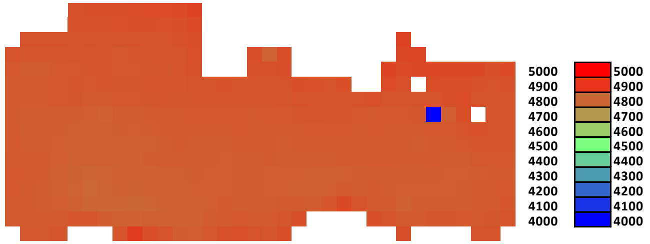
CO_2 Mole Fraction Distribution

Simulator (CMG) Results

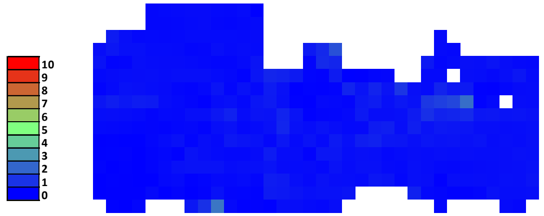
SRM Results

% Relative Error

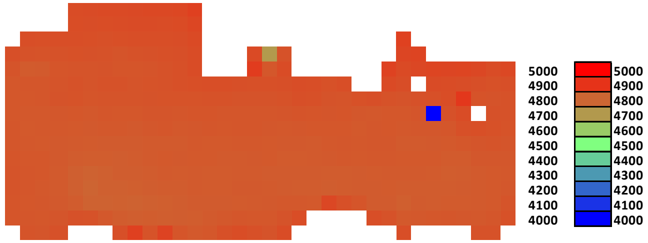


Actual Data: Realization # 8, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)

SRM Data: Realization # 8, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)

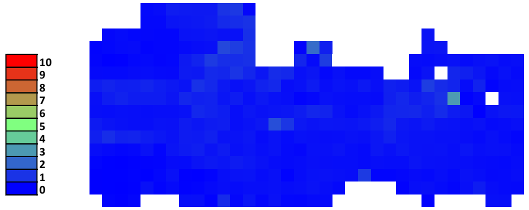


Realization # 8, Layer= 18, 100 yrs after Injection, Feature= Relative Error %

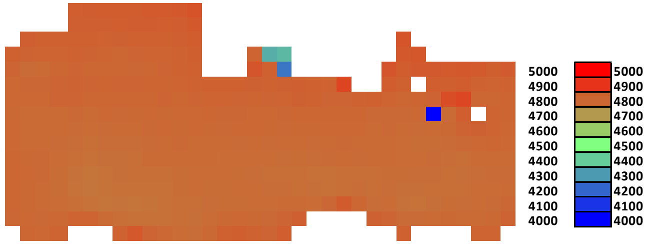


Actual Data: Realization # 9, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)

SRM Data: Realization # 9, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)

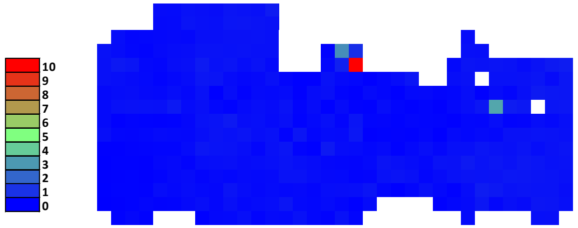


Realization # 9, Layer= 18, 100 yrs after Injection, Feature= Relative Error %



Actual Data: Realization # 10, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)

SRM Data: Realization # 10, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)



Realization # 10, Layer= 18, 100 yrs after Injection, Feature= Relative Error %

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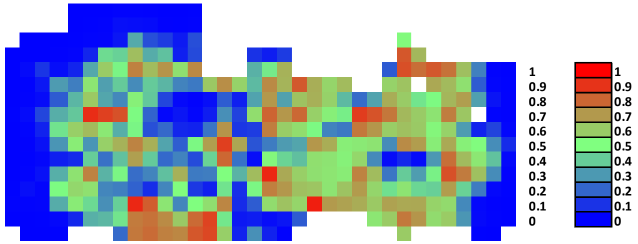
Pressure Distribution

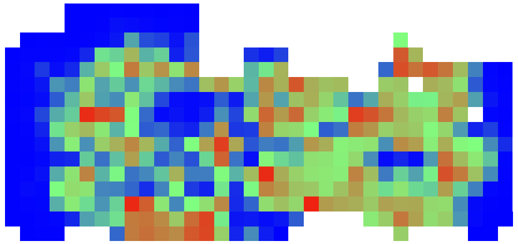
Simulator (CMG) Results

SRM Results

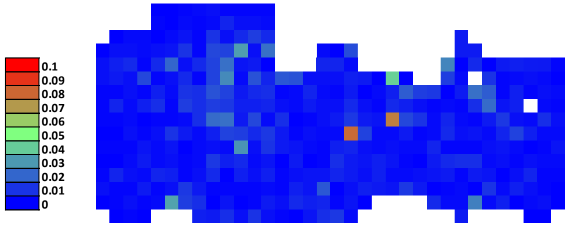
Absolute Error



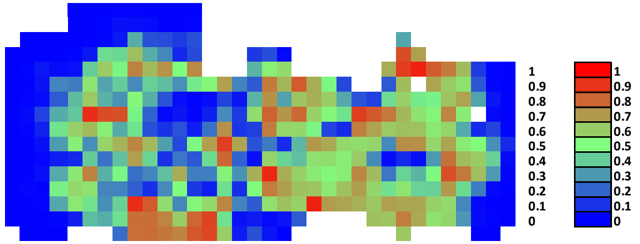
Actual Data: Realization # 9, Layer= 18, 9 years after Injection, Feature= CO2 Mole Fraction %



SRM Data: Realization # 9, Layer= 18, 9 years after Injection, Feature= CO2 Mole Fraction %



Realization # 9, Layer= 18, 9 years after Injection, Feature= Absolute Error %



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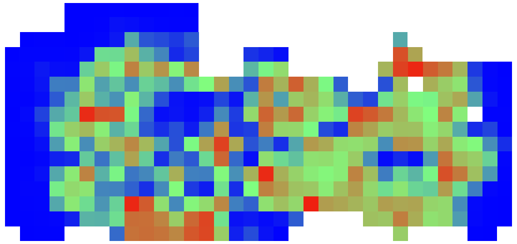
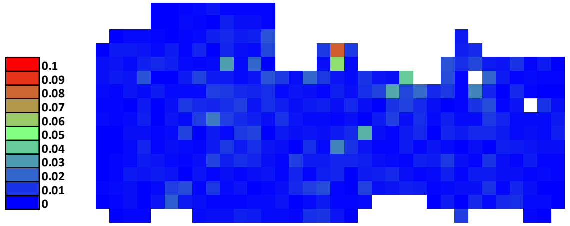
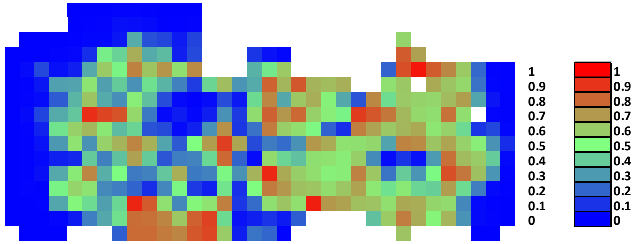


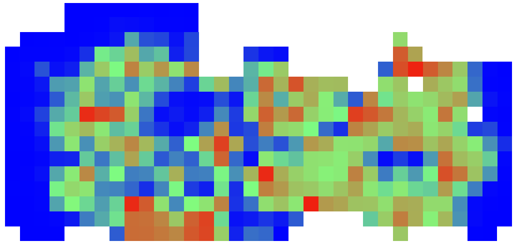
SRM Data: Realization # 10, Layer= 18, 9 years after Injection, Feature= CO2 Mole Fraction %



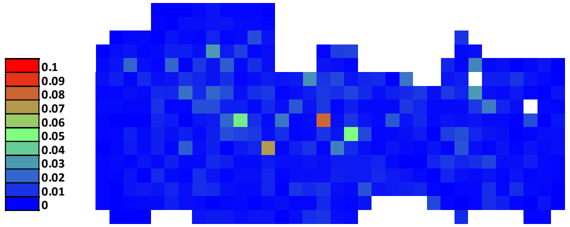
Realization # 10, Layer= 18, 100 years after Injection, Feature= Absolute Error %



Actual Data: Realization # 7, Layer= 18, 9 years after Injection, Feature= CO2 Mole Fraction %



SRM Data: Realization # 7, Layer= 18, 9 years after Injection, Feature= CO2 Mole Fraction %



Realization # 7, Layer= 18, 100 years after Injection, Feature= Absolute Error %

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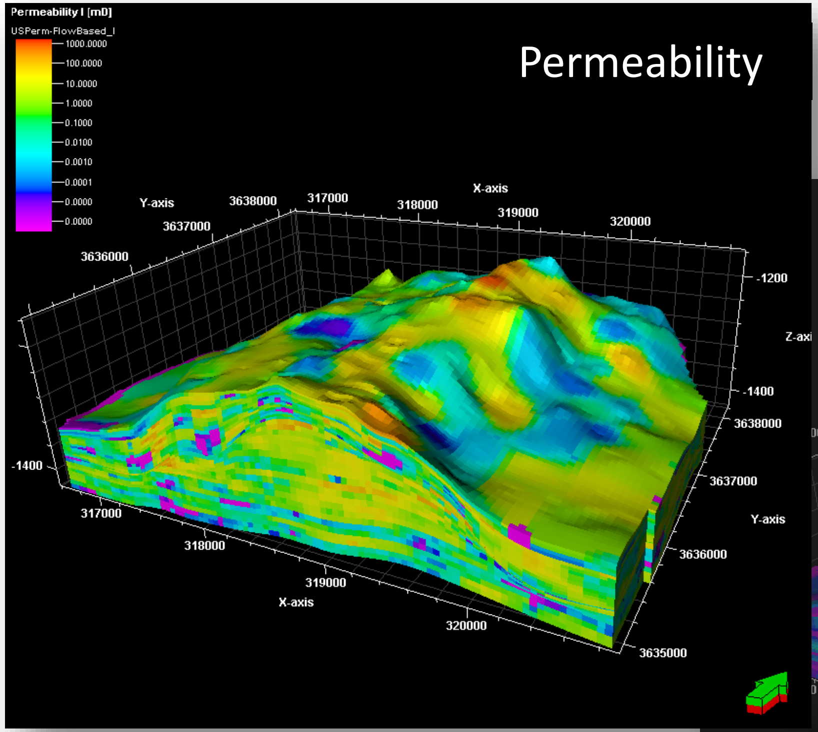

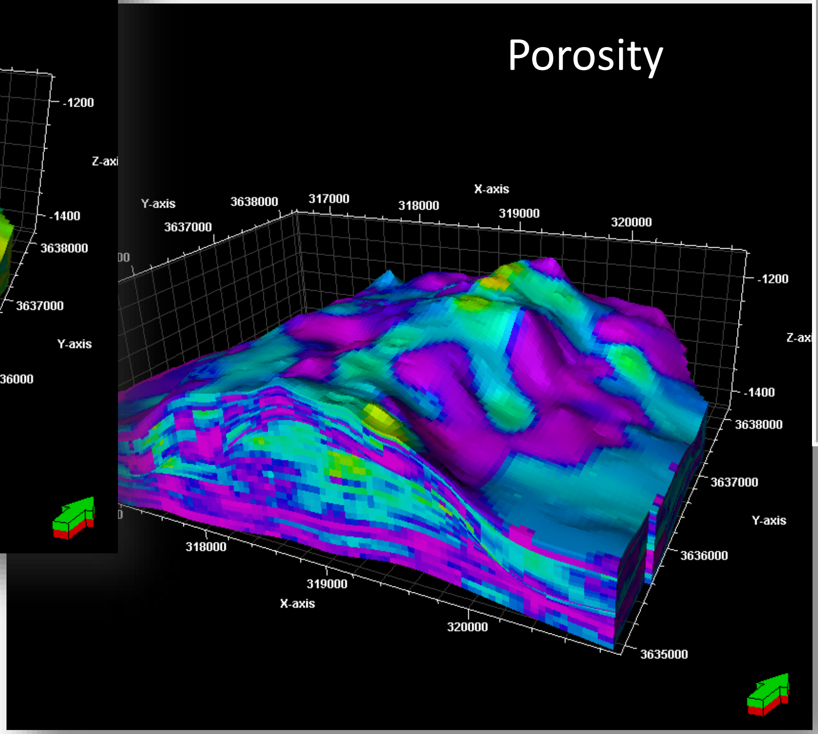

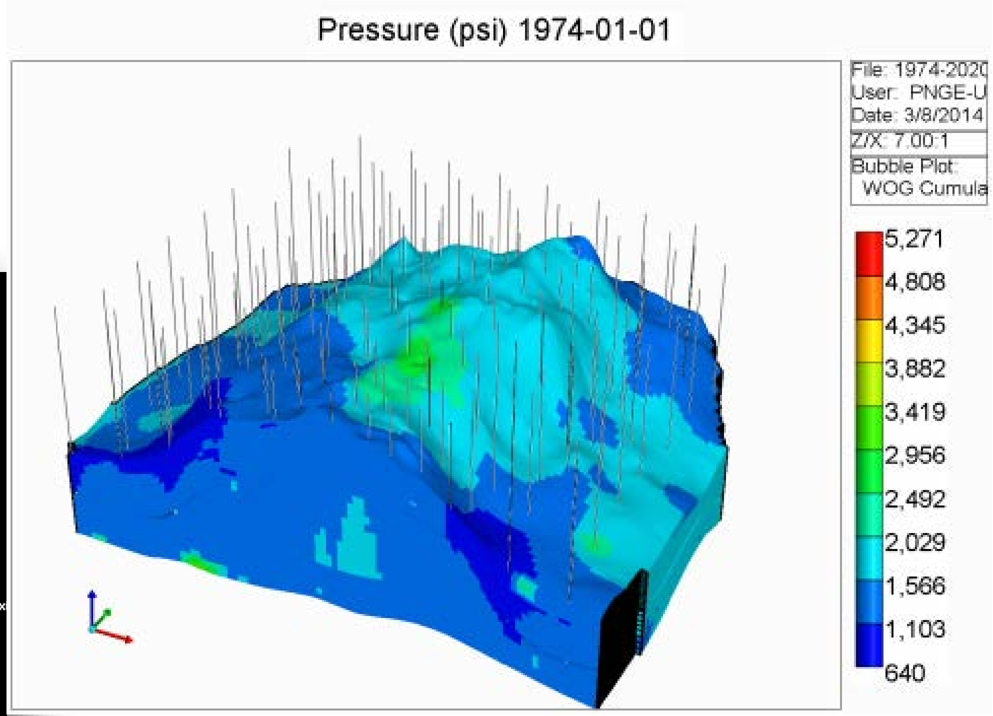

High Resolution Model

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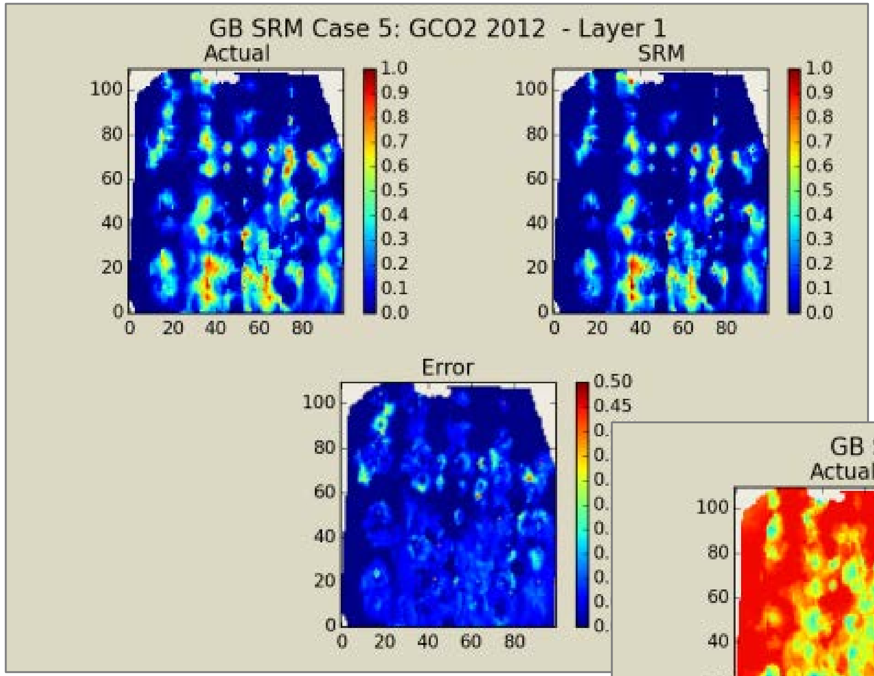
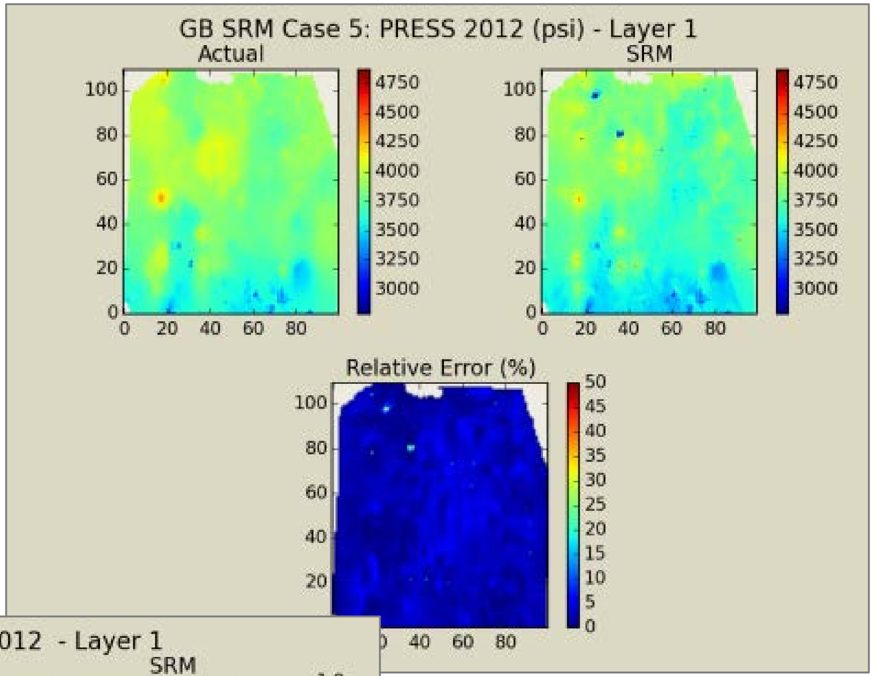
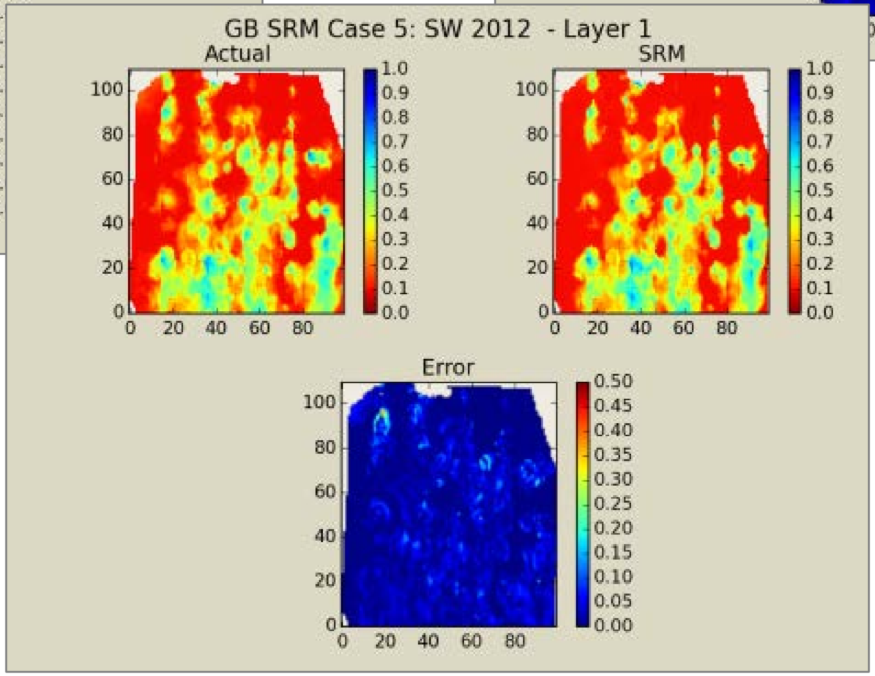
High Resolution Model







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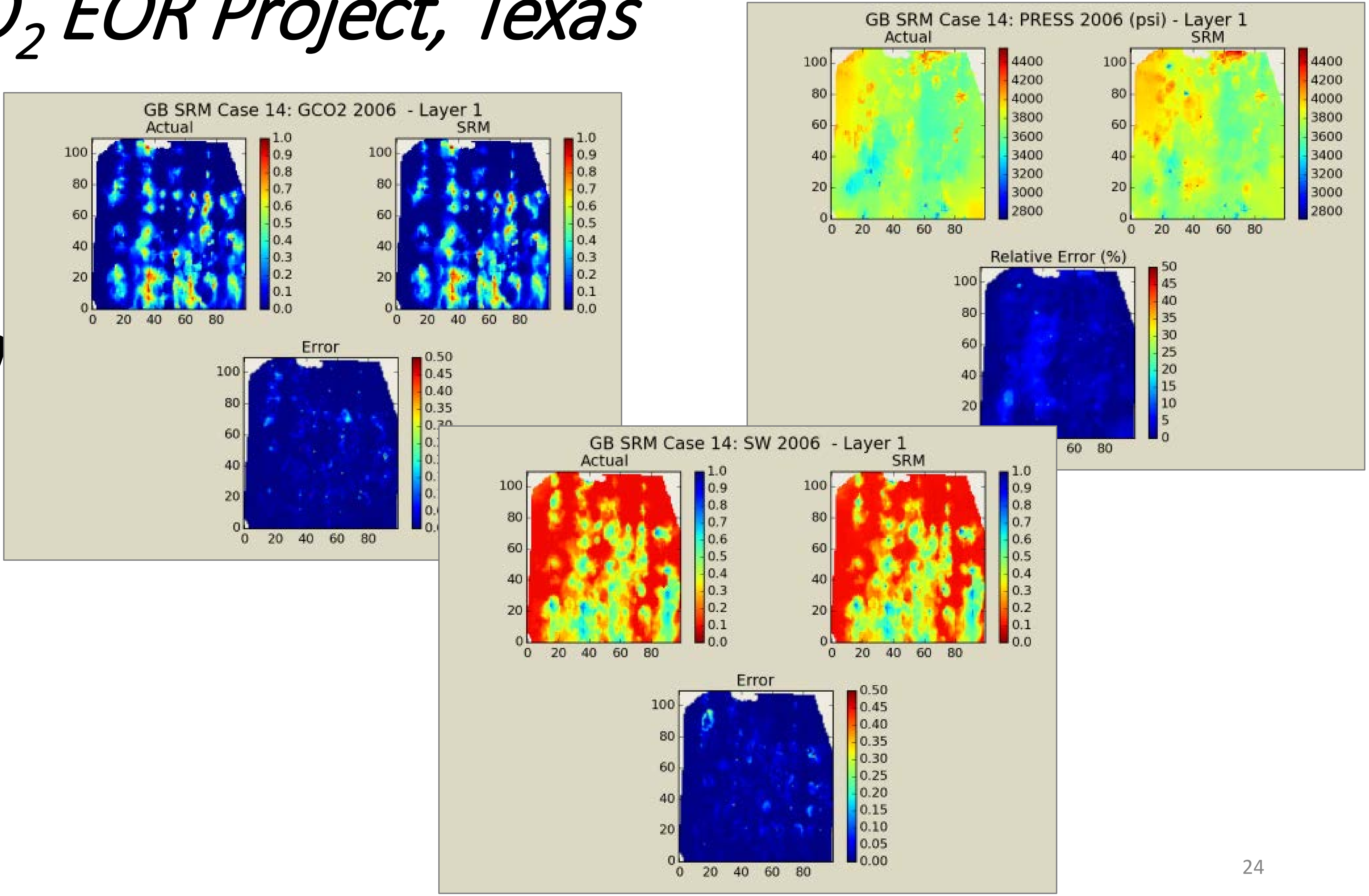
High Resolution Model



Smart Proxy for CFD

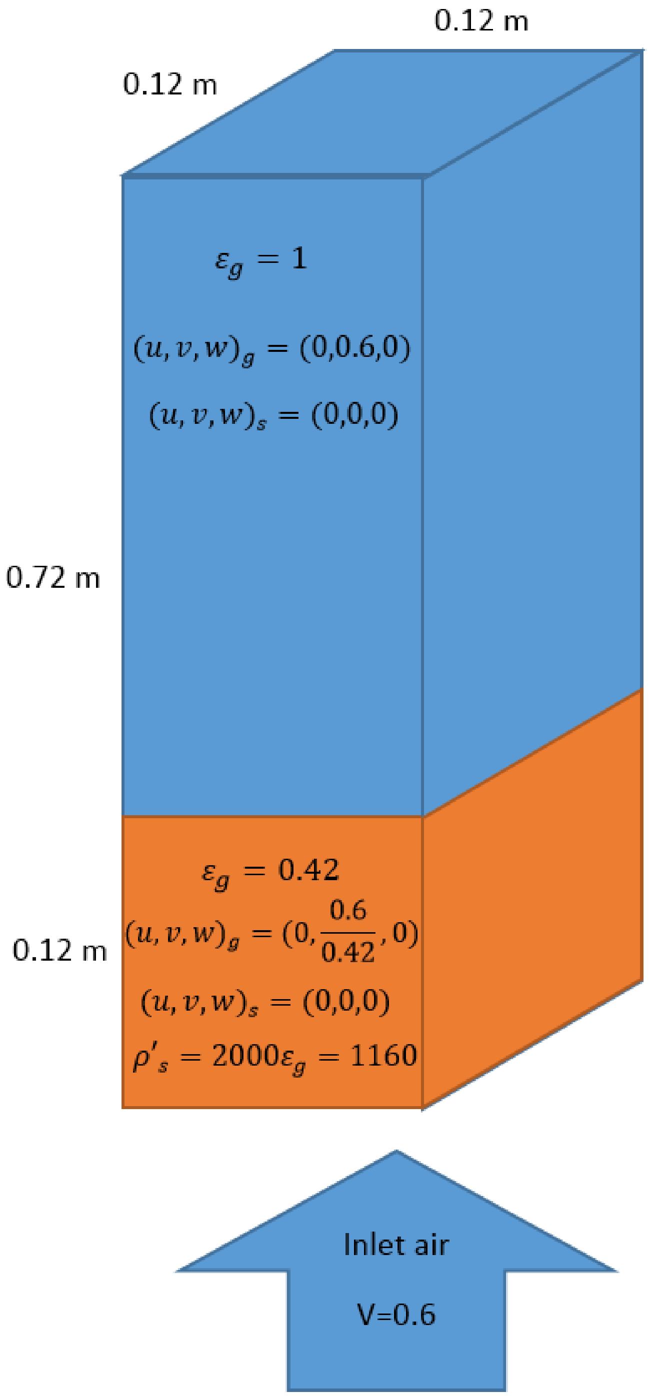
CAN SMART PROXY BE SUCCESSFULLY APPLIED TO CFD?

A Multi-phase CFD Model

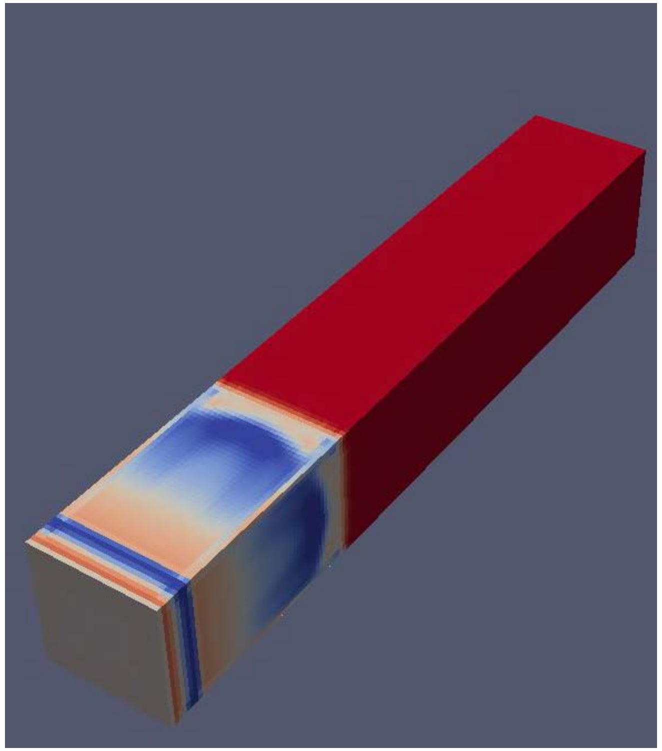
- Initial pressure is 1 atm. in the entire domain

1 atm. = 101,325 Pa

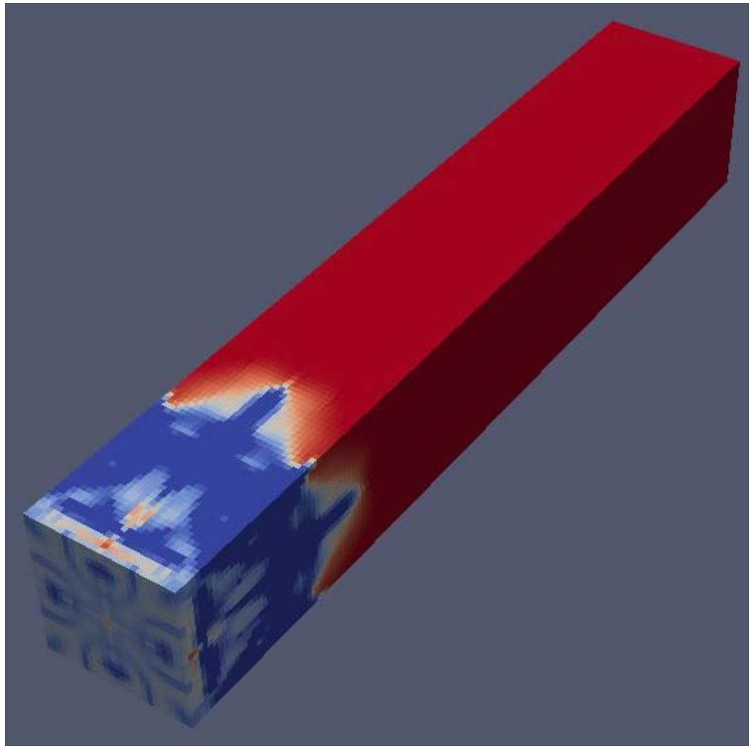
Grid Classification	I, j, k - Cell size	No. of Cell	No. of Grid
Coarse	8 x 48 x 8 (15 mm)	3,072	3,969
Medium	12 x 72 x 12 (10 mm)	10,368	12,337
Fine	18 x 108 x 18 (6.6 mm)	34,992	39,349
Very Fine	**27 x 162 x 27 (4.4 mm)**	**118,098**	**127,792**



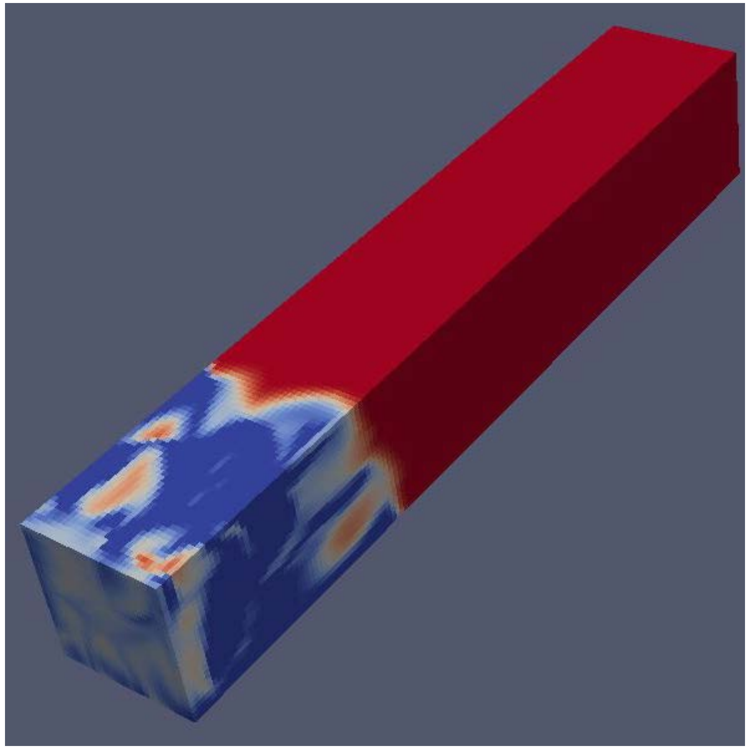
Three different physics



Early-time
Time step 200

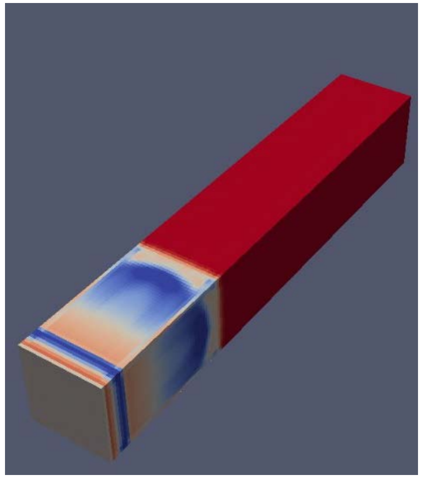


Mid-time
Time step 1000

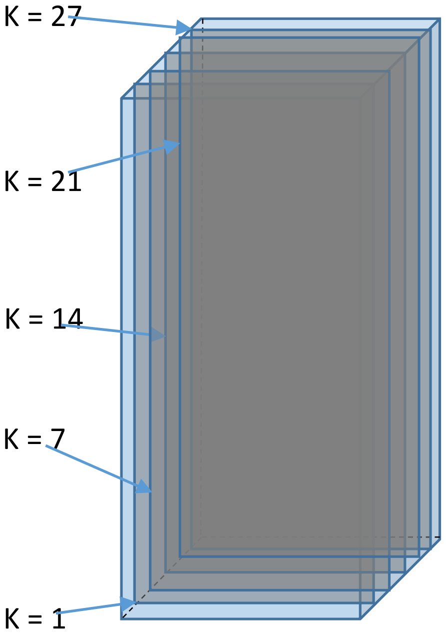


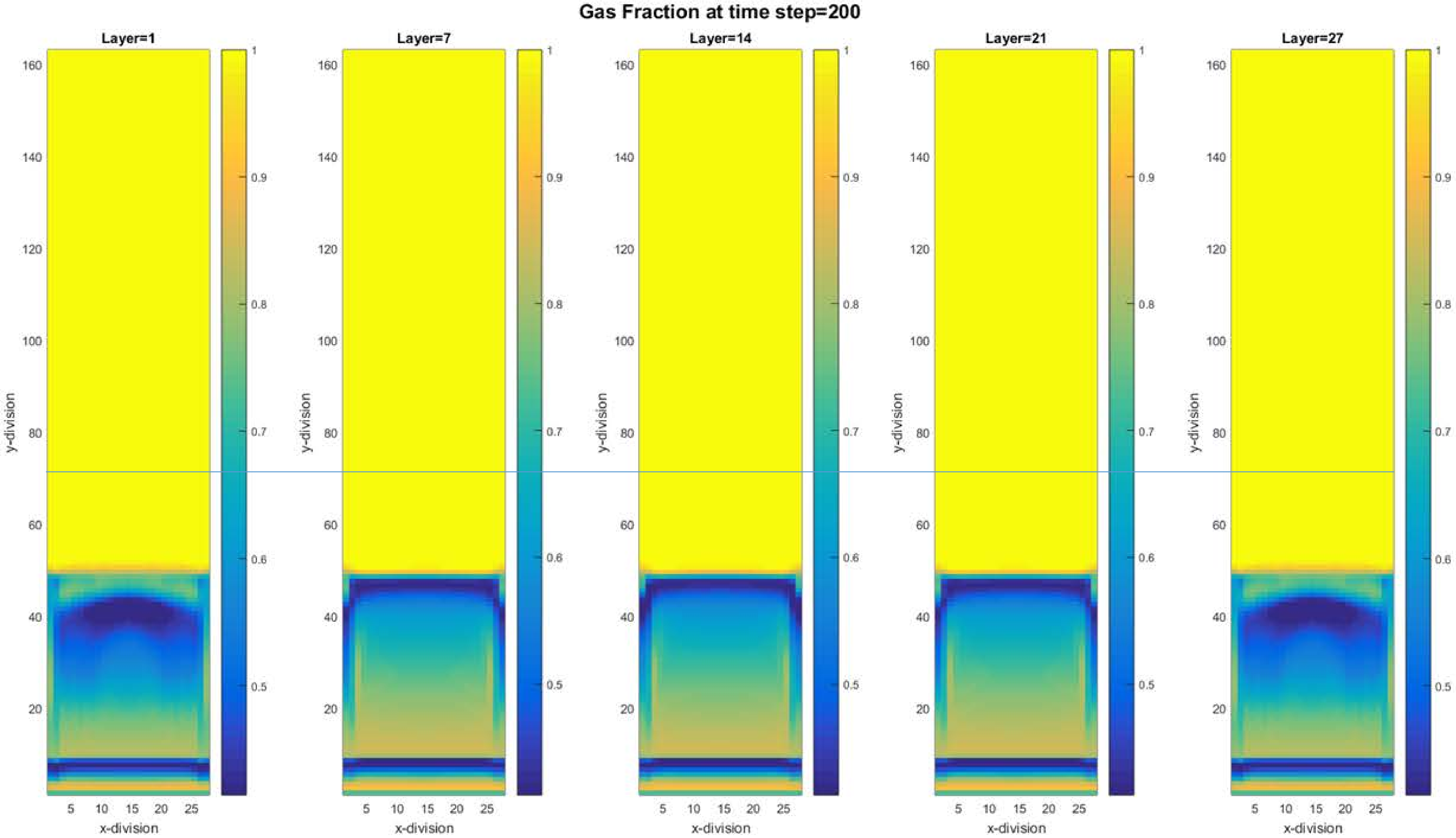
Late-time
Time step 4000

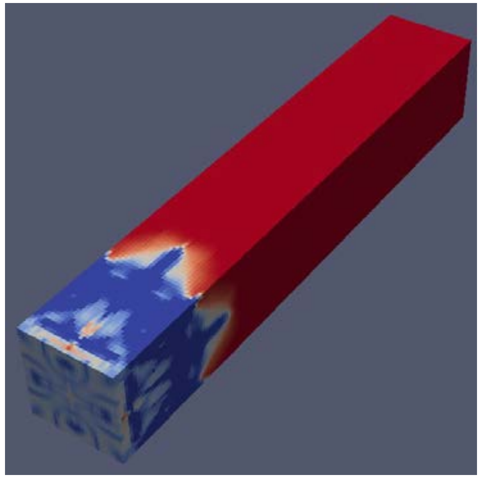
Five cross-sections used to show details in 2-D



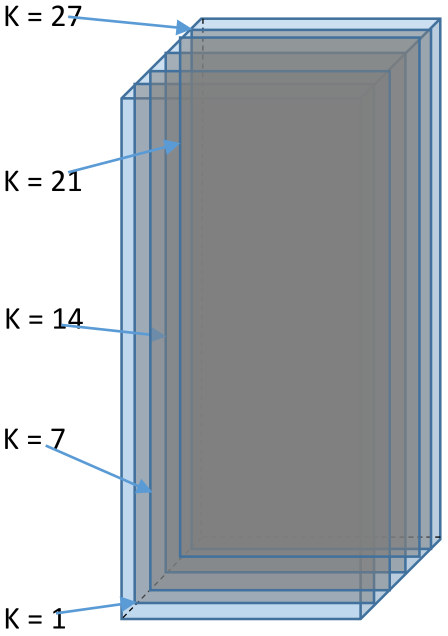
Early-time
Time step 200

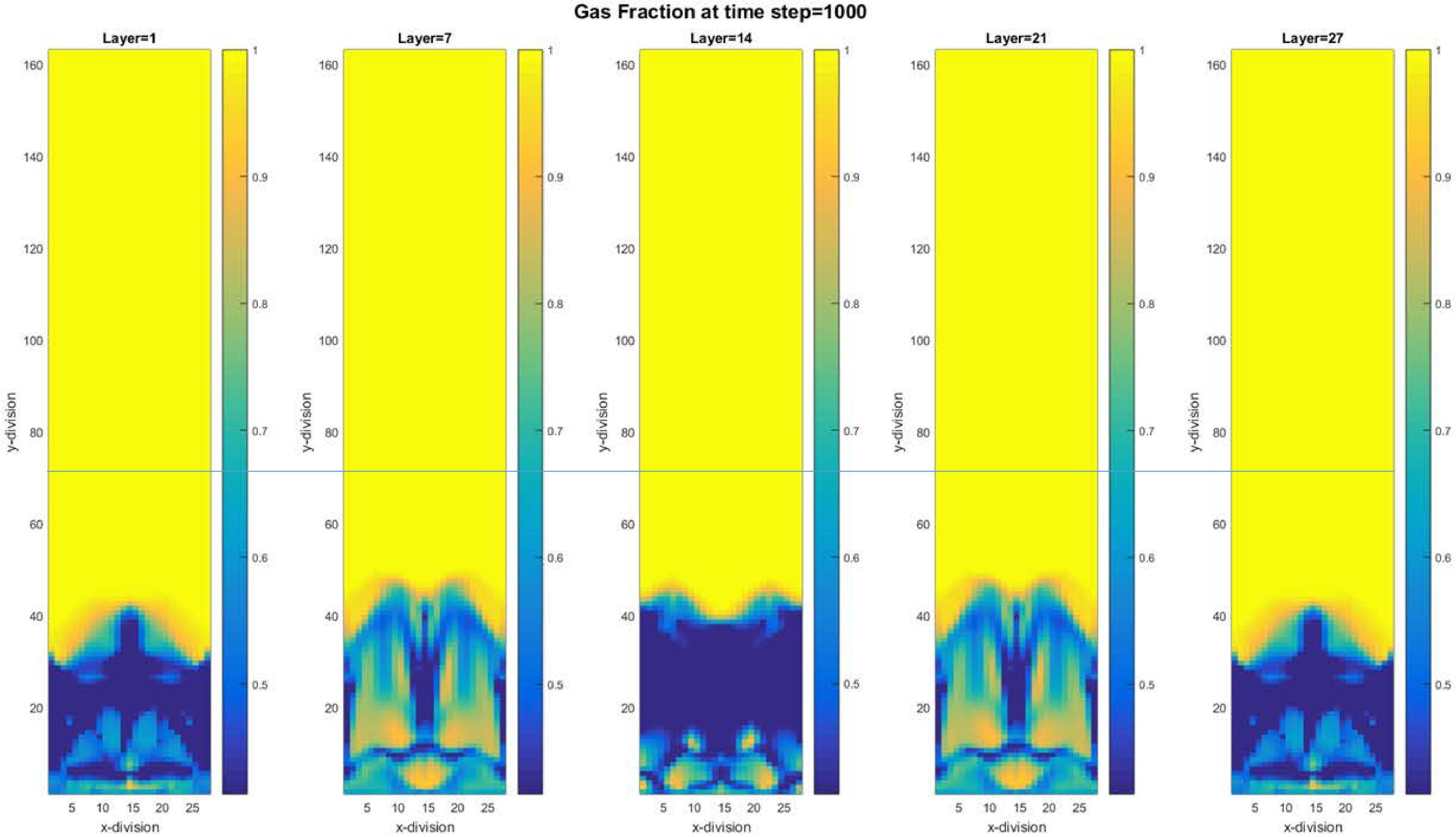


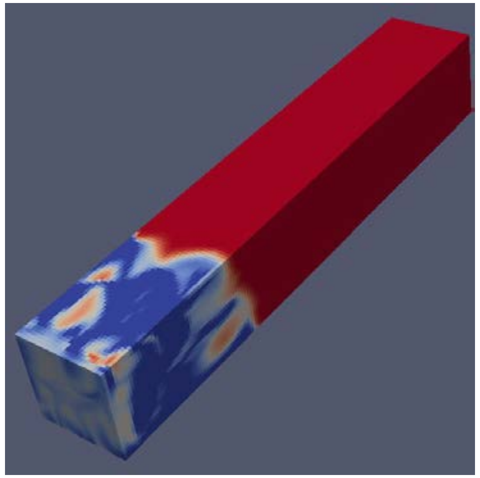




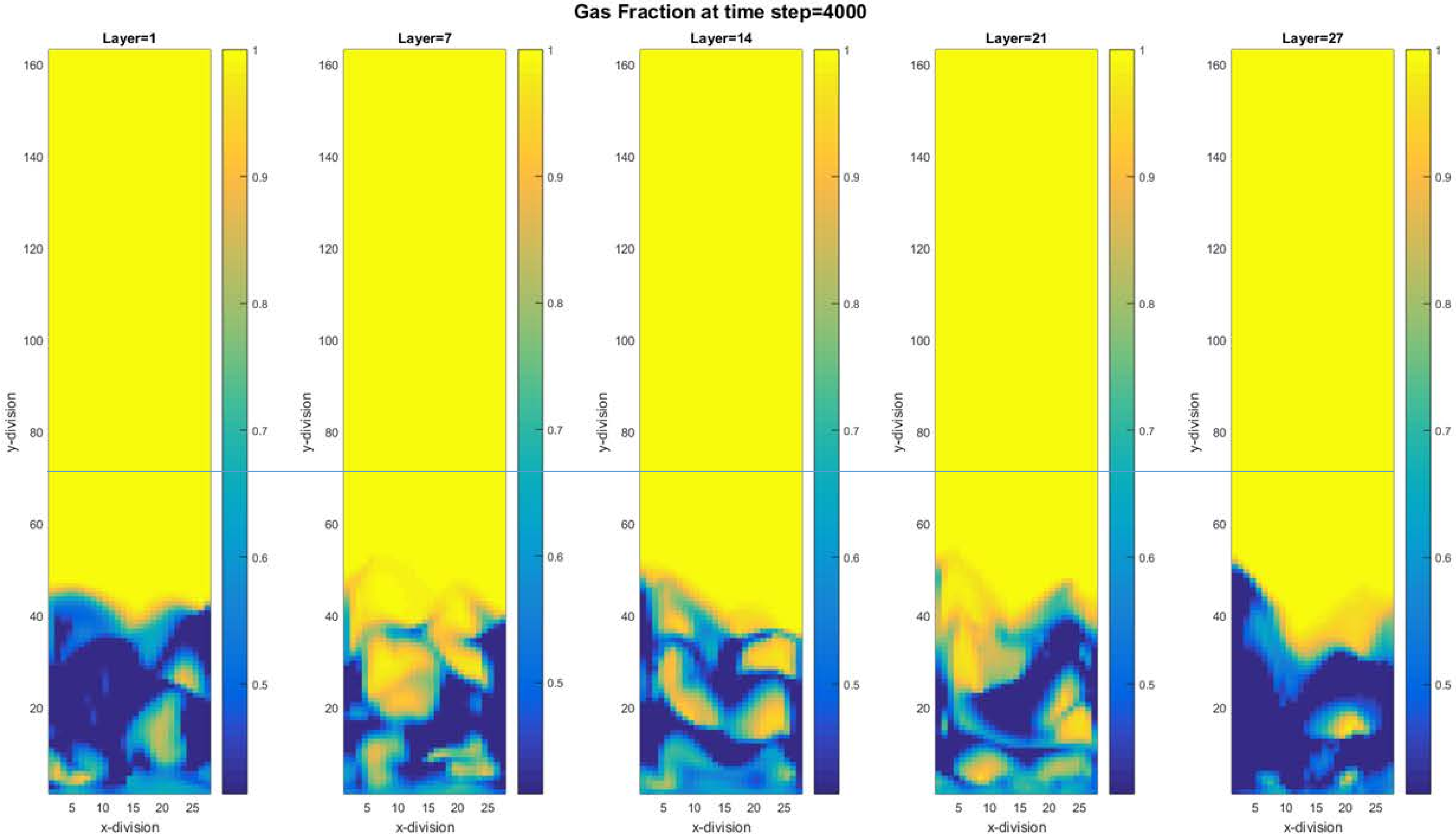
Mid-time
Time step 1000

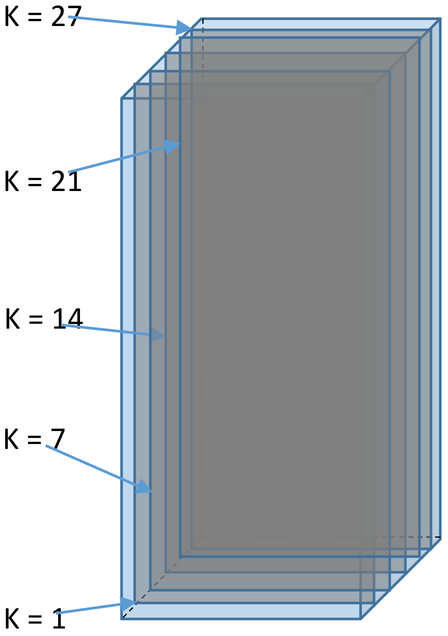






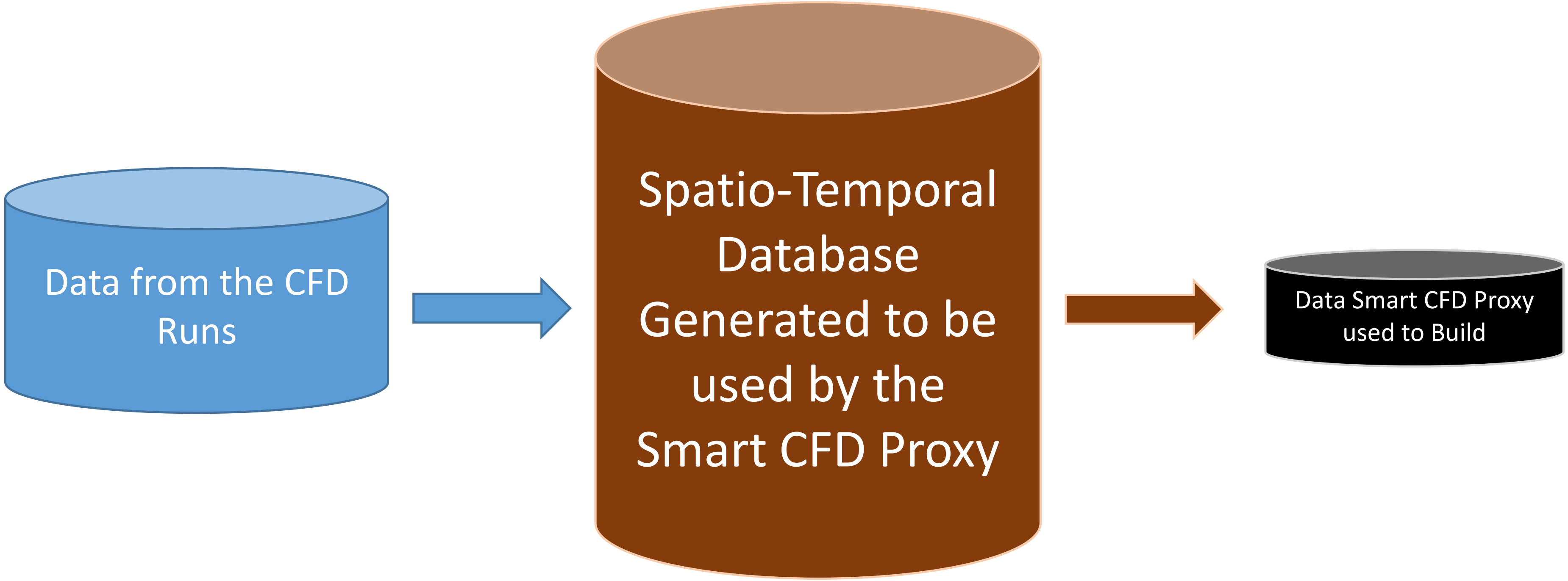
Late-time
Time step 4000





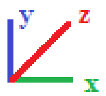
Data from the CFD Runs

Key factors of multi-phase gas-solid system	
Volume fraction (ε)	Gas Density (ρ)
Velocity vector of gas (u, v, w)	Particle diameter (d)
Velocity vector of solid (u, v, w)	Maximum packing volume fraction (ε*)
Pressure field of gas (P)	Location to the boundaries
Pressure field of solid(P)	Location to the interface(x, y, z)
Time (t)	Viscosity (μ and λ)
	Gravity force (g)

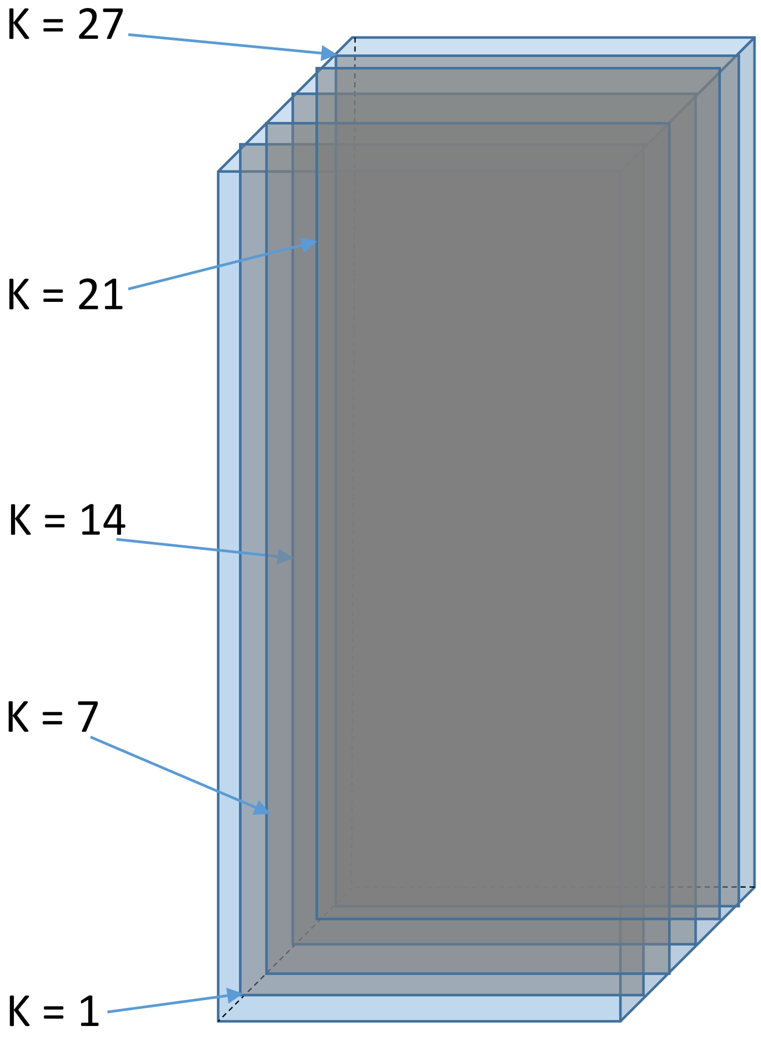


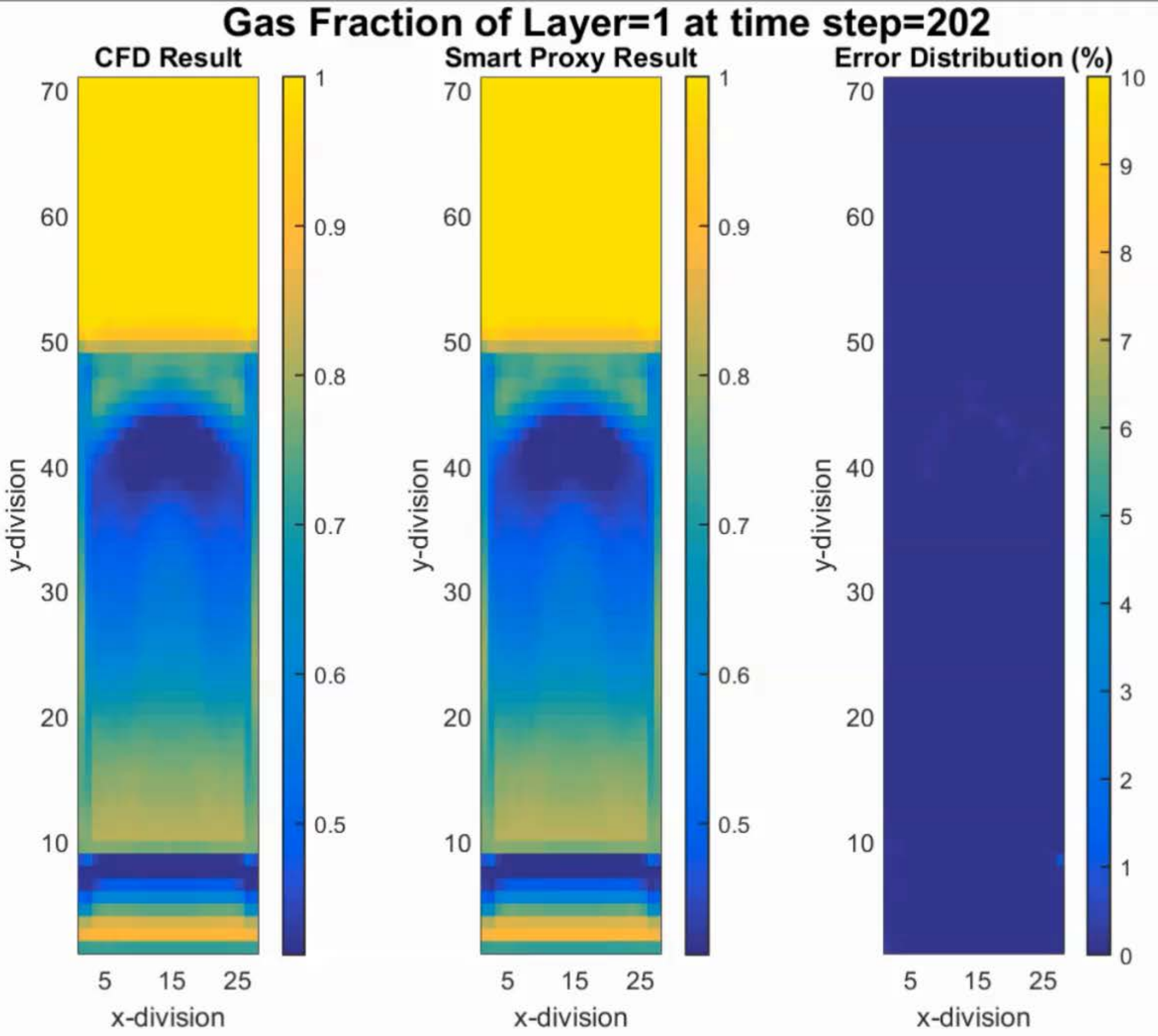
Displaying Smart CFD Proxy

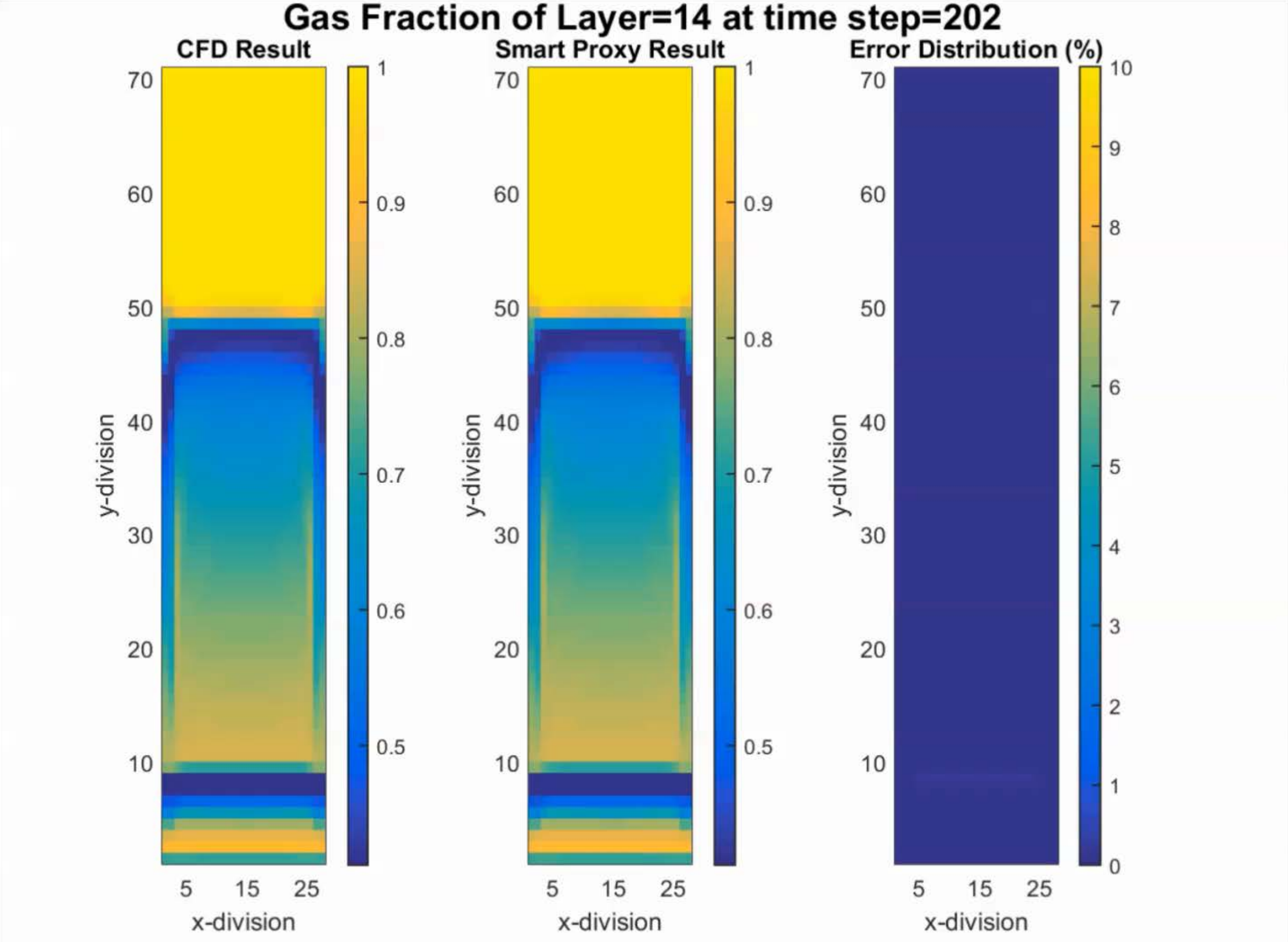
- Results are displayed in 5 different cross-sections:
- K = 1, 7, 14, 21, 27



X = 27
Y = 162
Z = 27




Gas Fraction of Layer=1 at time step=202
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
70
60
50
40
30
20
10
5
15
25
1
0.9
0.8
0.7
0.6
0.5
10
9
8
7
6
5
4
3
2
1
0



Gas Fraction of Layer=14 at time step=202
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division

Thank you

Extra Slides

n
C

Part One – Non-Cascading Results

- In Non-Cascading scheme at every time-step actual CFD results are used as input and the trained Smart Proxy forecasts the results for the next time-step.

- No error accumulation takes place in this scheme.

- This scheme, as the first step, explores the learning capabilities of the Smart Proxy.

n
C

Early Time Results

- Smart Proxy is generated for the early time in the system when the bubble behavior is reasonably calm and non-chaotic.

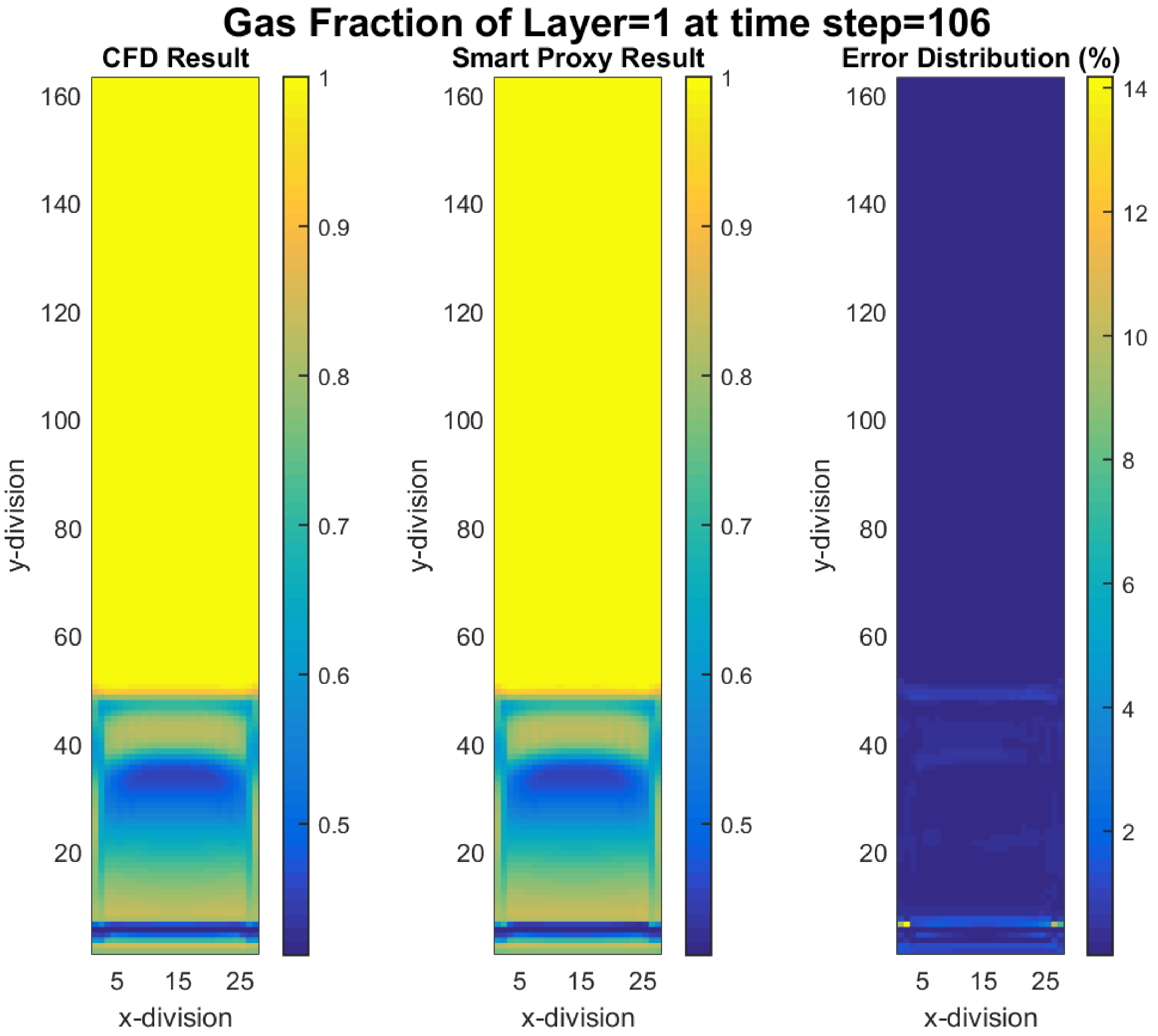
Results of Layer 1 – Gas Fraction

- Model was trained using Time-step 101 as input and Time-step 102 as output.
  - Trained on 75% of data and validated using the remaining 25%

- Trained model was deployed in forecast mode and generated Time-step 102 through Time-step 126

- Results generated by the Smart Proxy are compared with actual CFD output.

n
C



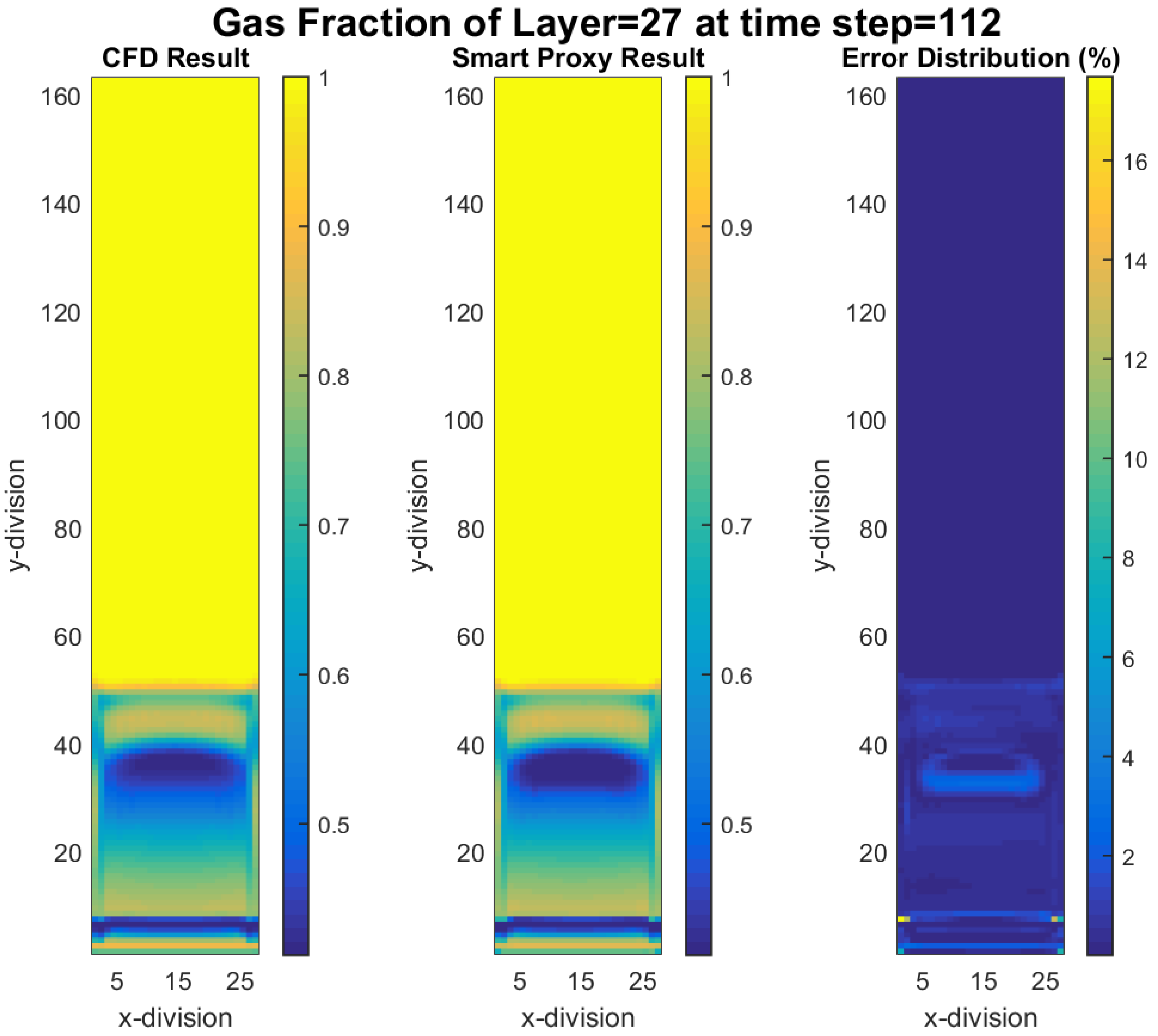
Gas Fraction of Layer=1 at time step=106
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division

n
C

n
C

Results of Layer 27 – Gas Fraction

- Model was trained using Time-step 101 as input and Time-step 102 as output.
  - Trained on 75% of data and validated using the remaining 25%
- Trained model was deployed in forecast mode and generated Time-step 102 through Time-step 126
- Results generated by the Smart Proxy are compared with actual CFD output.


Gas Fraction of Layer=27 at time step=112
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division

n
C

n
C

Multiple bubbles in the system

- The process is now repeated when several bubbles have already been formed in the system.

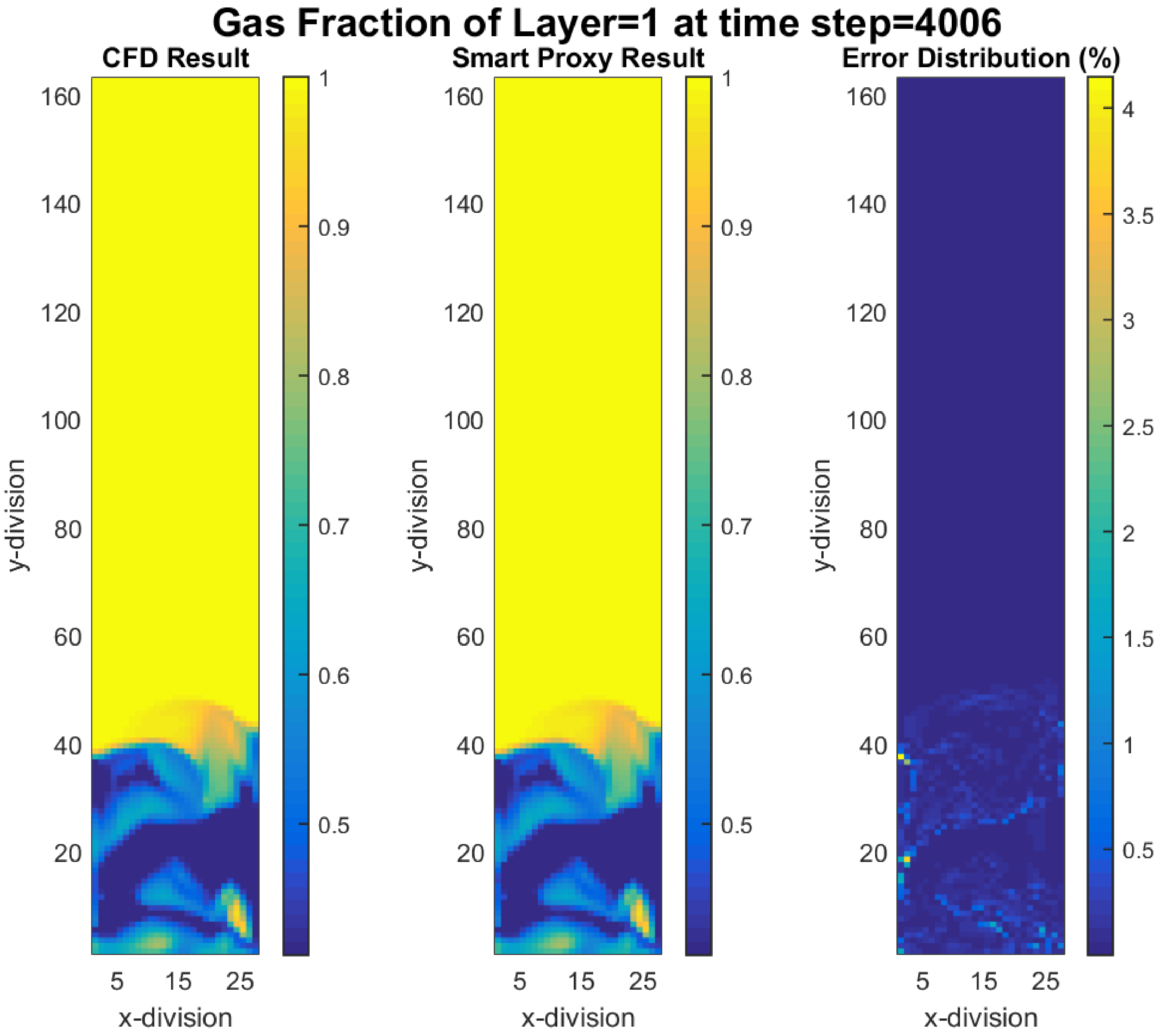
n
C

Results of Layer 1 – Gas Fraction

- Model was trained using Time-step 4001 as input and Time-step 4002 as output.
    - Trained on 75% of data and validated using the remaining 25%

- Trained model was deployed in forecast mode and generated Time-step 4001 through Time-step 4040

- Results generated by the Smart Proxy are compared with actual CFD output.



Gas Fraction of Layer=1 at time step=4006
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
4
3.5
3
2.5
2
1.5
1
0.5

n
C

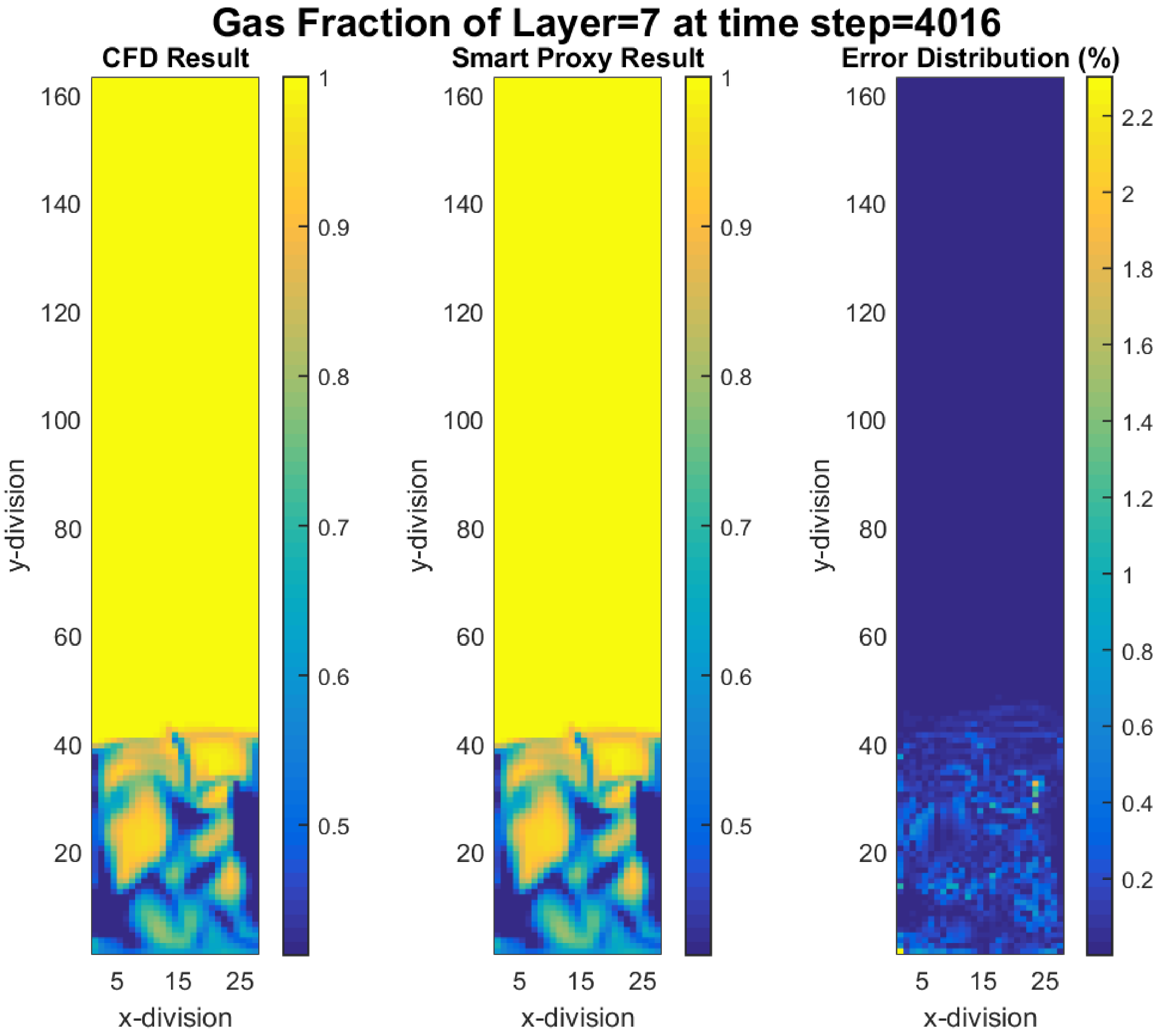
Results of Layer 7 – Gas Fraction

- Model was trained using Time-step 4001 as input and Time-step 4002 as output.
  - Trained on 75% of data and validated using the remaining 25%

- Trained model was deployed in forecast mode and generated Time-step 4001 through Time-step 4040

- Results generated by the Smart Proxy are compared with actual CFD output.

n
C



Gas Fraction of Layer=7 at time step=4016
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2

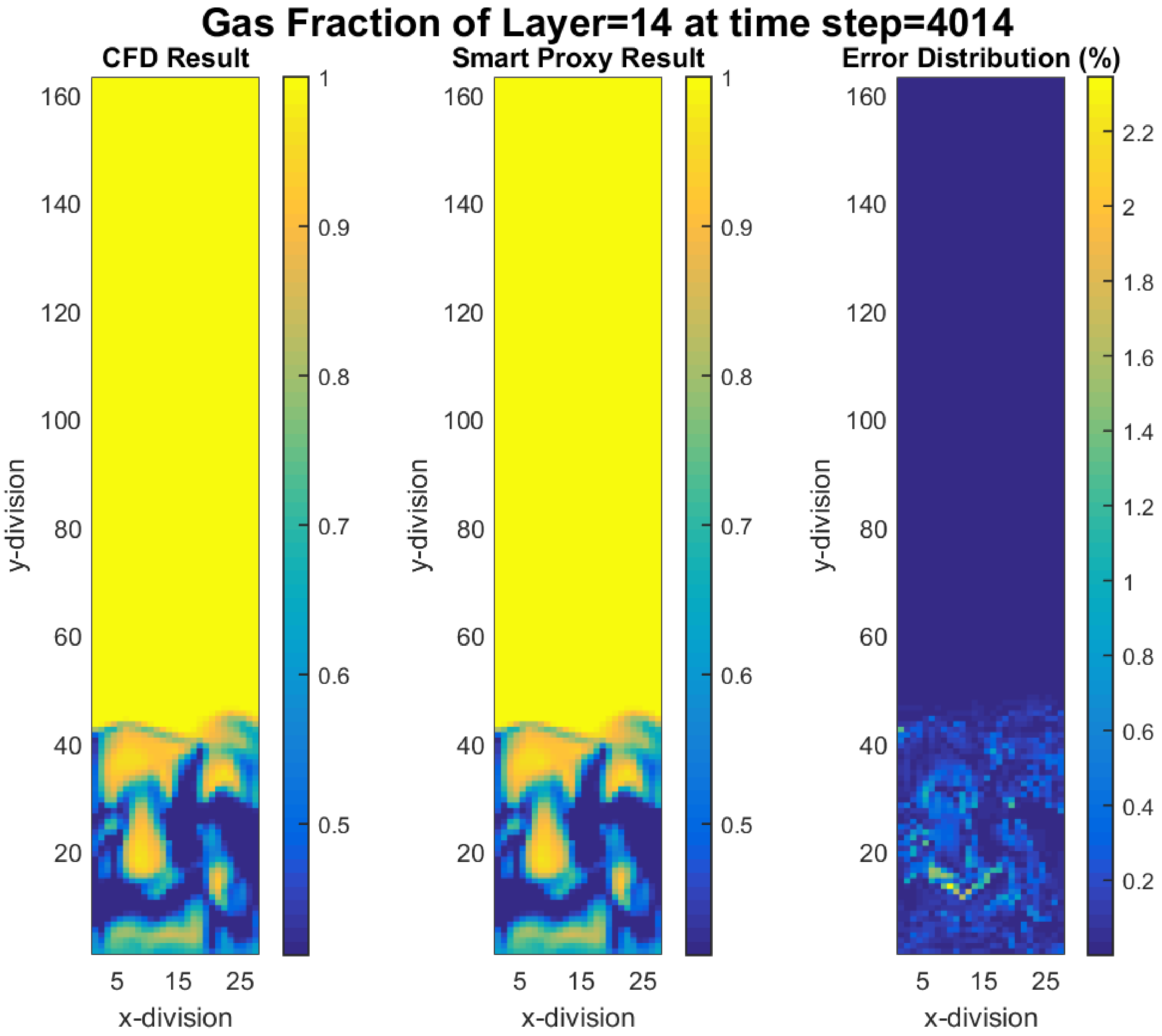
n
C

Results of Layer 14 – Gas Fraction

- Model was trained using Time-step 4001 as input and Time-step 4002 as output.
  - Trained on 75% of data and validated using the remaining 25%

- Trained model was deployed in forecast mode and generated Time-step 4001 through Time-step 4040

- Results generated by the Smart Proxy are compared with actual CFD output.



Gas Fraction of Layer=14 at time step=4014
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2

n
C

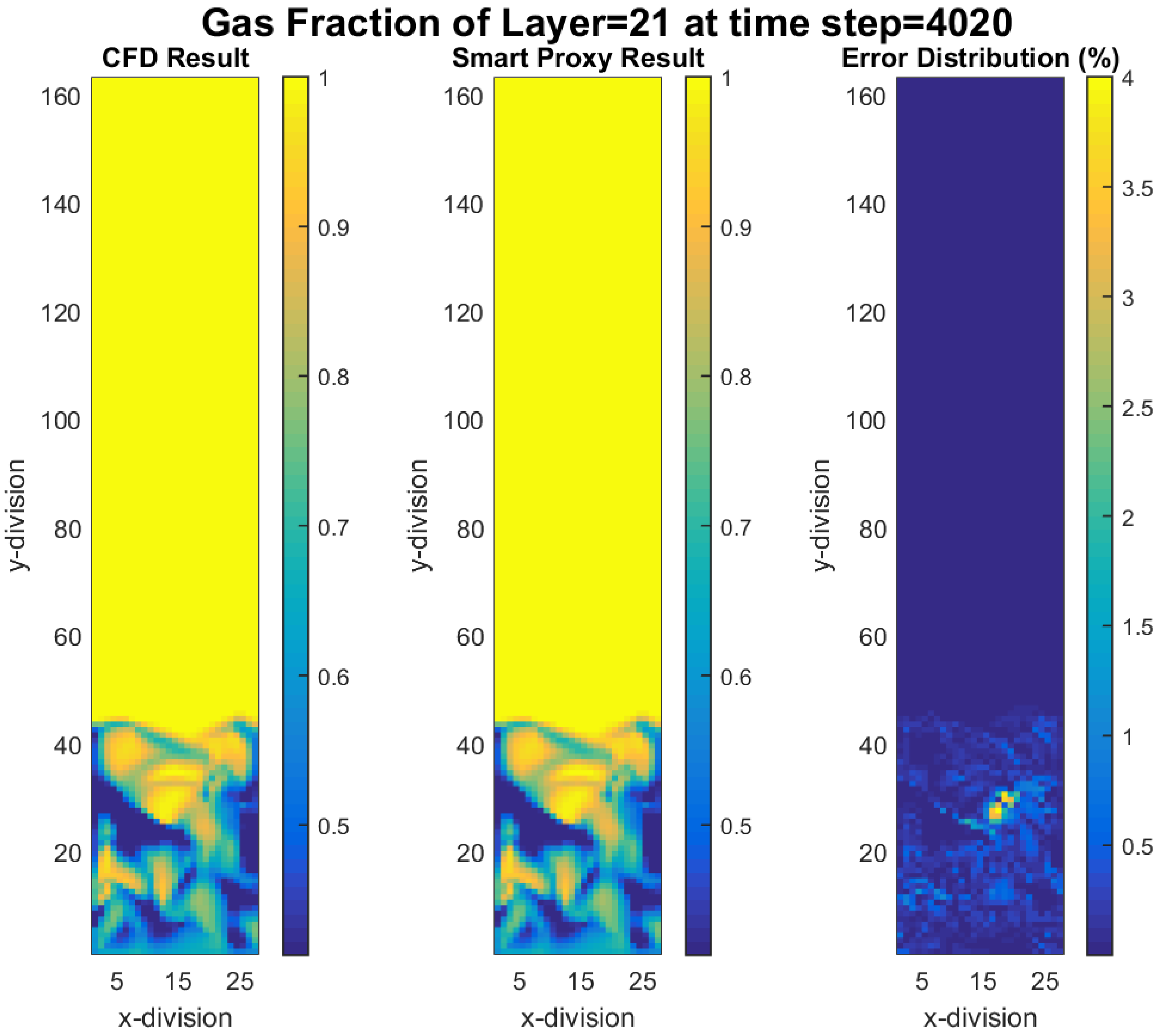
n
C

Results of Layer 21 – Gas Fraction

- Model was trained using Time-step 4001 as input and Time-step 4002 as output.
  - Trained on 75% of data and validated using the remaining 25%

- Trained model was deployed in forecast mode and generated Time-step 4001 through Time-step 4040

- Results generated by the Smart Proxy are compared with actual CFD output.


Gas Fraction of Layer=21 at time step=4020
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
4
3.5
3
2.5
2
1.5
1
0.5

n
C

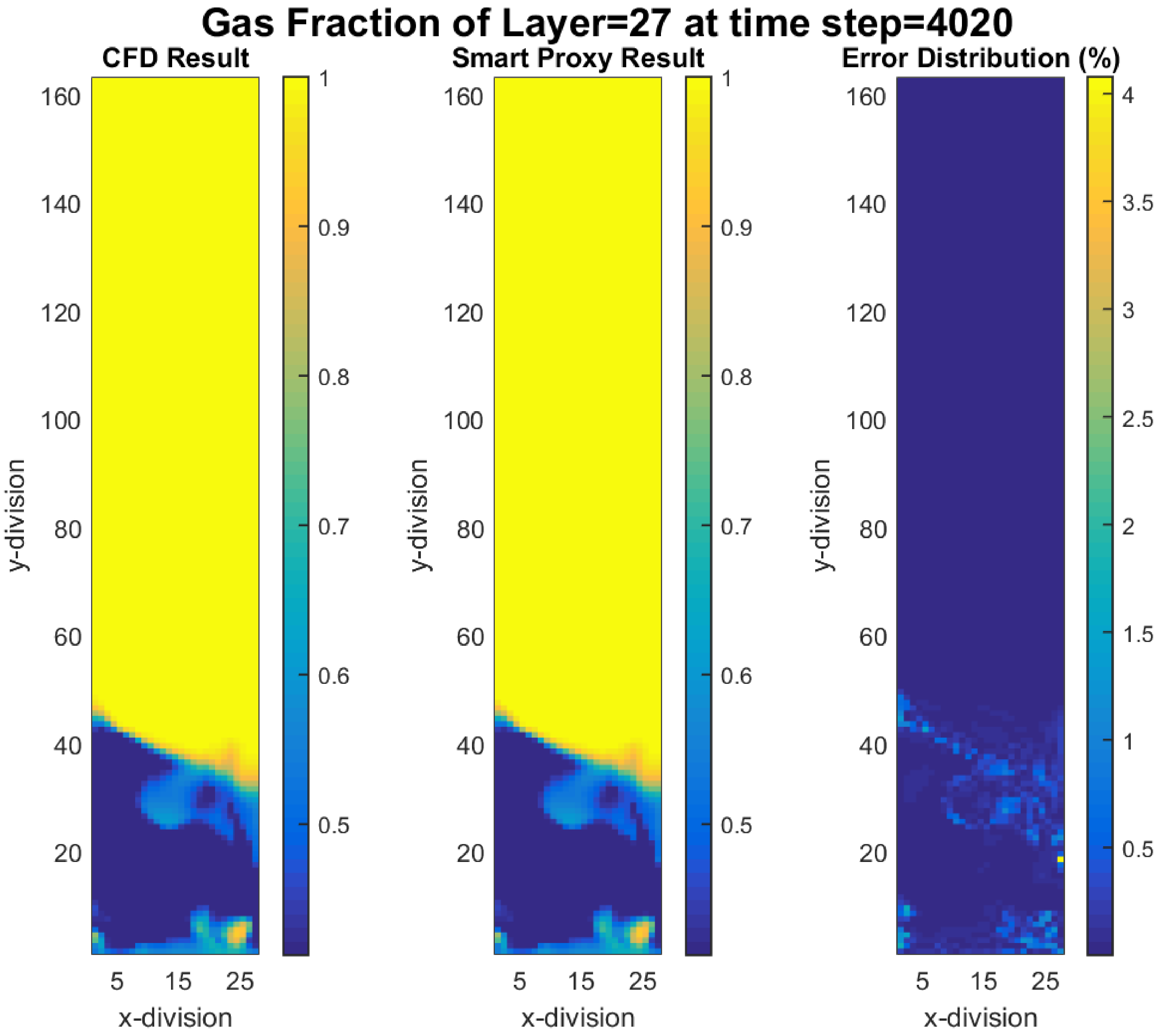
n
C

Results of Layer 27 – Gas Fraction

- Model was trained using Time-step 4001 as input and Time-step 4002 as output.
  - Trained on 75% of data and validated using the remaining 25%

- Trained model was deployed in forecast mode and generated Time-step 4001 through Time-step 4040

- Results generated by the Smart Proxy are compared with actual CFD output.



Gas Fraction of Layer=27 at time step=4020
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division

n
C

Part Two – Cascading Results

- In Cascading scheme at every time-step results from the Smart Proxy are used as input and the trained Smart Proxy forecasts the results for the next time-step. (Smart Proxy receives feedback from itself)
  - **Models are developed for all output variables in CFD such as Void Fraction, and gas/solid Pressure and Velocity.**
- In this scheme the error has the opportunity to accumulate.
- Limits of the information content of each time-step is explored in this scheme.

Early Time Results

- Smart Proxy is generated for the early time in the system when the bubble behavior is reasonably calm and non-chaotic.

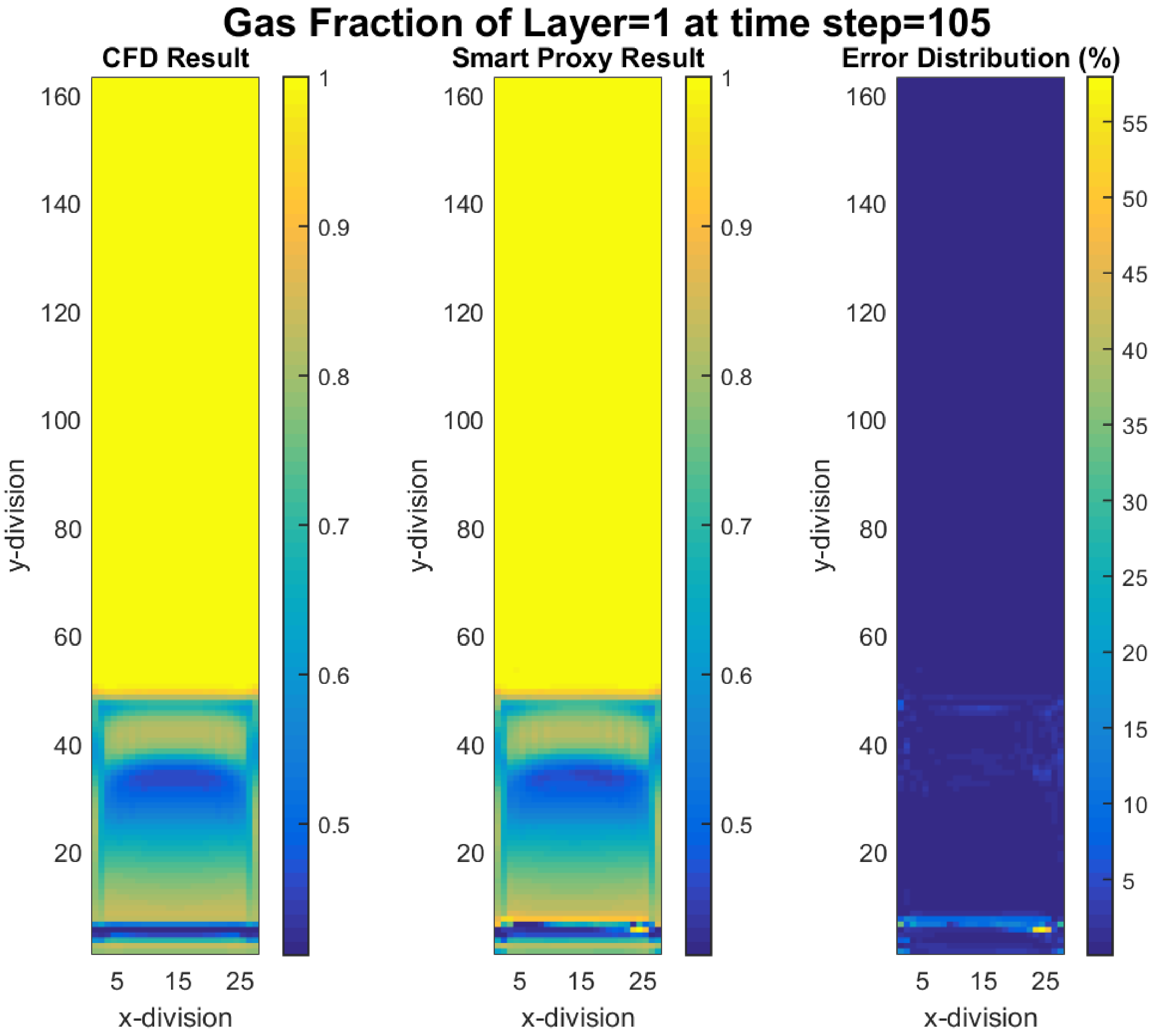
Results of Layer 1 – Gas Fraction

- Model was trained using Time-step 101 as input and Time-step 102 as output.
  - Trained on 75% of data and validated using the remaining 25%

- Trained model was deployed in forecast mode and generated Time-step 101 through Time-step 105

- Results generated by the Smart Proxy are compared with actual CFD output.

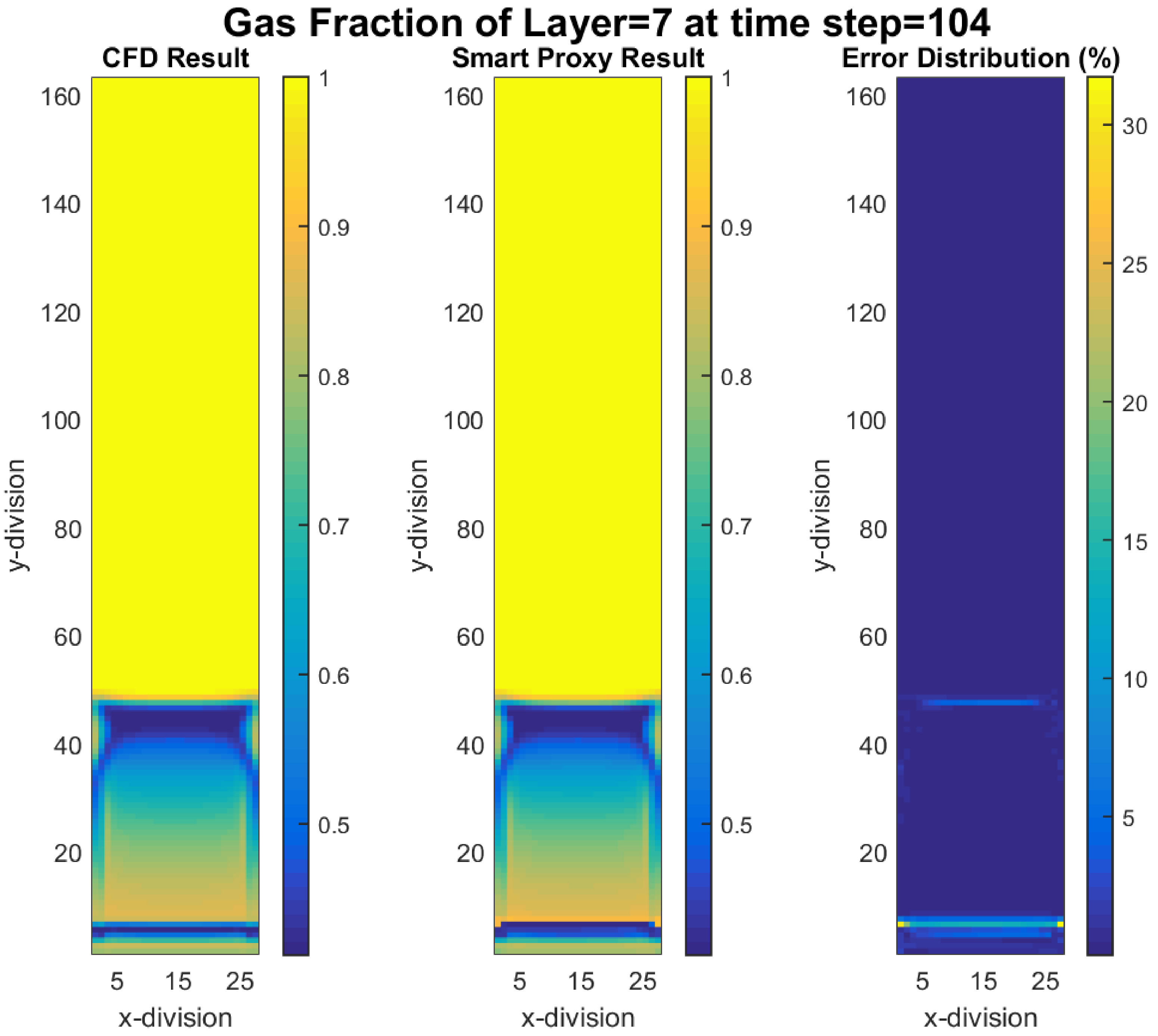
C



Gas Fraction of Layer=1 at time step=105
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
55
50
45
40
35
30
25
20
15
10
5

Results of Layer 7 – Gas Fraction

- Model was trained using Time-step 101 as input and Time-step 102 as output.
  - Trained on 75% of data and validated using the remaining 25%
- Trained model was deployed in forecast mode and generated Time-step 101 through Time-step 105
- Results generated by the Smart Proxy are compared with actual CFD output.

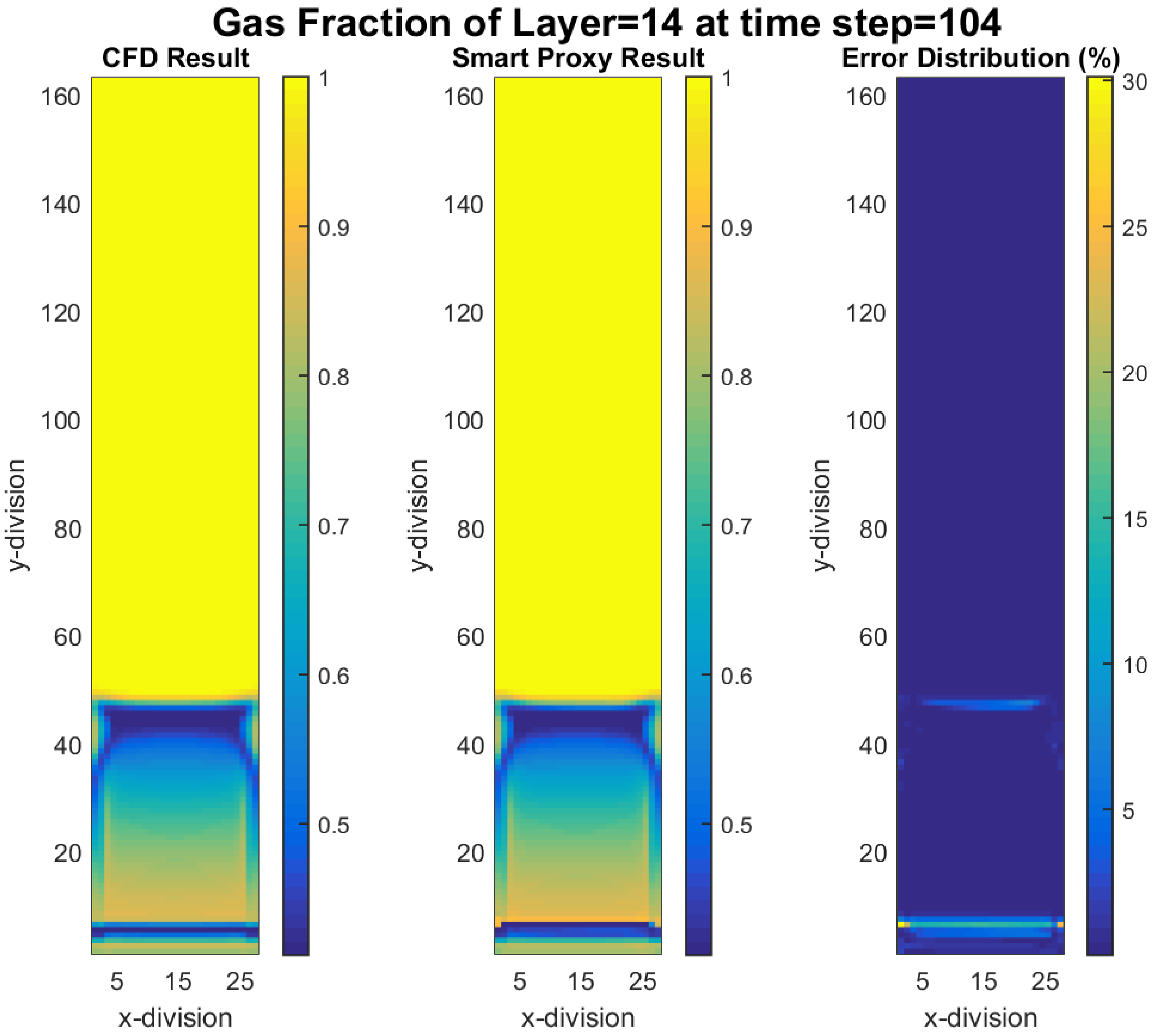


Gas Fraction of Layer=7 at time step=104
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
30
25
20
15
10
5

C

Results of Layer 14 – Gas Fraction

- Model was trained using Time-step 101 as input and Time-step 102 as output.
  - Trained on 75% of data and validated using the remaining 25%
- Trained model was deployed in forecast mode and generated Time-step 101 through Time-step 105
- Results generated by the Smart Proxy are compared with actual CFD output.

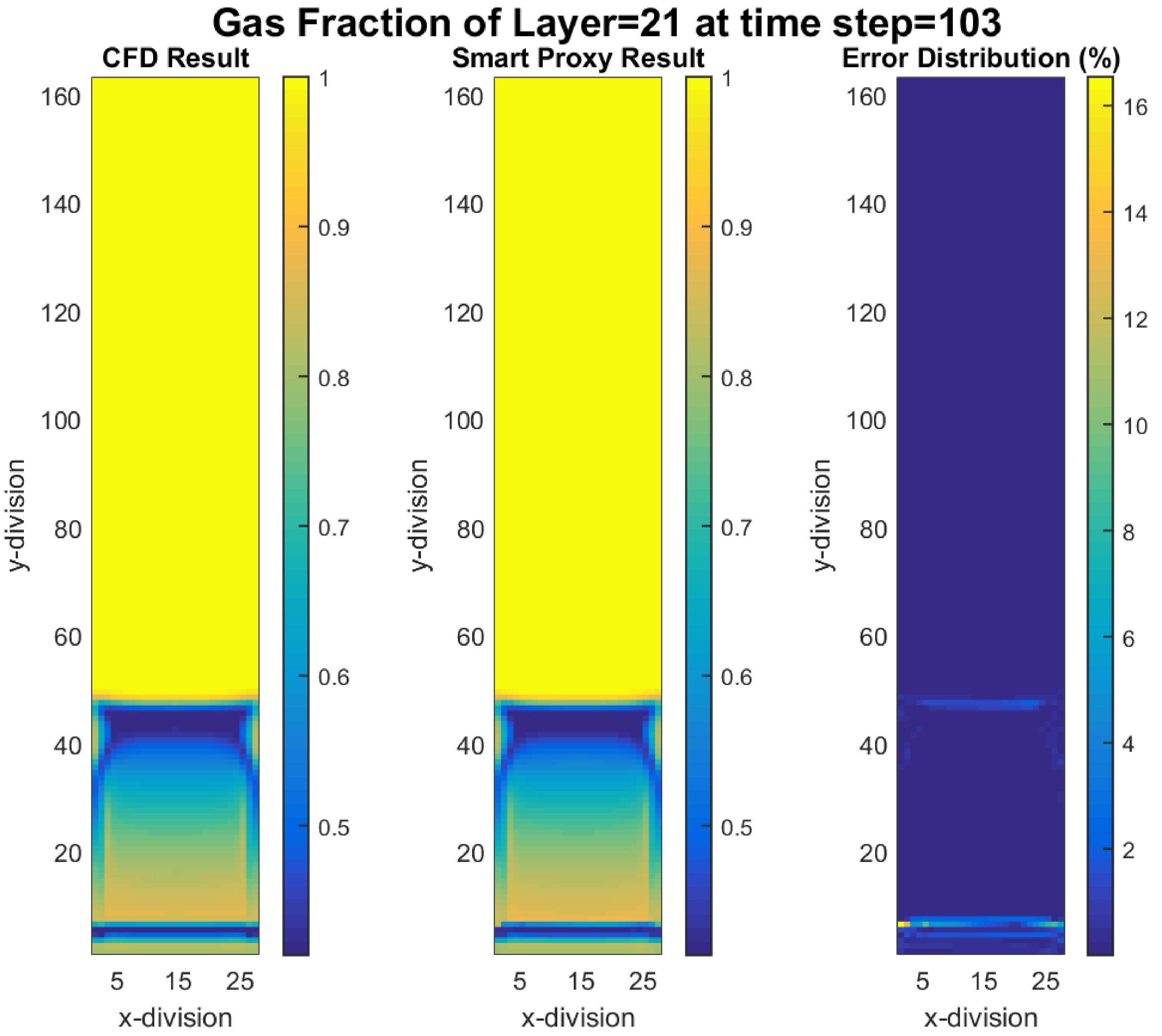

Gas Fraction of Layer=14 at time step=104
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
30
25
20
15
10
5

C

Results of Layer 21 – Gas Fraction

- Model was trained using Time-step 101 as input and Time-step 102 as output.
  - Trained on 75% of data and validated using the remaining 25%
- Trained model was deployed in forecast mode and generated Time-step 102 through Time-step 126
- Results generated by the Smart Proxy are compared with actual CFD output.

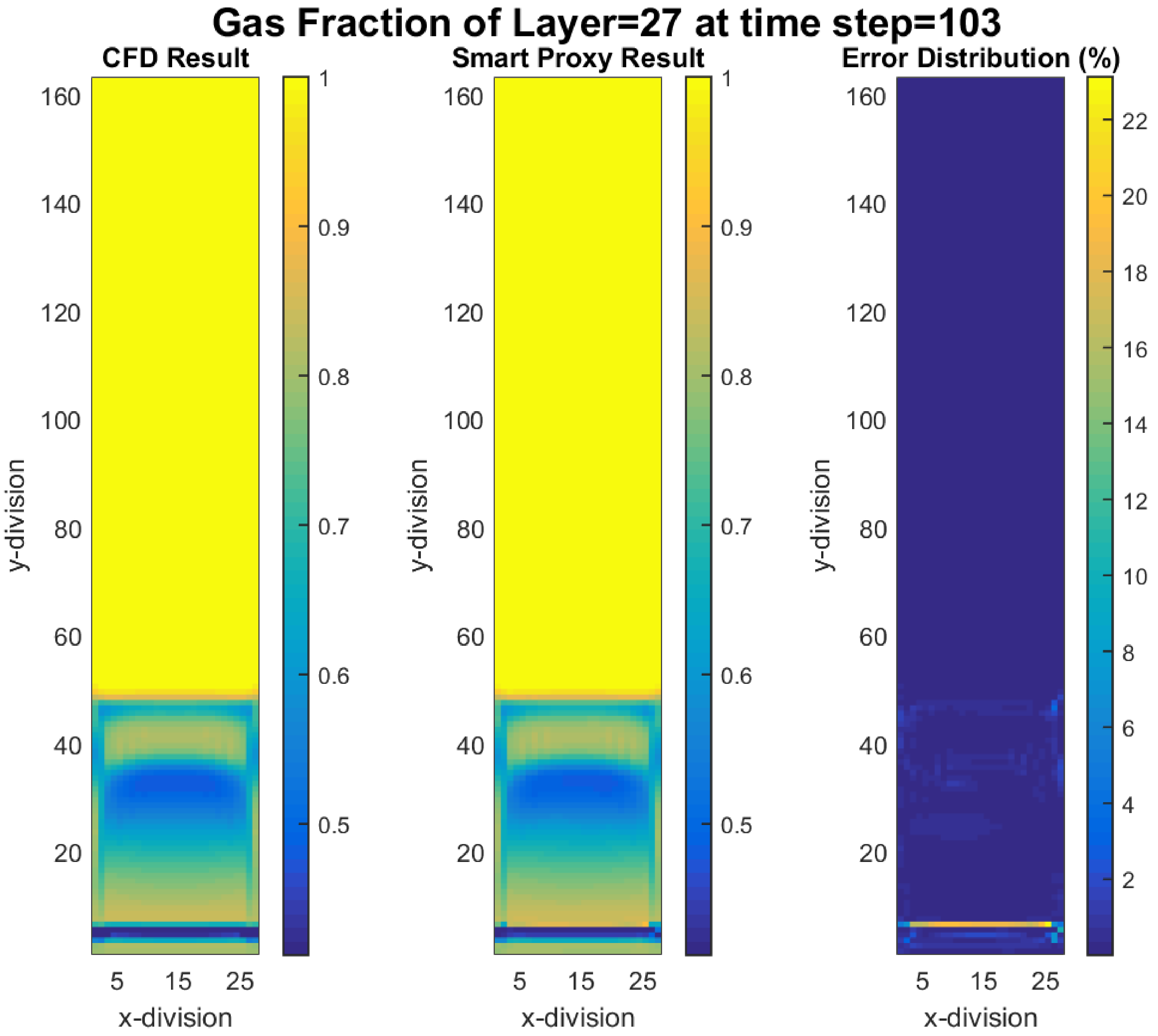
C



Gas Fraction of Layer=21 at time step=103
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
16
14
12
10
8
6
4
2

Results of Layer 27 – Gas Fraction

- Model was trained using Time-step 101 as input and Time-step 102 as output.
  - Trained on 75% of data and validated using the remaining 25%
- Trained model was deployed in forecast mode and generated Time-step 101 through Time-step 105
- Results generated by the Smart Proxy are compared with actual CFD output.



Gas Fraction of Layer=27 at time step=103
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
22
20
18
16
14
12
10
8
6
4
2

C

Multiple bubbles in the system

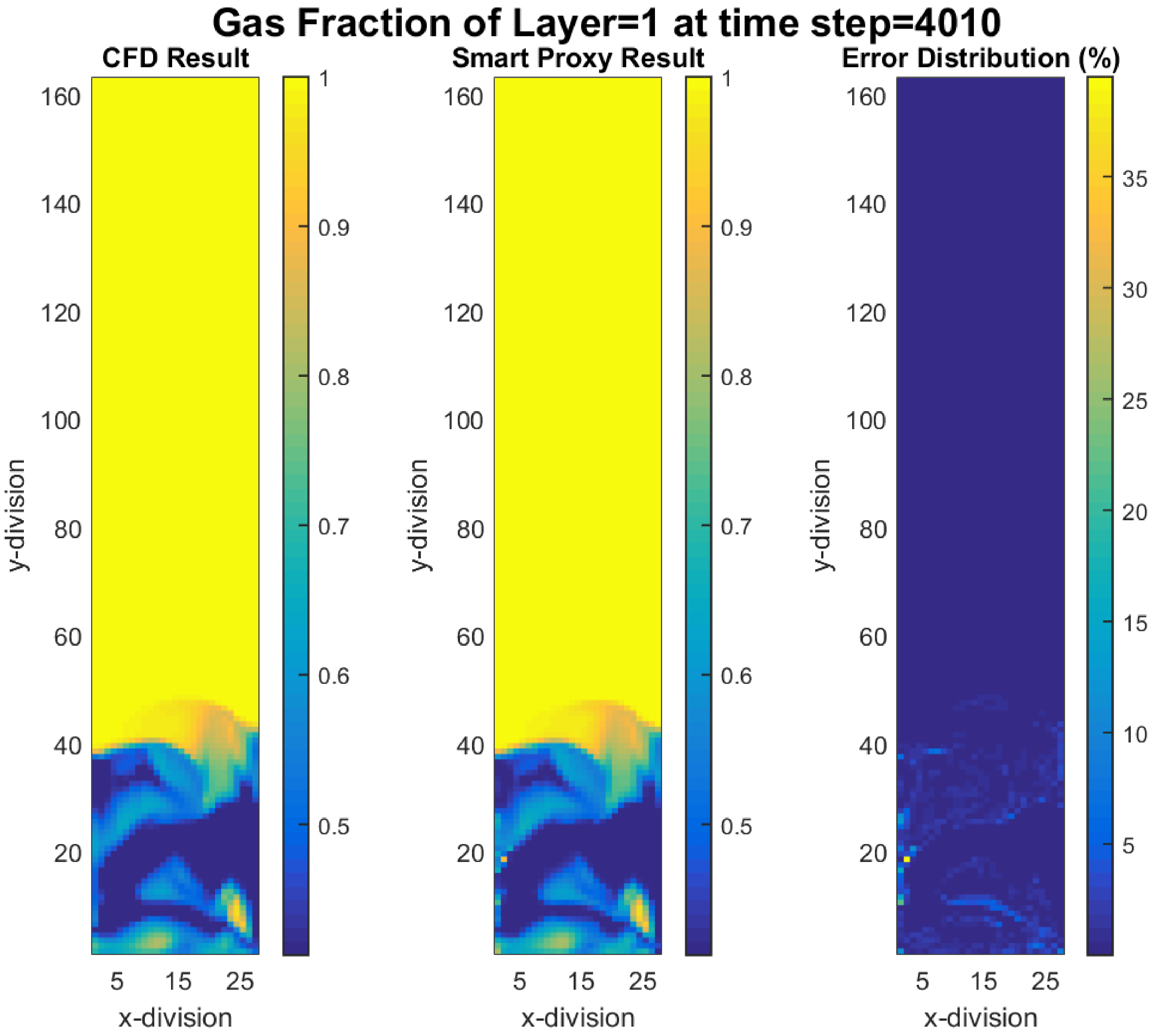
- The process is now repeated when several bubbles have already been formed in the system.

Results of Layer 1 – Gas Fraction

- Model was trained using Time-step 4001 as input and Time-step 4002 as output.
  - Trained on 75% of data and validated using the remaining 25%

- Trained model was deployed in forecast mode and generated Time-step 4002 through Time-step 4014

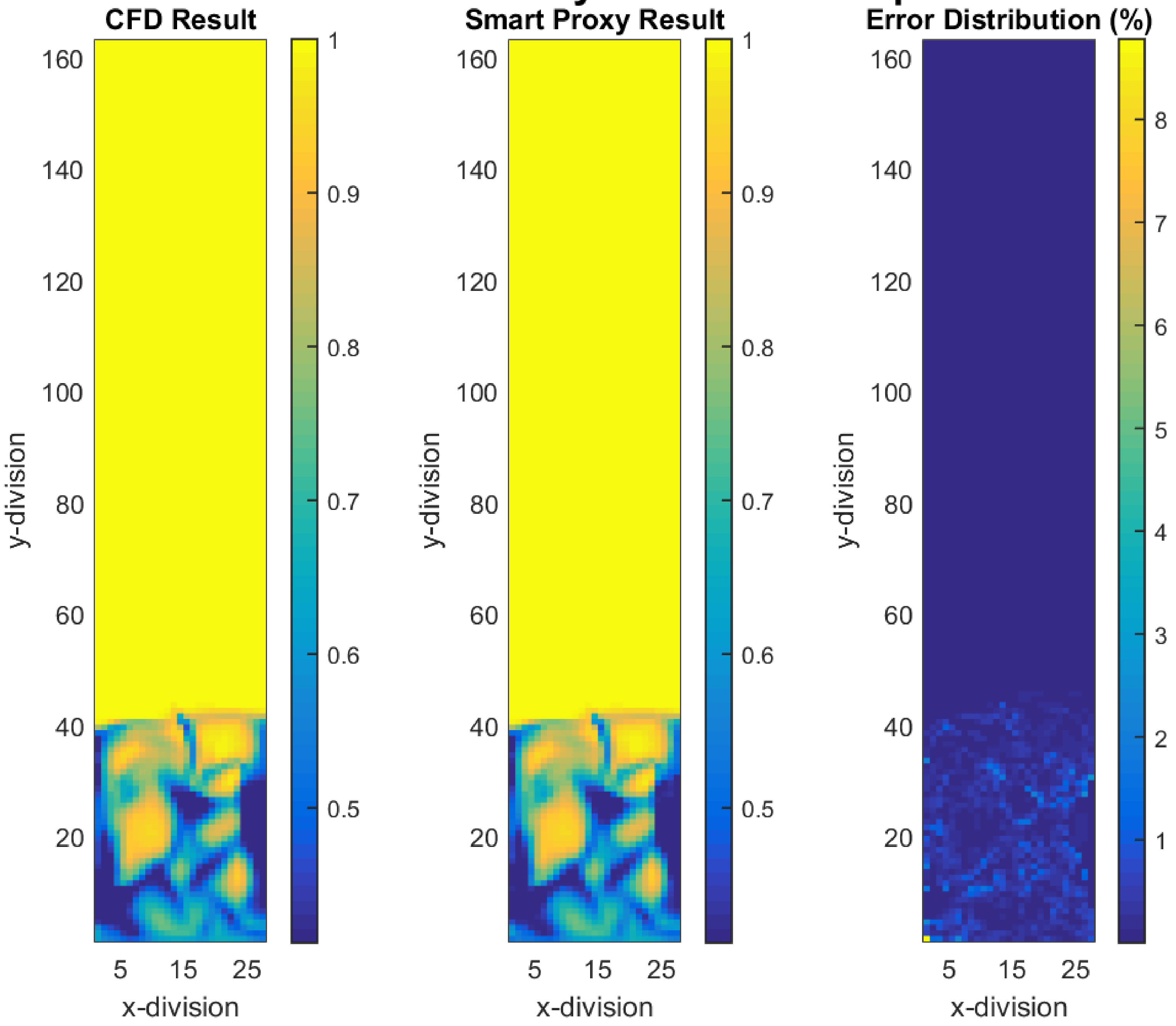
- Results generated by the Smart Proxy are compared with actual CFD output.


Gas Fraction of Layer=1 at time step=4010
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
35
30
25
20
15
10
5
C

Results of Layer 7 – Gas Fraction

- Model was trained using Time-step 4001 as input and Time-step 4002 as output.
  - Trained on 75% of data and validated using the remaining 25%
- Trained model was deployed in forecast mode and generated Time-step 4002 through Time-step 4010
- Results generated by the Smart Proxy are compared with actual CFD output.

Gas Fraction of Layer=7 at time step=4006

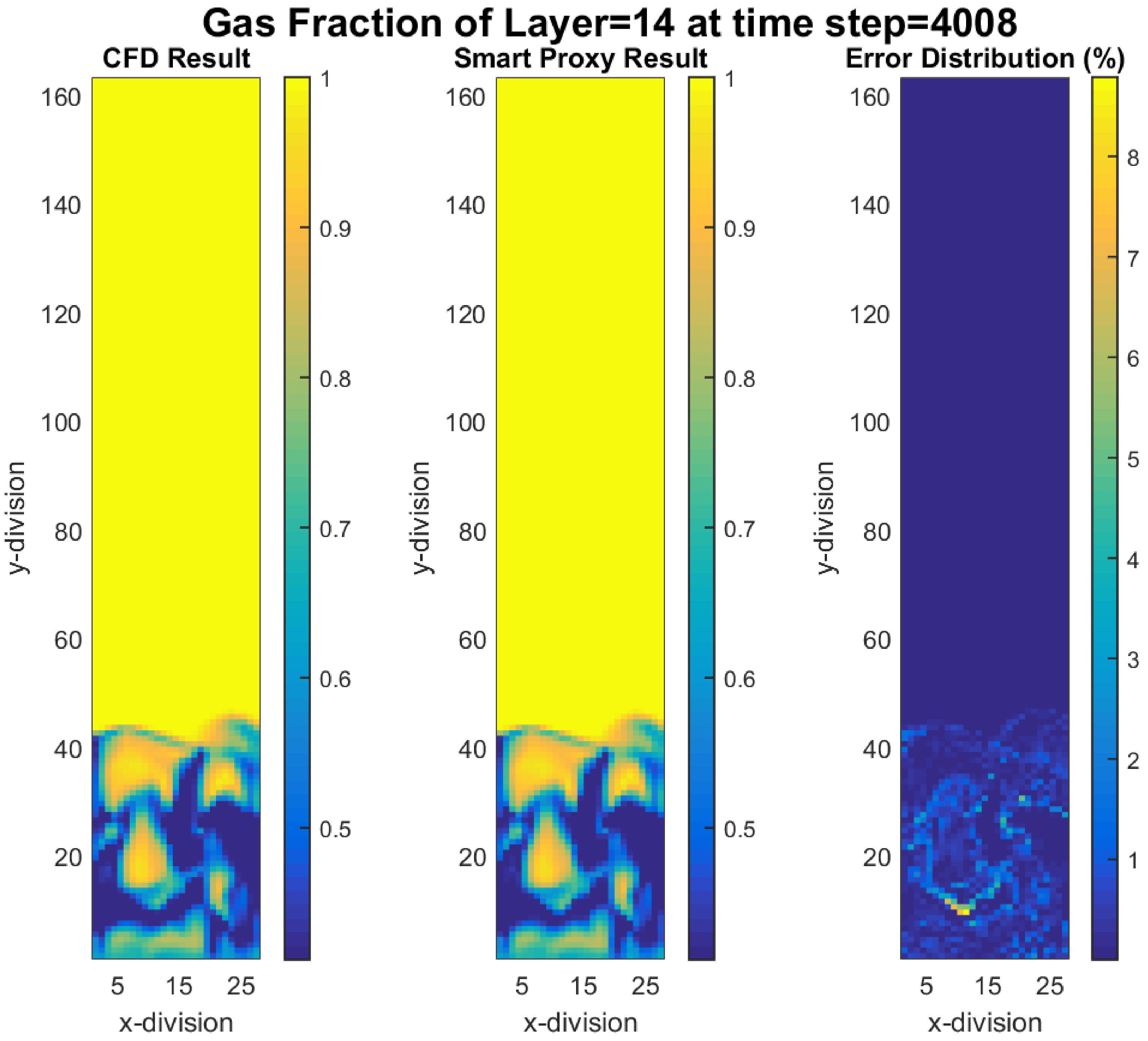


C

C

Results of Layer 14 – Gas Fraction

- Model was trained using Time-step 4001 as input and Time-step 4002 as output.
  - Trained on 75% of data and validated using the remaining 25%
- Trained model was deployed in forecast mode and generated Time-step 4002 through Time-step 4024
- Results generated by the Smart Proxy are compared with actual CFD output.

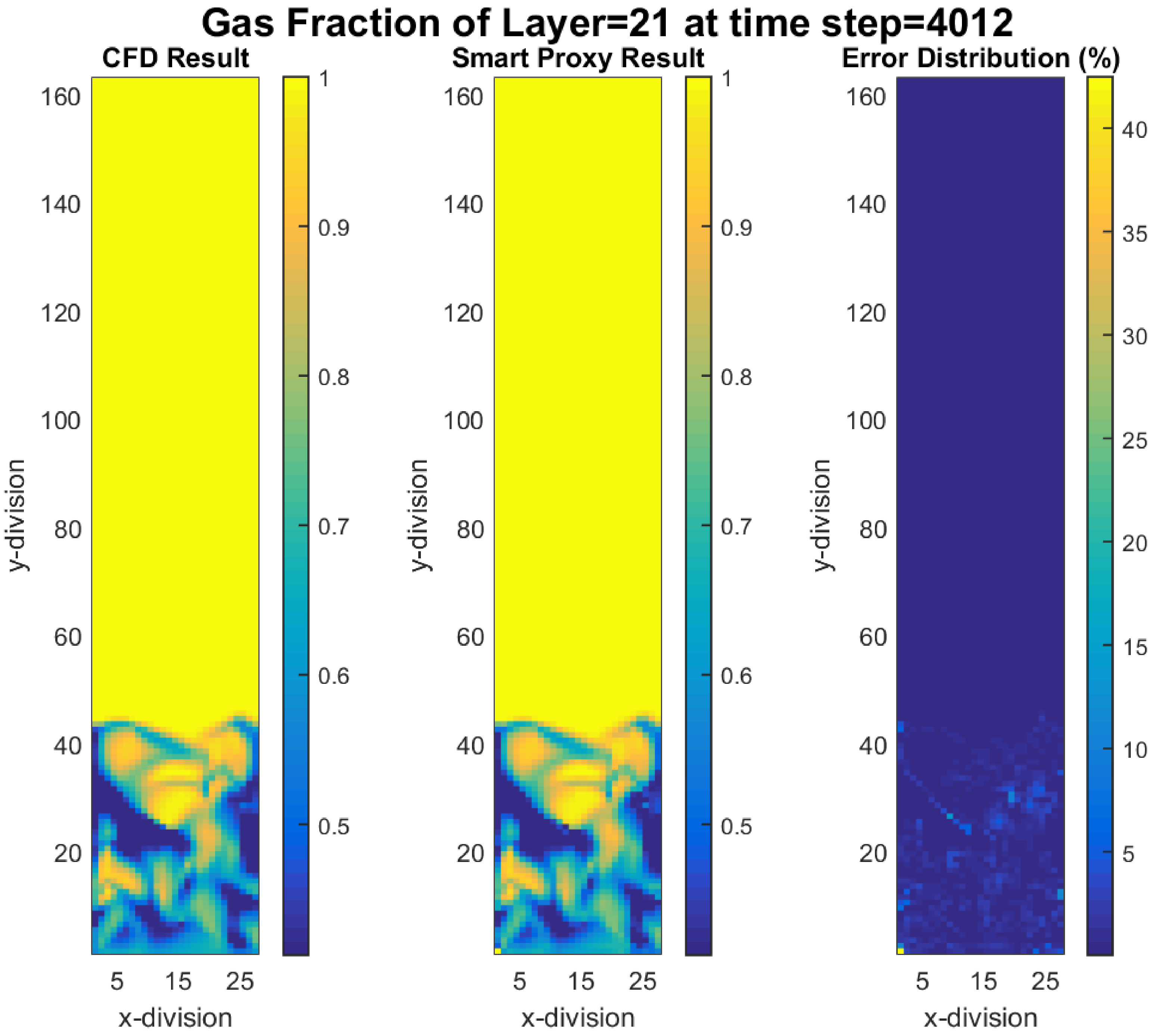


Gas Fraction of Layer=14 at time step=4008
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
8
7
6
5
4
3
2
1

C

Results of Layer 21 – Gas Fraction

- Model was trained using Time-step 4001 as input and Time-step 4002 as output.
  - Trained on 75% of data and validated using the remaining 25%
- Trained model was deployed in forecast mode and generated Time-step 4002 through Time-step 4020
- Results generated by the Smart Proxy are compared with actual CFD output.



Gas Fraction of Layer=21 at time step=4012
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
40
35
30
25
20
15
10
5

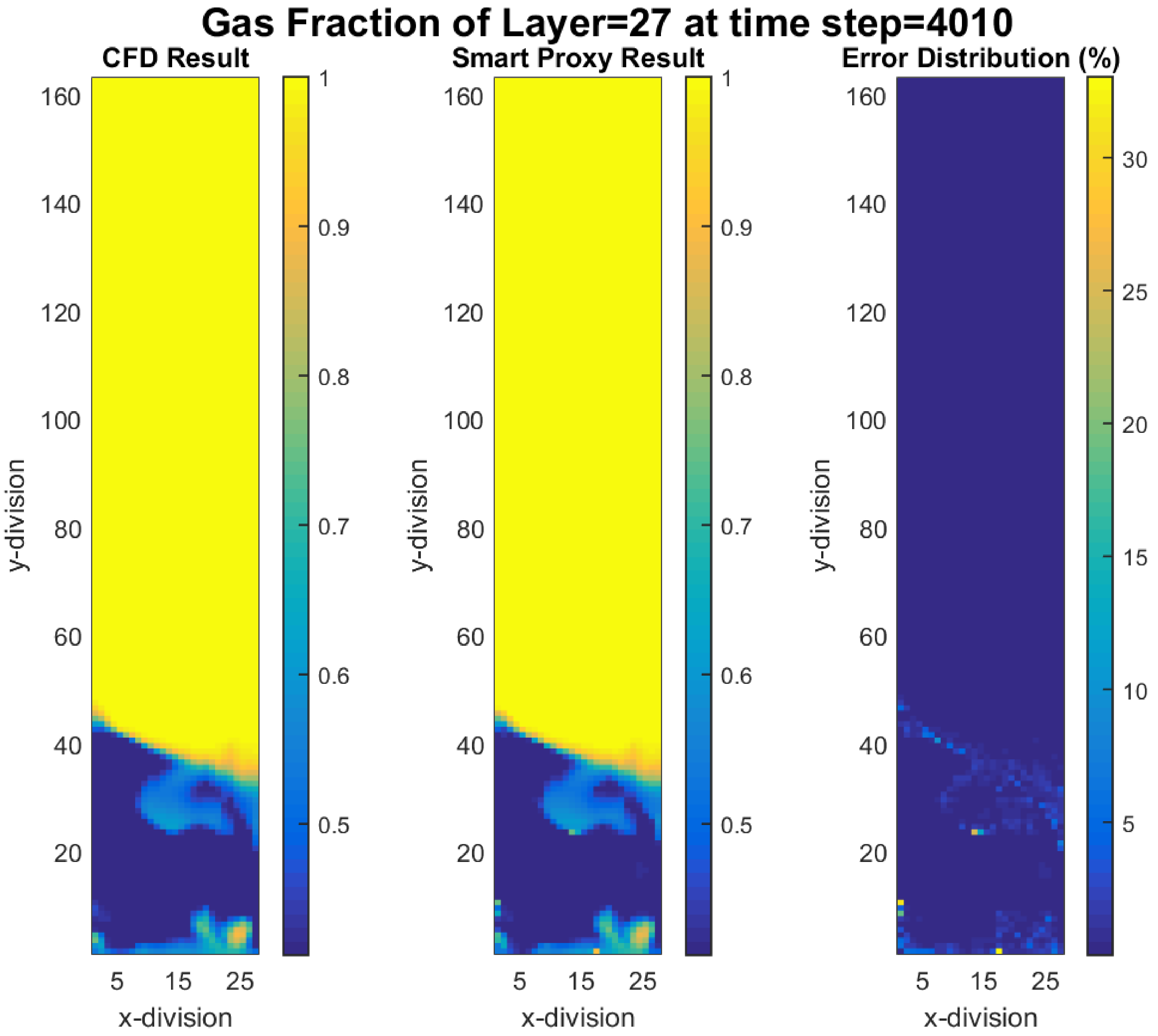
C

Results of Layer 27 – Gas Fraction

- Model was trained using Time-step 4001 as input and Time-step 4002 as output.
  - Trained on 75% of data and validated using the remaining 25%

- Trained model was deployed in forecast mode and generated Time-step 4002 through Time-step 4012

- Results generated by the Smart Proxy are compared with actual CFD output.


Gas Fraction of Layer=27 at time step=4010
CFD Result
Smart Proxy Result
Error Distribution (%)
y-division
x-division
160
140
120
100
80
60
40
20
5
15
25
1
0.9
0.8
0.7
0.6
0.5
30
25
20
15
10
5

C

Paradigm Shift in Proxy Modeling

- ***VERY LARGE AMOUNTS OF DATA*** is carefully extracted from a handful of runs of the original model.

- The process of data extraction from several runs of the original model is ***ENGINEERED*** such that it can be used to train, calibrate and validate a smart, new model.

Paradigm Shift in Proxy Modeling

- The Smart Proxy model is developed using ***MACHINE LEARNING*** that is now the main paradigm for treating and handling ***"BIG DATA"***.

- The Smart Proxy learns to mimic the behavior of the original model with all its complexities and intricacies.

- Once developed, the Smart Proxy Model runs at very low computational cost (thousands of simulation runs in minutes).

The Spatio-Temporal Database

Tier One
Neighbor Cells

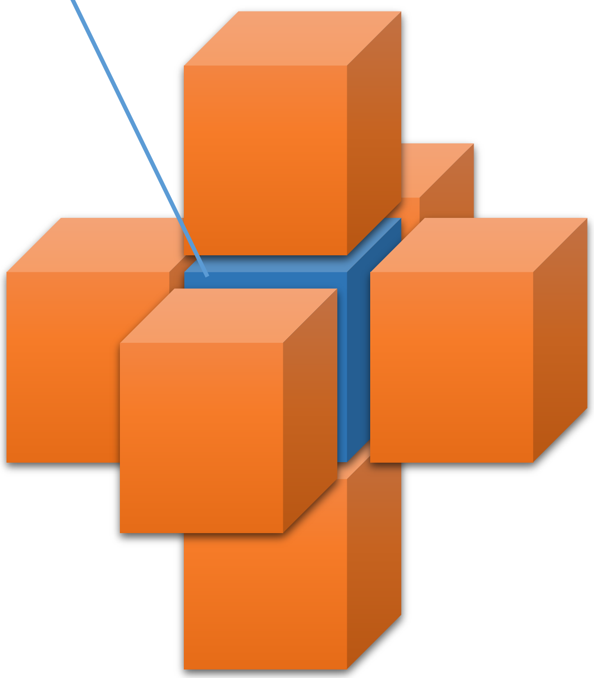
$Cell_{ijk}$ at time step n								
ε_g	P	P_s	u_g	v_g	w_g	u_s	v_s	w_s

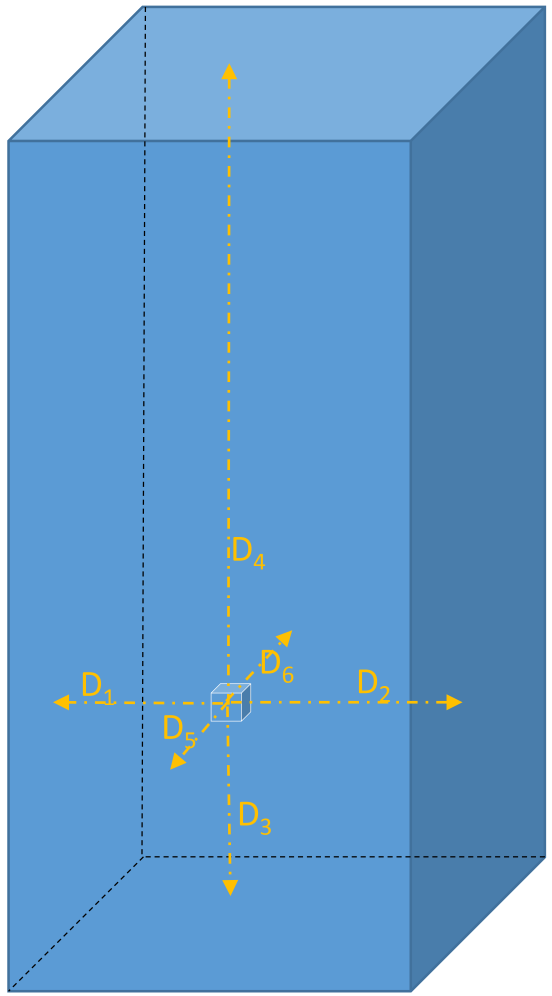
Tier $Cell_{ijk}$ at time step n								
ε_g	P	P_s	u_g	v_g	w_g	u_s	v_s	w_s

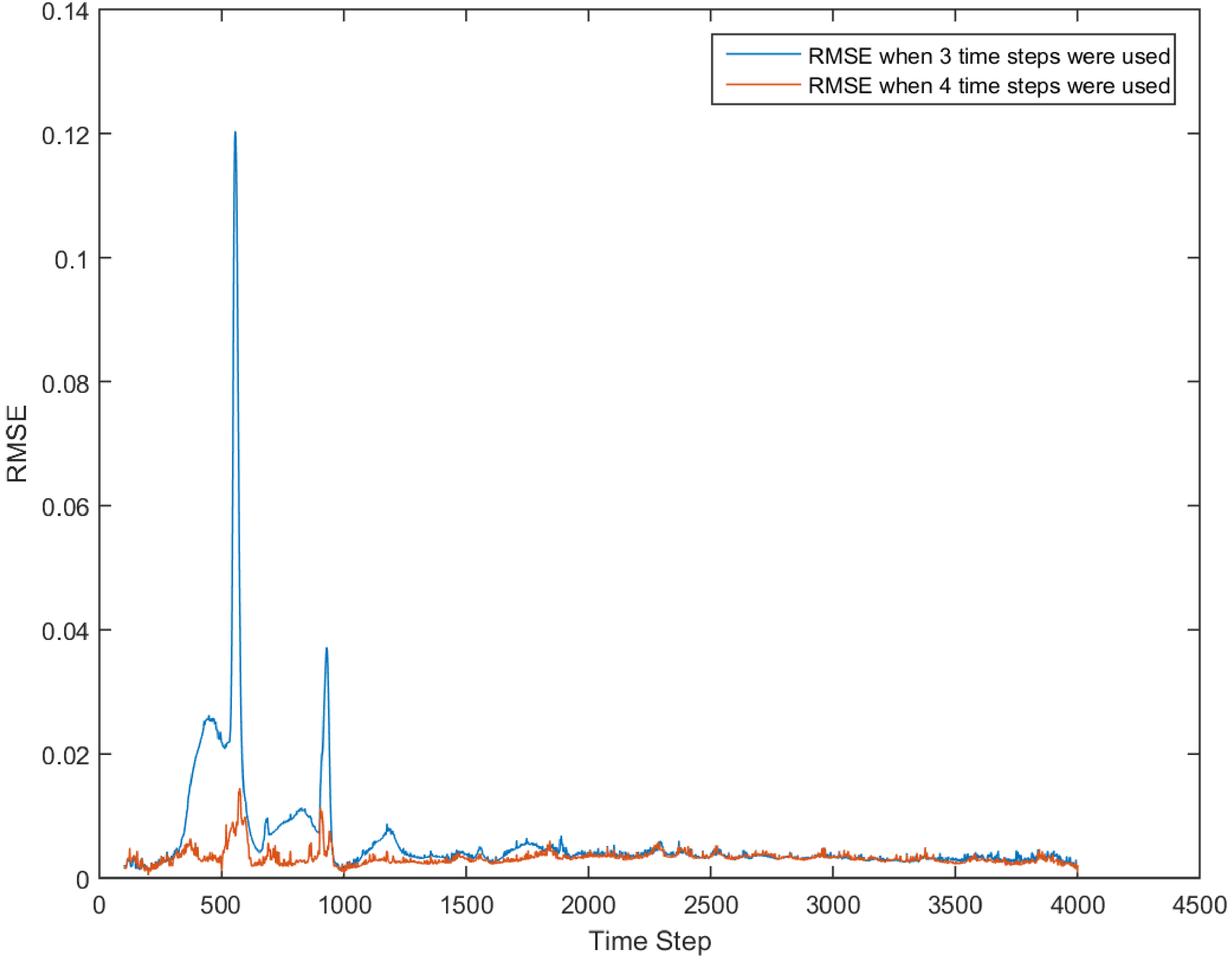
$Cell_{ijk}$ at time step $(n+1)$								
ε_g	P	P_s	u_g	v_g	w_g	u_s	v_s	w_s

Number of inputs 6 + 9 + 6 x 9 = 69
Number of outputs = 9

Location of $Cell_{ijk}$					
D_1	D_2	D_3	D_4	D_5	D_6

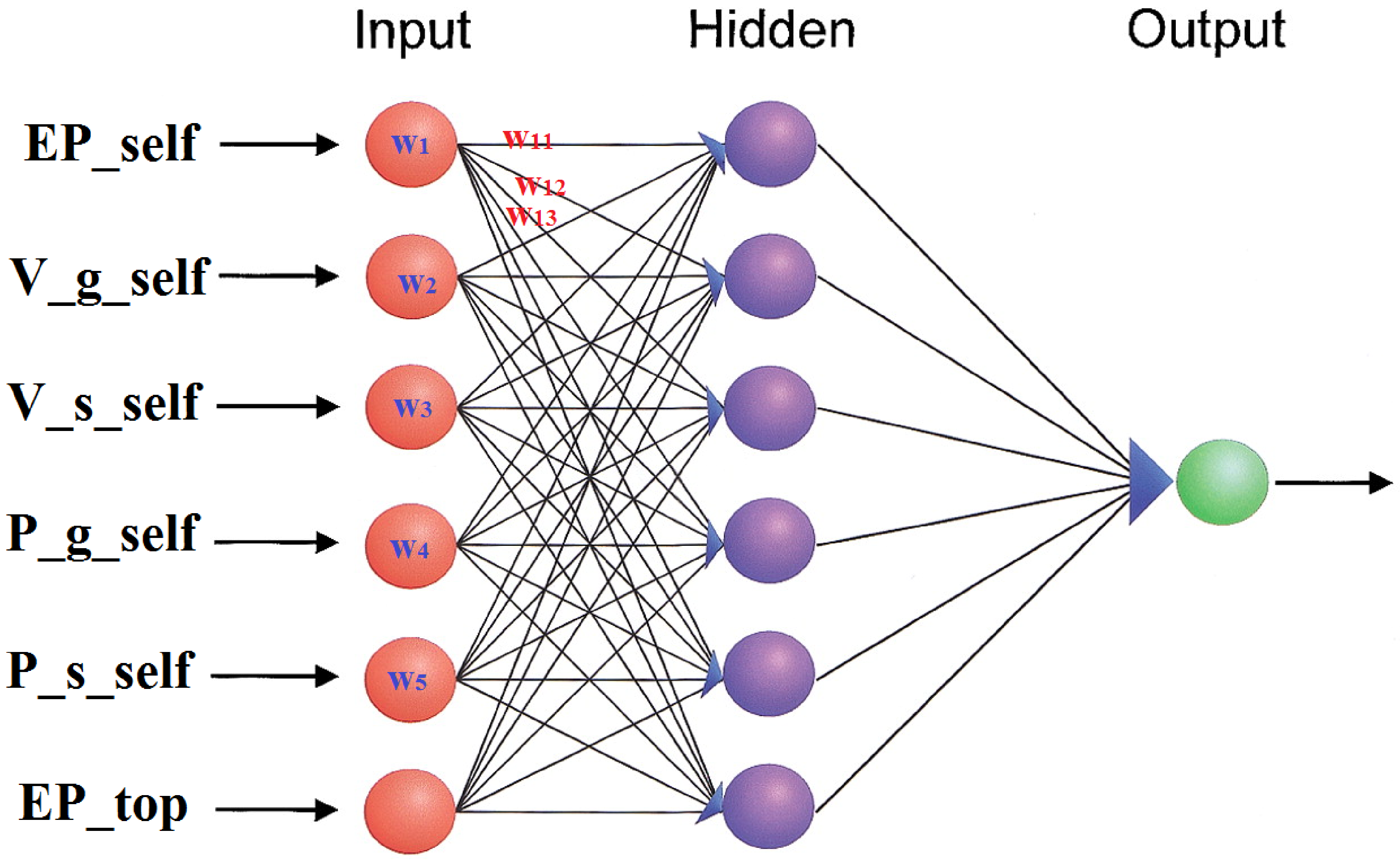




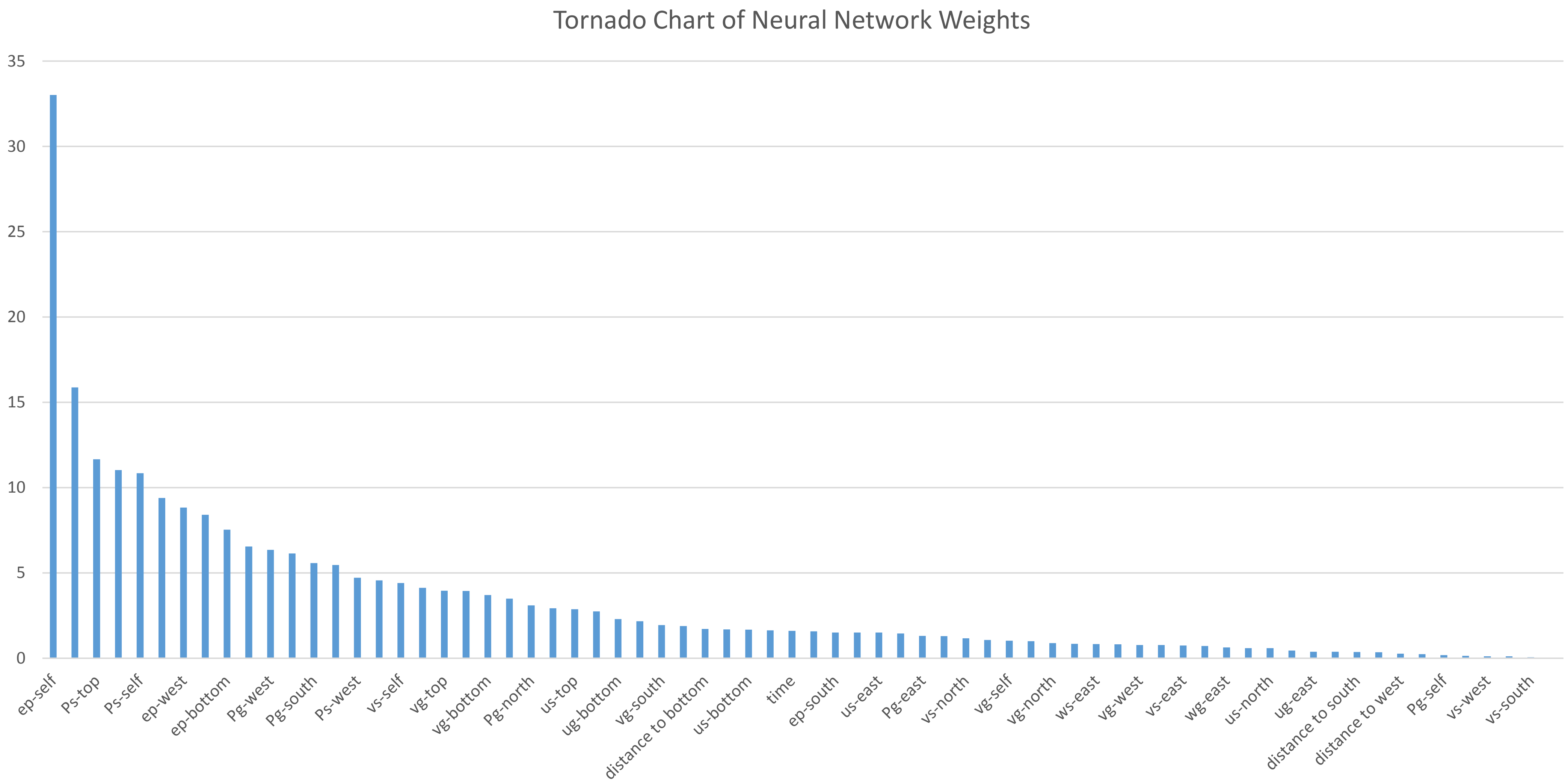


RMSE when 3 time steps were used
RMSE when 4 time steps were used
RMSE
Time Step
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500

Optimize the number of inputs

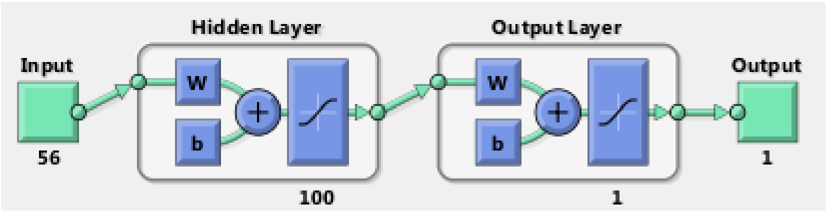


Tornado chart by adding all the weights

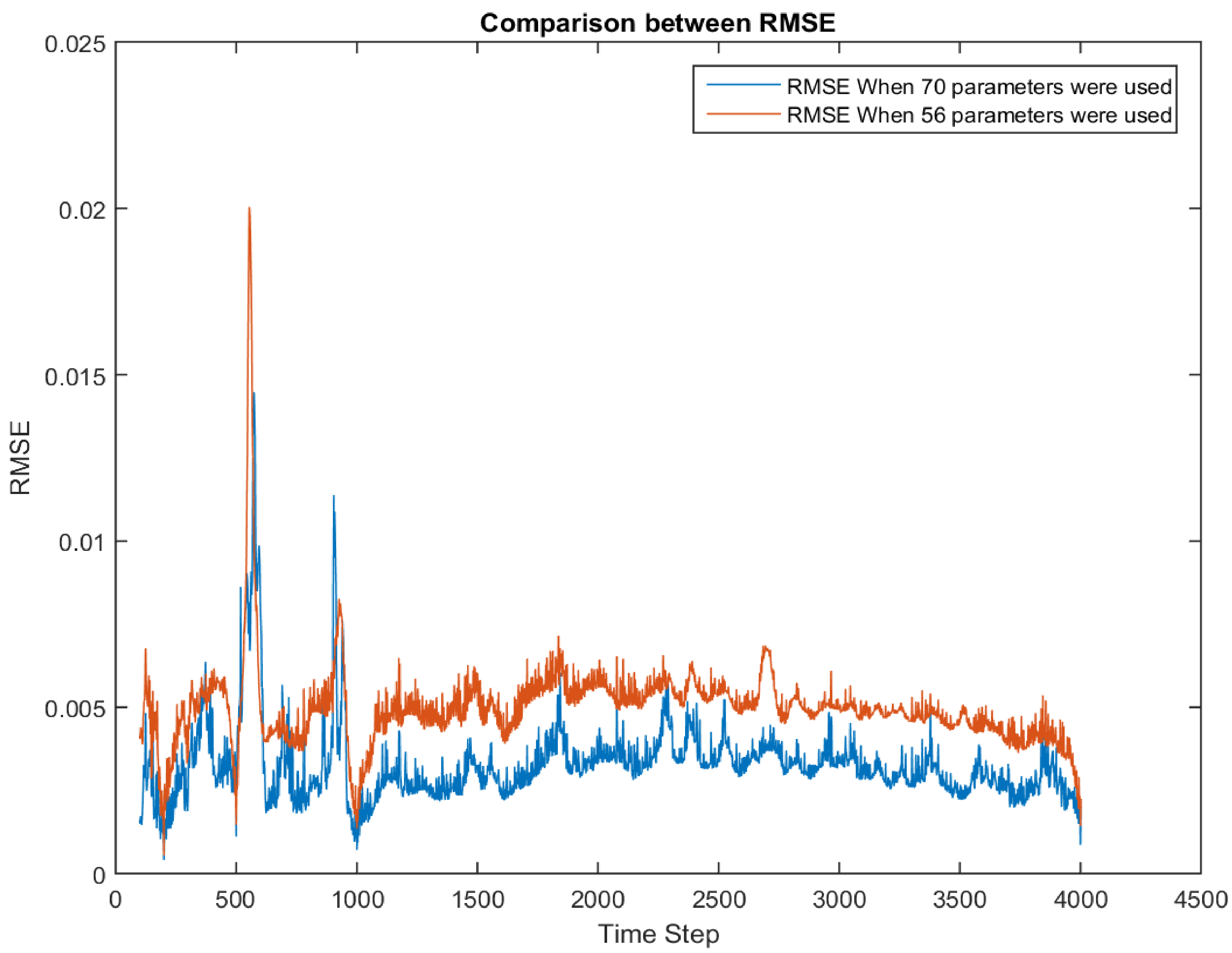


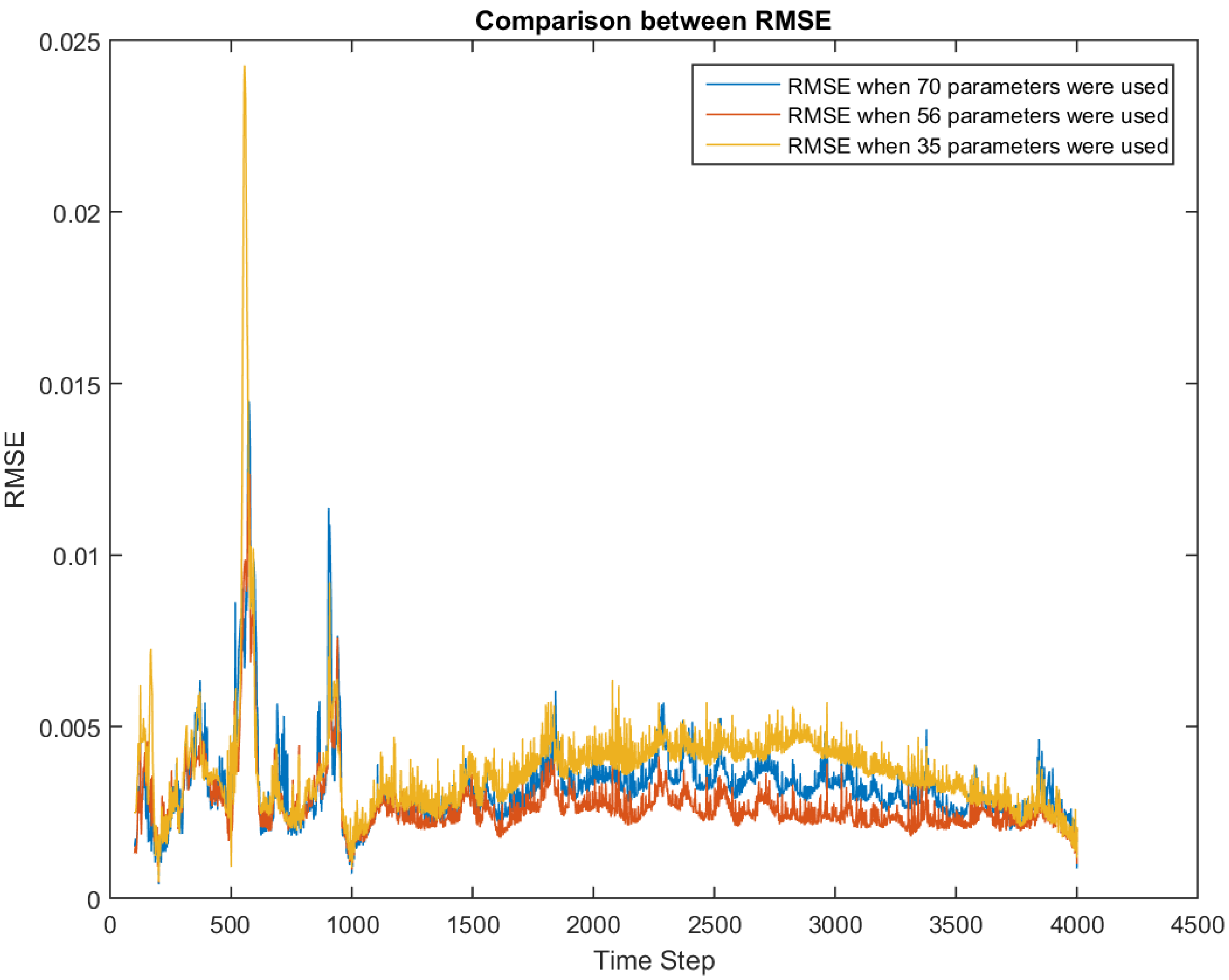
Eliminating 14 parameters

By parameter	By location
ug-west	vg-self
ug-north	
ug-south	vs-bottom
ug-east	
	ug-north
vg-self	wg-north
vg-west	us-north
wg-north	ug-south
us-north	ws-west
	vs-west
ws-west	ug-west
	vg-west
vs-west	
vs-bottom	ug-east
distance to south	distance to south
distance to east	distance to east
distance to west	distance to west

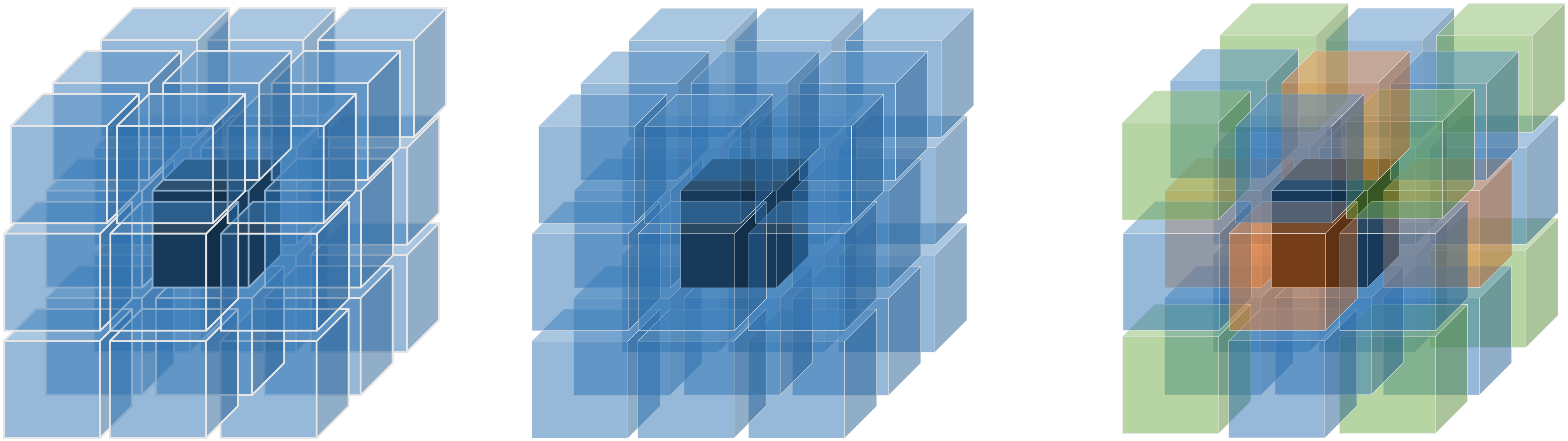


RSM

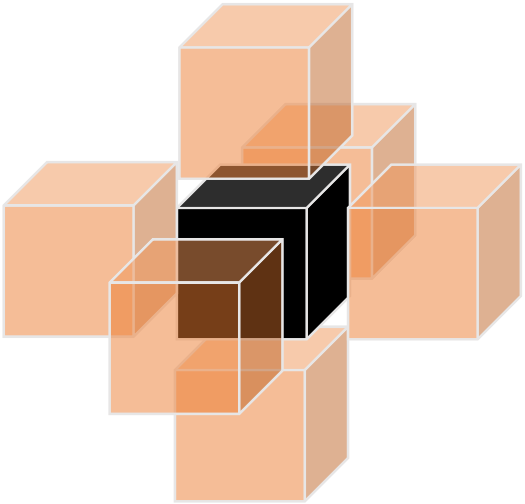

Comparison between RMSE
RMSE When 70 parameters were used
RMSE When 56 parameters were used
RMSE
Time Step
0.025
0.02
0.015
0.01
0.005
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500


Comparison between RMSE
RMSE when 70 parameters were used
RMSE when 56 parameters were used
RMSE when 35 parameters were used
RMSE
Time Step
0.025
0.02
0.015
0.01
0.005
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500

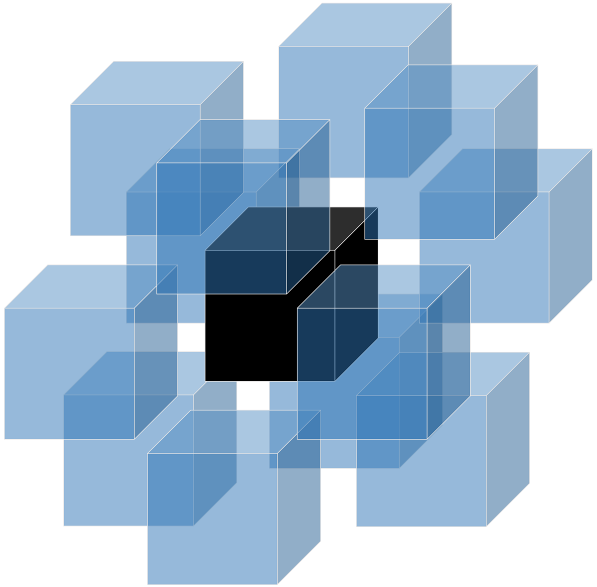
The Tier System



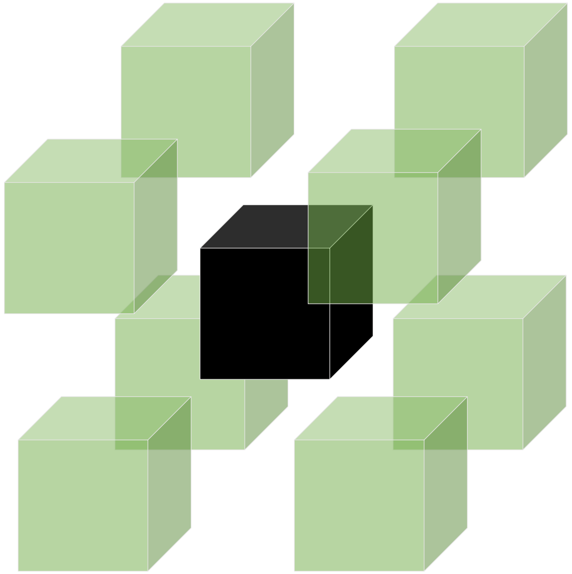
The Tier System



Tier One
Interface: Plane

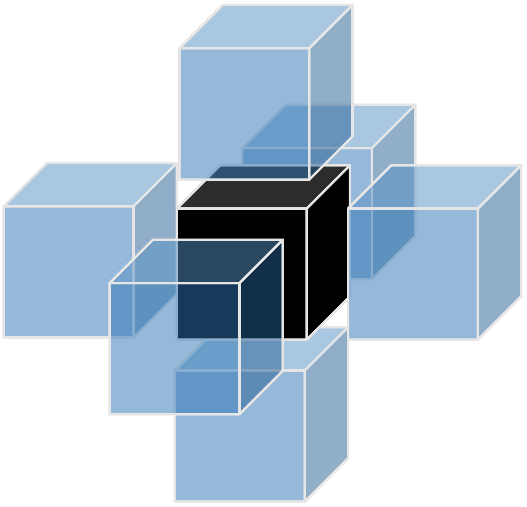


Tier Two
Interface: Line

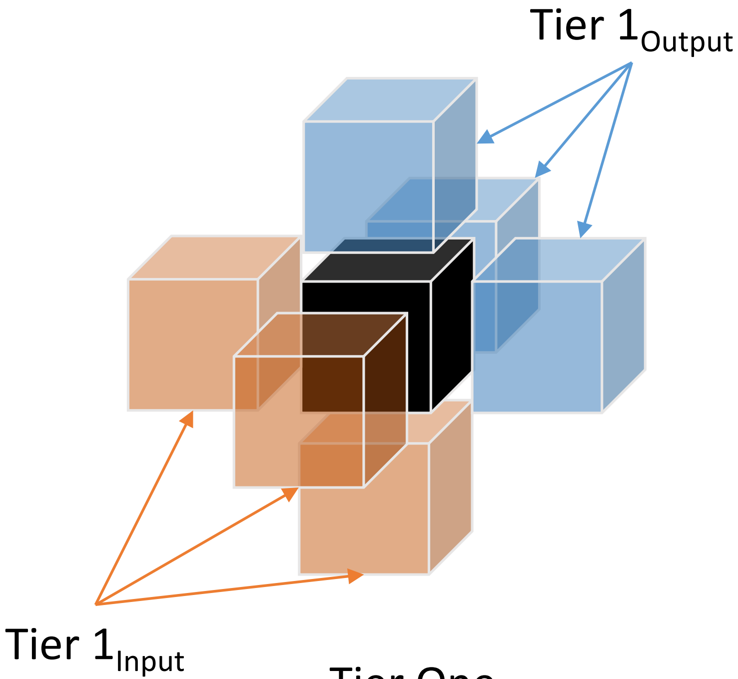


Tier Three
Interface: Point

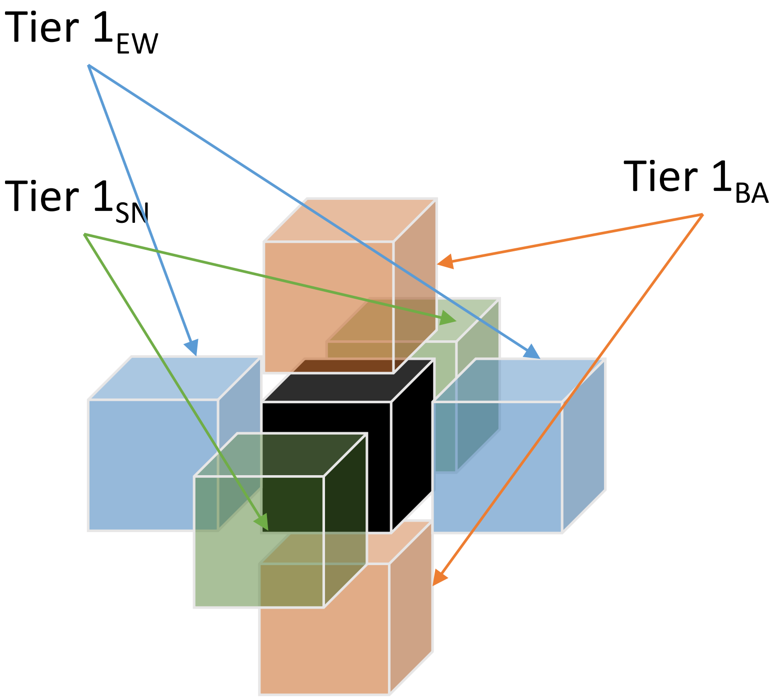
Tier One - Subsystem



Tier One
Interface: Plane



Tier One
Two Subsystems
Tier 1_{Input} and Tier 1_{Output}



Tier One
Three Subsystems
Tier 1_{EW} , Tier 1_{SN} , and Tier 1_{BA}