Icosahedral Maps for a Multiresolution Representation of Earth Data

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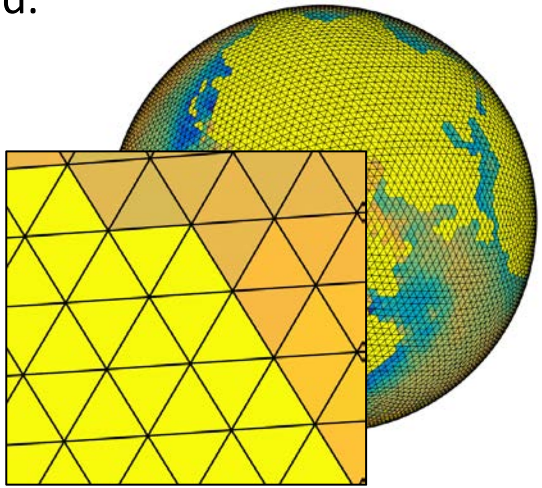
INTRODUCTION

ICON

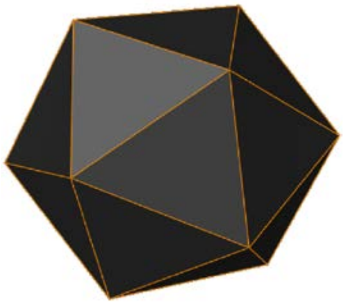
- **Icosahedral Non-hydrostatic (ICON):**
  - A 3D Earth model used for numerical weather prediction.
  - Earth surface is descritized and data is assigned.



- Jointly developed by the **Max Planck Institute for Meteorology (MPI-M)** and the **German Weather Service (DWD)**.

ICON

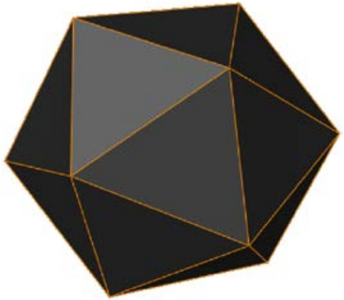
- ICON is designed via **Discrete Global Grid System (DGGS).**



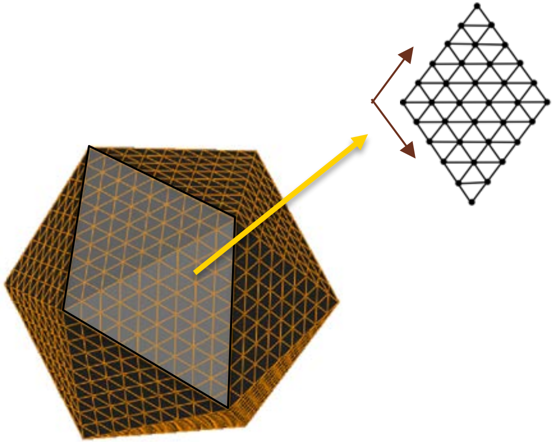
Base Icosahedron

ICON

- ICON is designed via **Discrete Global Grid System (DGGS).**



Base
Icosahedron



Refinement

ICON

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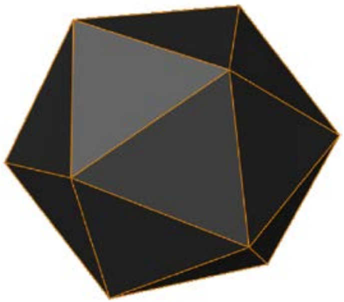

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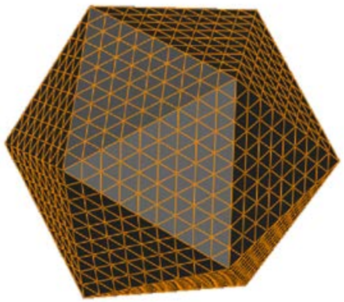
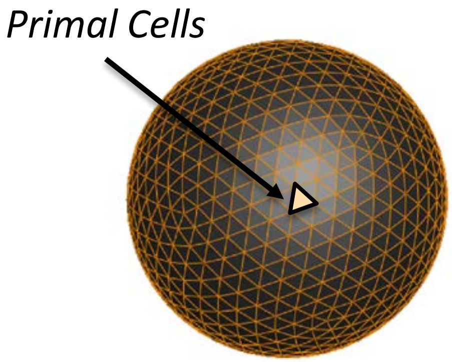


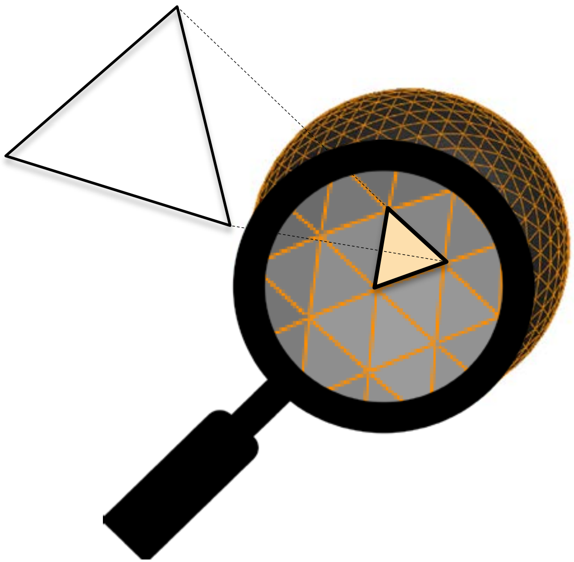
Refinement



Spherical Projection

Cells

- For improved numerical solution, different data is assigned at different locations of the **primal cell (triangle).**



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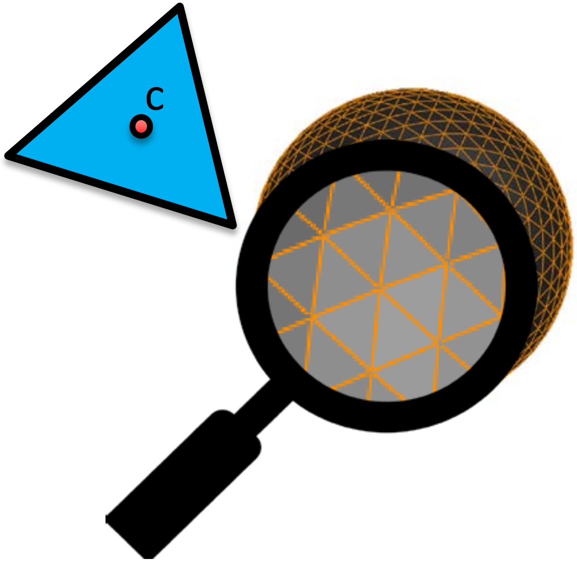
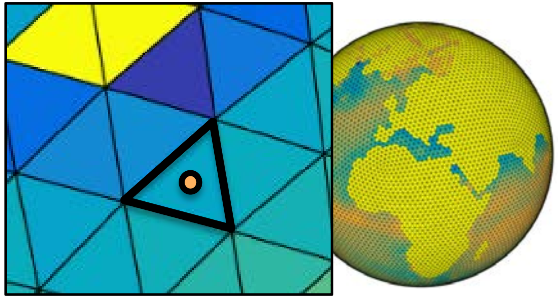


1 Centroids



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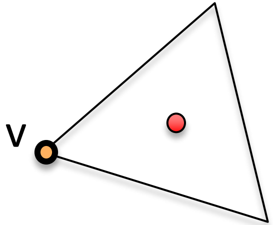
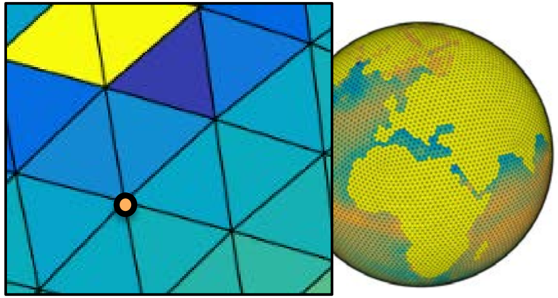


2 **Vertices**



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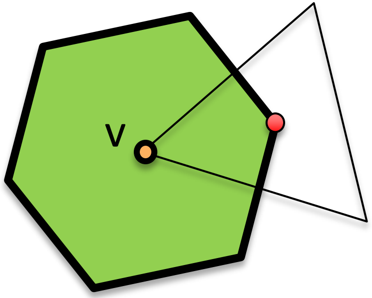
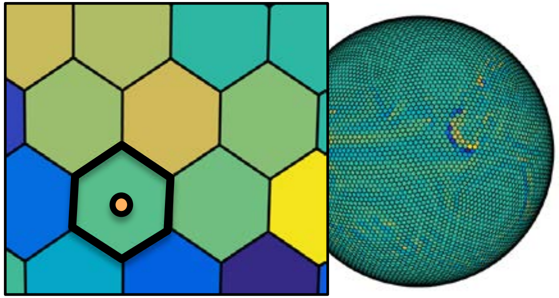


2 **Vertices** ➤ Centroids of **hexagons** (dual of primal cell)



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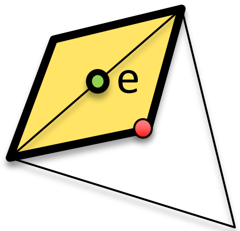
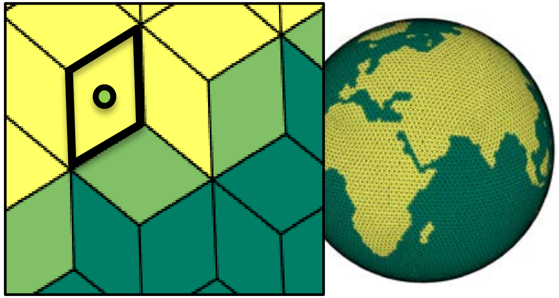


3 **Edge midpoints** → Centroids of **quads**



RESEARCH GOAL

Research Problem

1 Visualization

- Interactive exploration of ICON demands efficient use of-
  - Memory.
  - I/O bandwidth.
- But, ICON data is high resolution.

- *How can we improve visualization?*

One solution is:

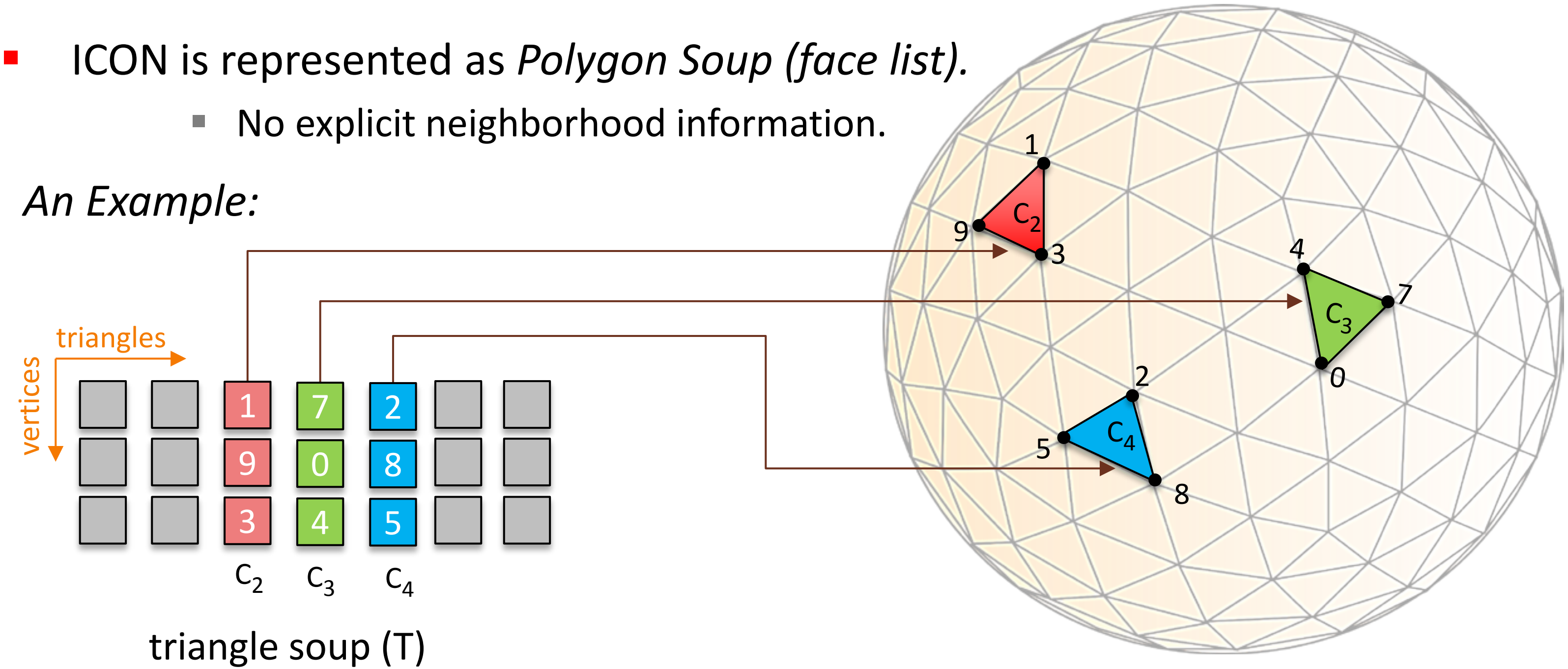
A multiresolution representation of ICON.

— Level-of-Detail Rendering.

2 Data Structure

- ICON is represented as *Polygon Soup (face list).*
  - No explicit neighborhood information.

An Example:



triangle soup (T)

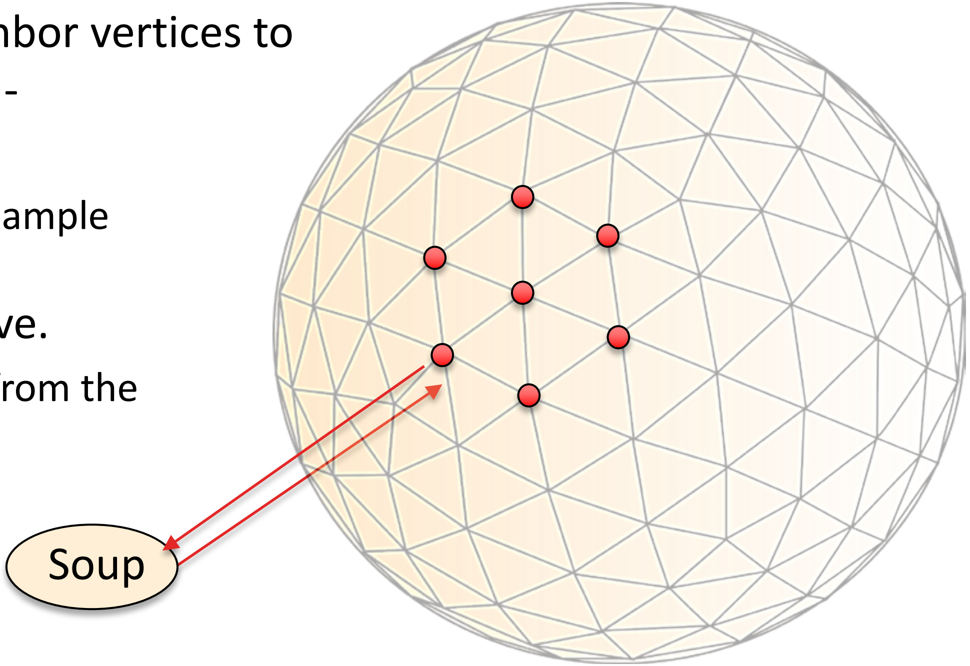
2 Data Structure

- Multiresolution needs neighbor vertices to perform its operations, e.g. -
  - Convolution
  - Downsample and upsample

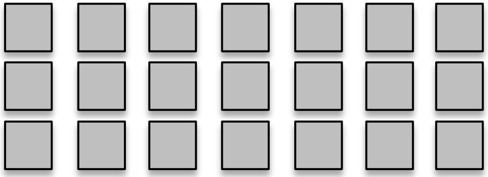
But, *soup* makes it expensive.

- Retrieving neighbors from the soup for every vertex.

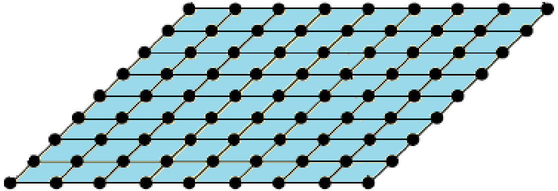
- *How can we make these operations faster?*



1 Mapping **unstructured soup** into a **structured 2D representation,** we call it *‘Icosahedral maps’.*



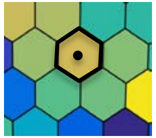
Polygon soup



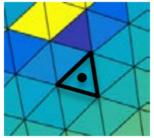
structured 2D array

2 Mapping works for **all three cell-types**.

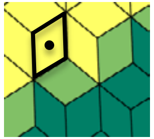
Centroids of **Hexagons**

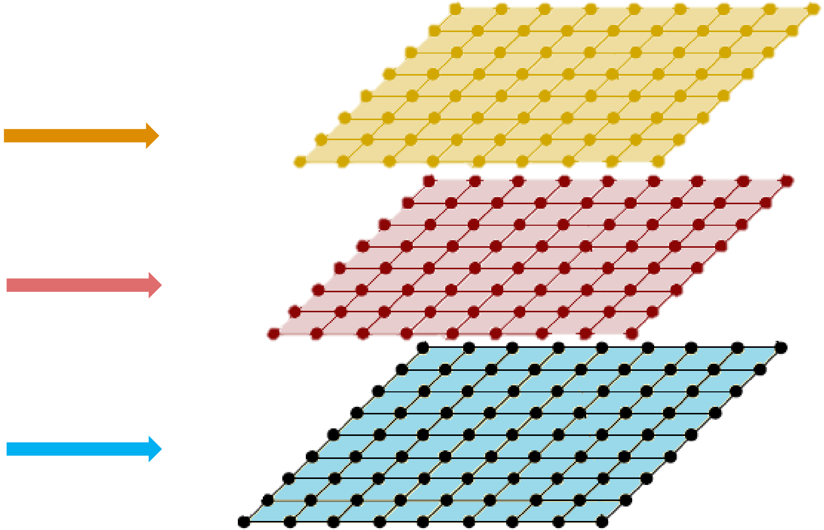


Centroids of **Triangles**



Centroids of **Quads**

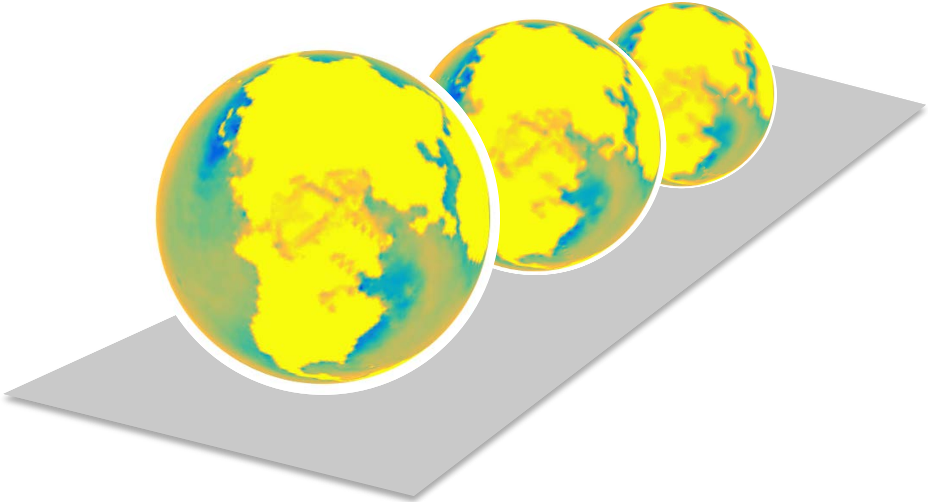


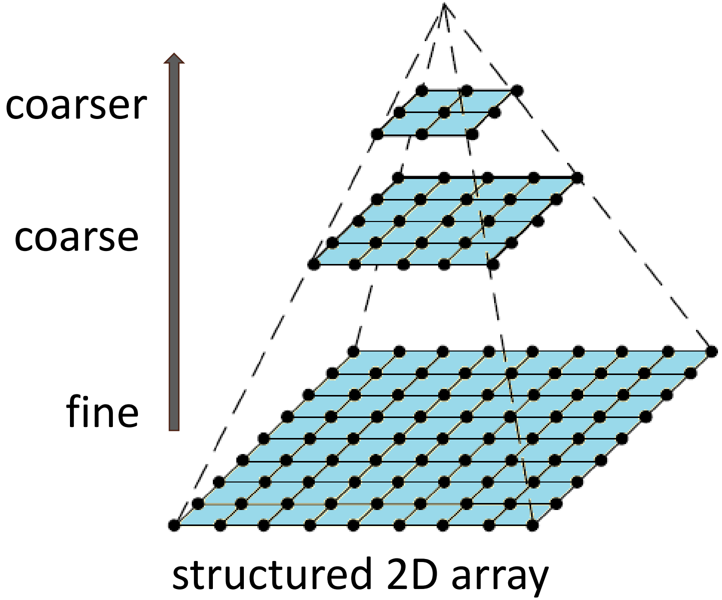


structured 2D array

Research Goal

3 **LoD** representation of Earth data by applying a **multiresolution scheme** on the icosahedral maps.





METHODOLOGY

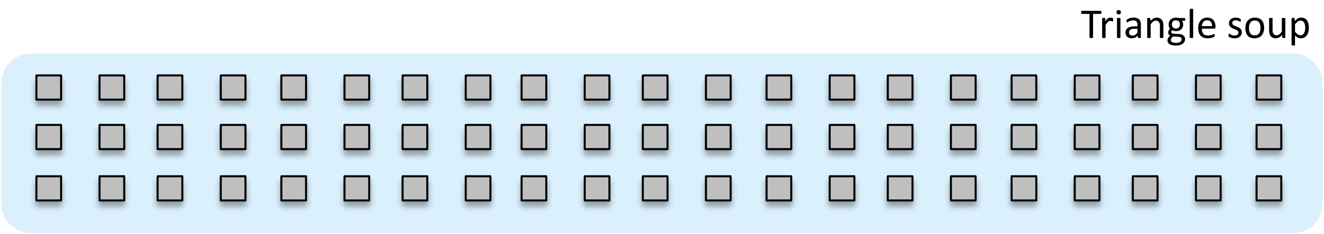
Icosahedral Maps

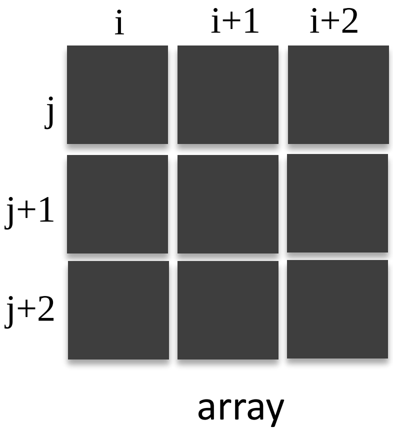
Hexagonal Fan

Given one **triangle** from a triangle **soup**, a hexagonal fan finds its hexagonal **neighbors** of a vertex and store the information in a **2D array.**

Hexagonal Fan

- *An example :*





Hexagonal Fan

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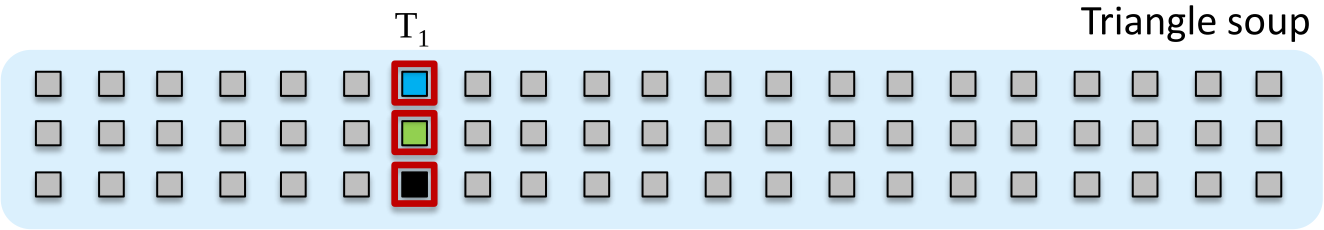

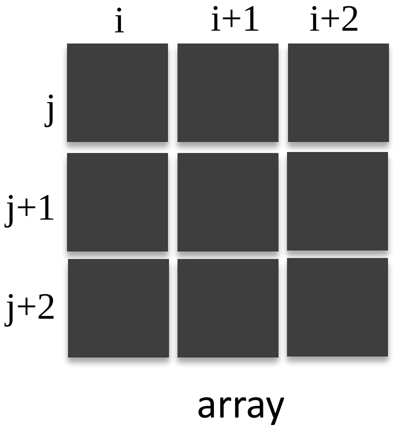

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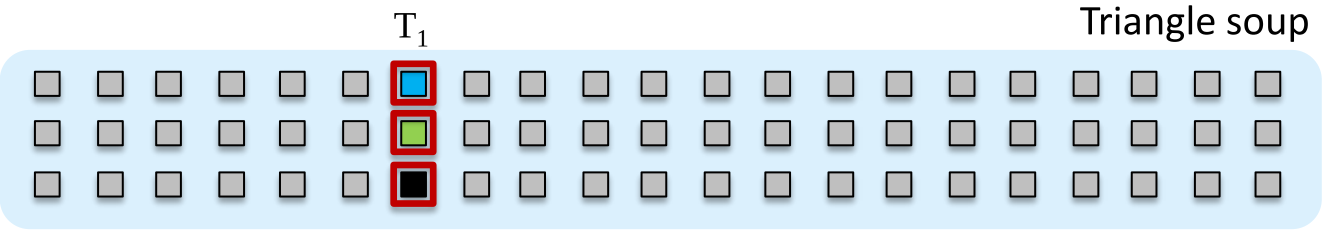

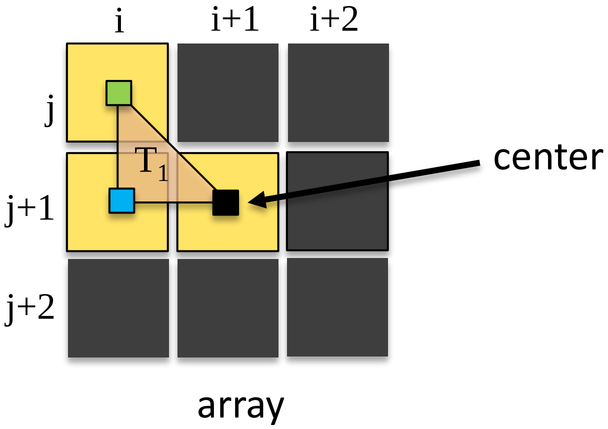

Hexagonal Fan

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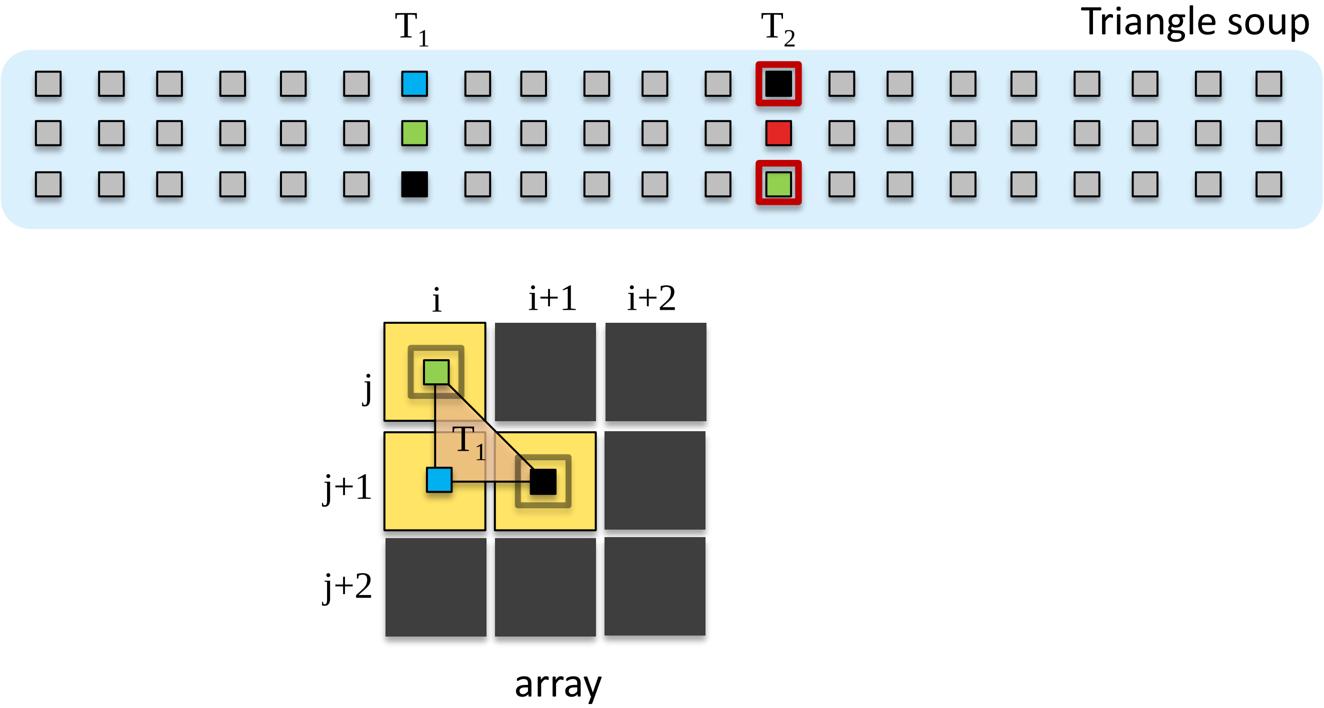

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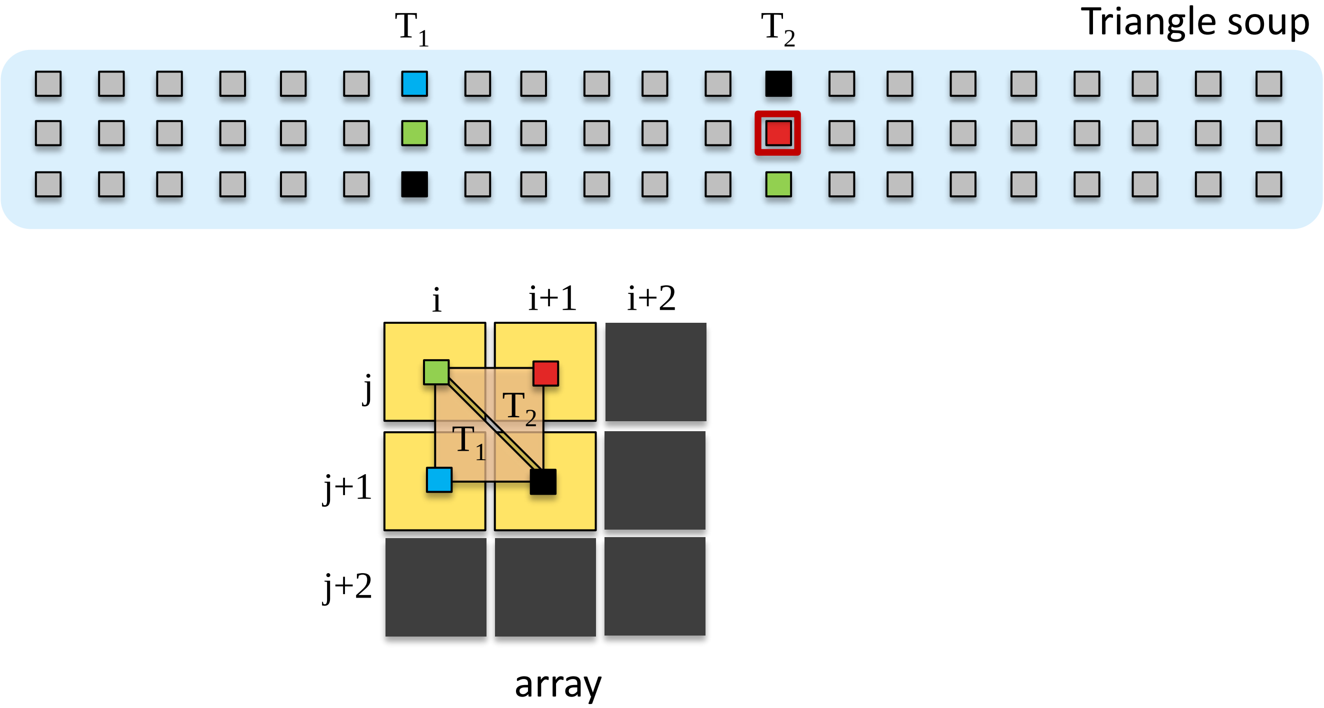

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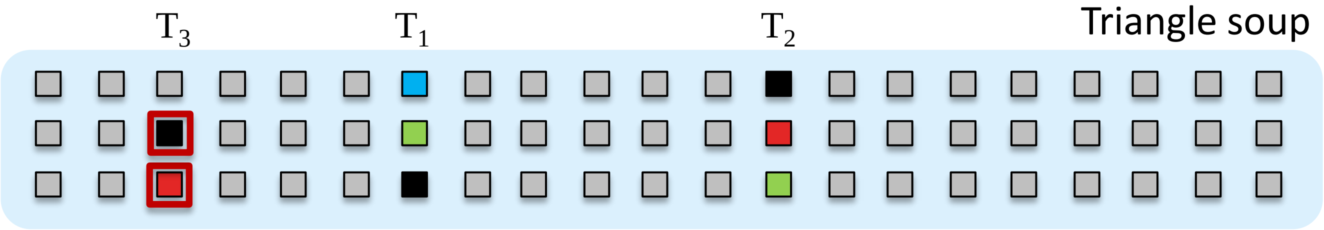

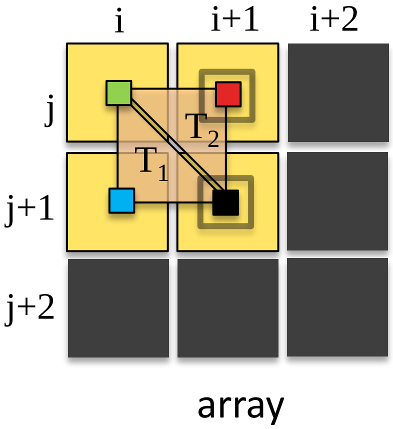

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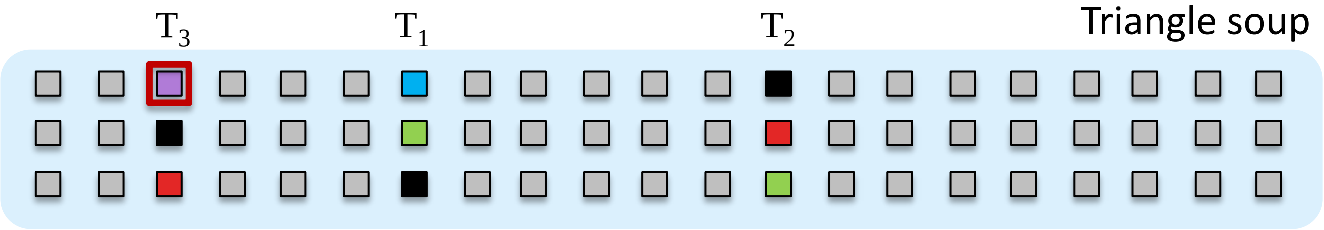

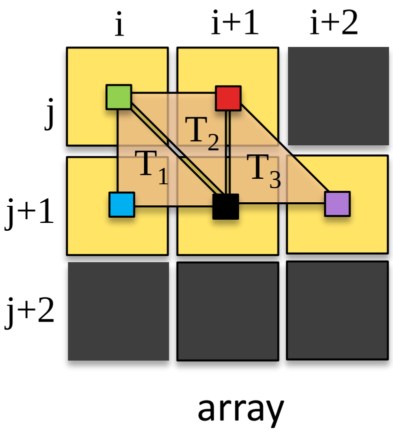

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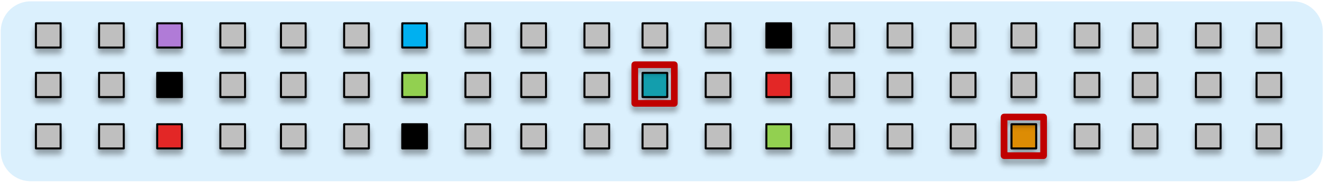
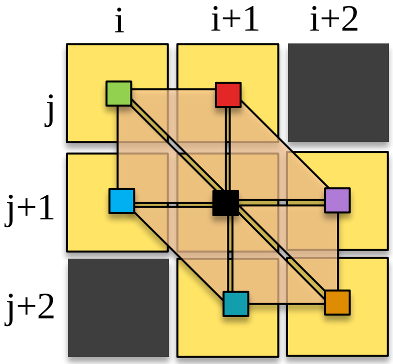
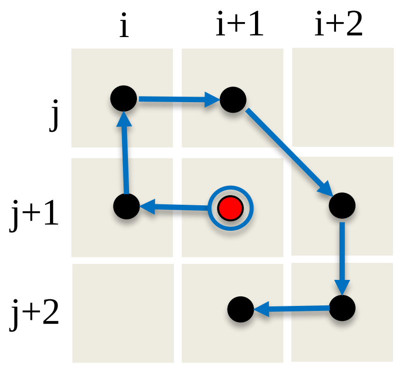




array

Hexagonal Fan

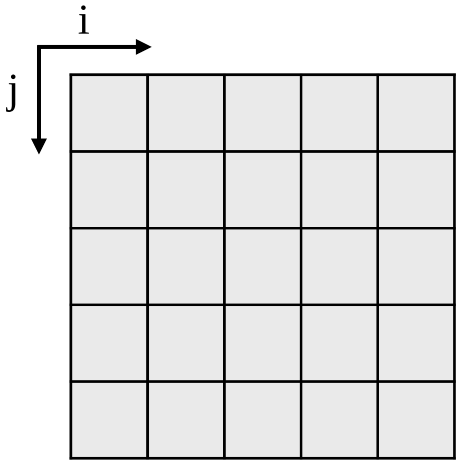
— This traversal scheme will be used for capturing information for three-types of cell centroids of ICON.



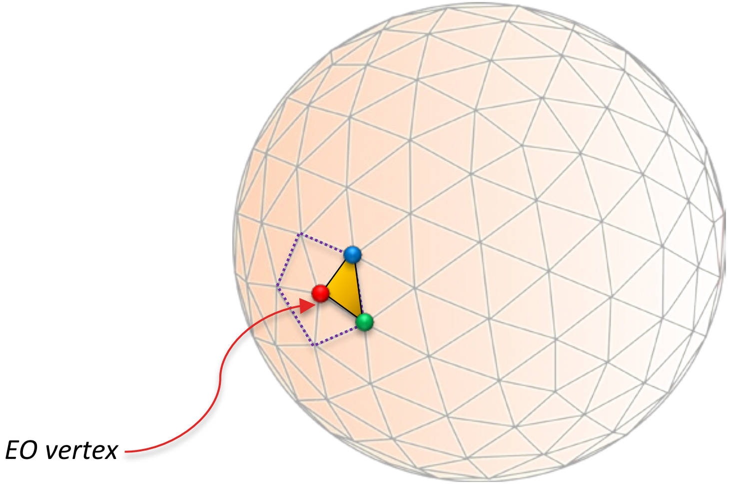
Mapping Technique

1 Mapping Centroids of Hexagons:

– Vertices of the primal cells



2D array

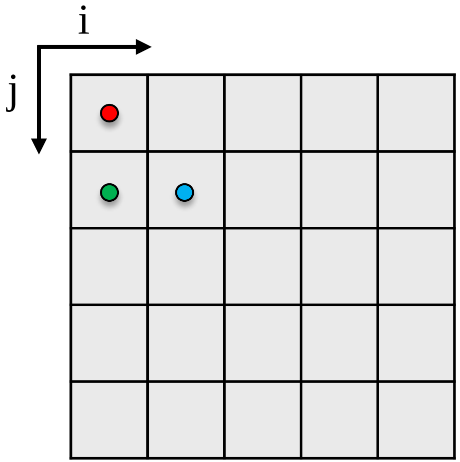


3D Earth

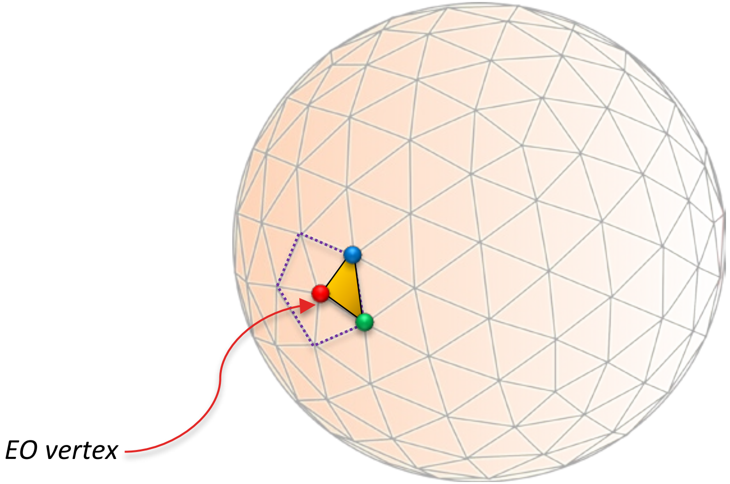
Mapping Technique

1 Mapping Centroids of Hexagons:

– Initial triangle vertices.



2D array

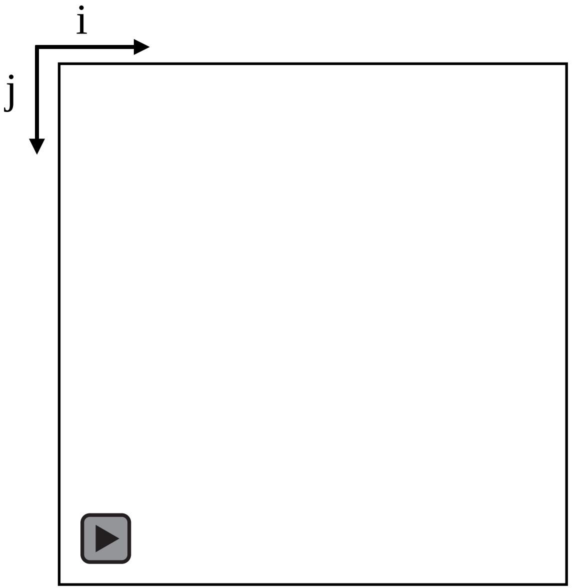


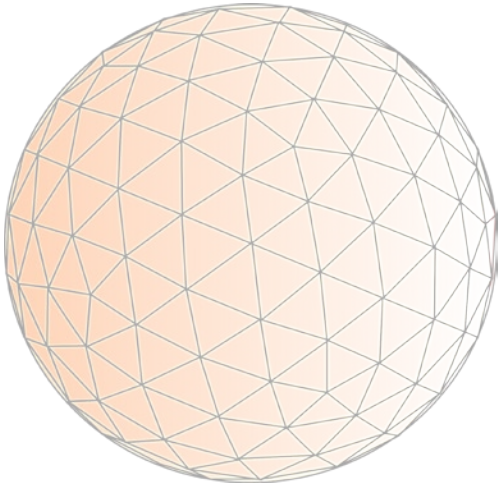
3D Earth

Mapping Technique

1 Mapping Centroids of Hexagons:

– Hexagonal fan sweeps to fill up array.

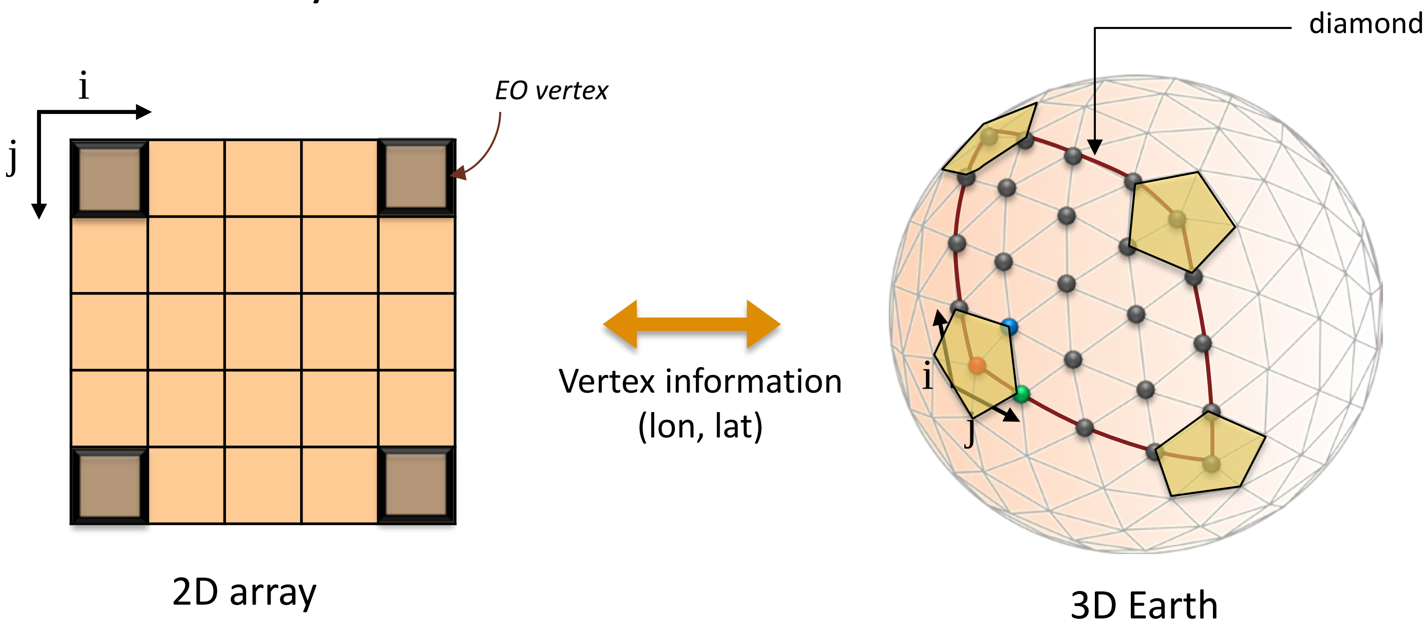




3D Earth

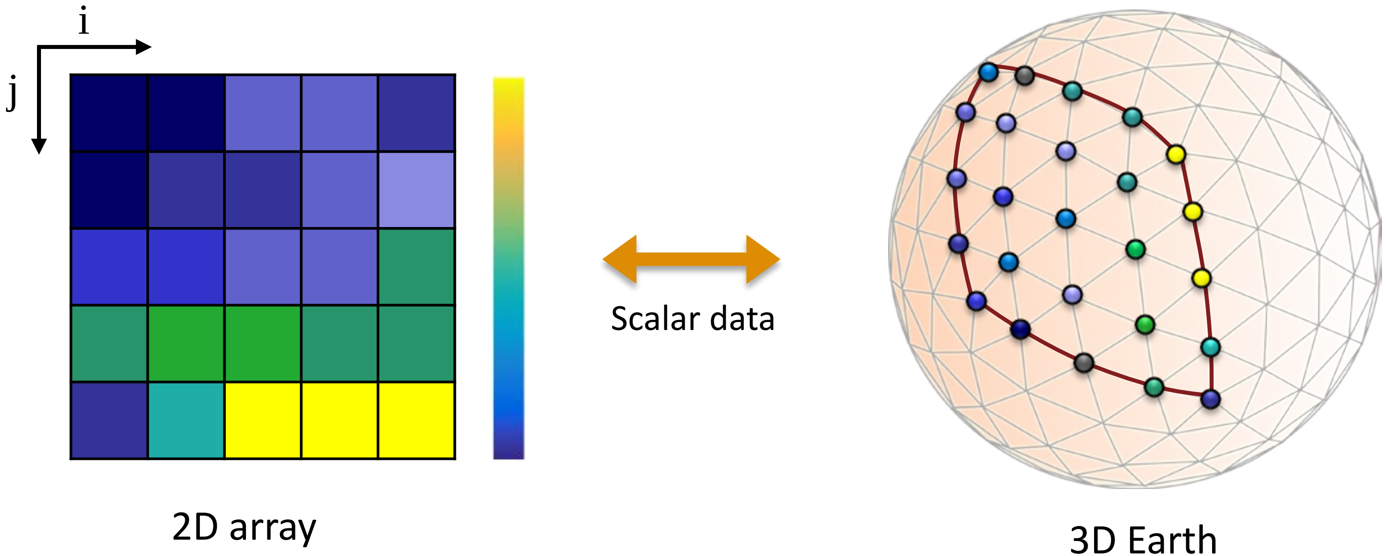
1 Mapping Centroids of Hexagons:

– One array extract one diamond on Earth.



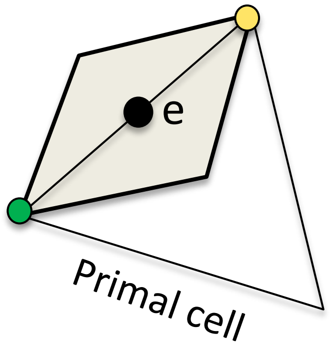
1 Mapping Centroids of Hexagons:

— Associated data is also extracted.



2 Mapping Centroids of Quads:

- Edge midpoints of the primal cells



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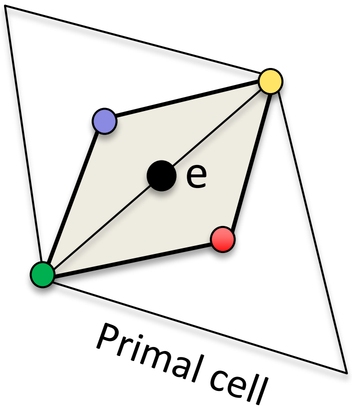
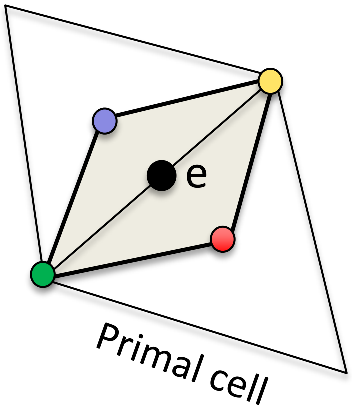
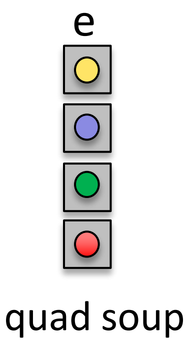


2 Mapping Centroids of Quads:

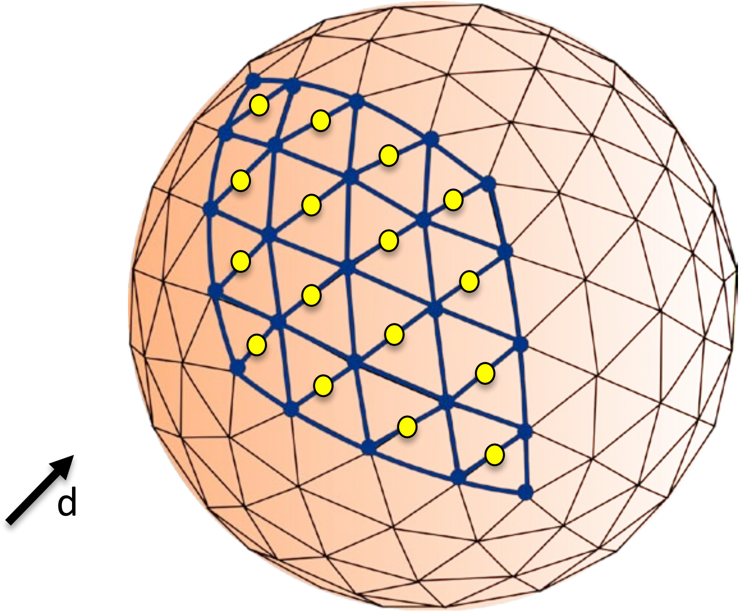
— Vertices stored as quad soup





2 Mapping Centroids of Quads:

- Three directional edges



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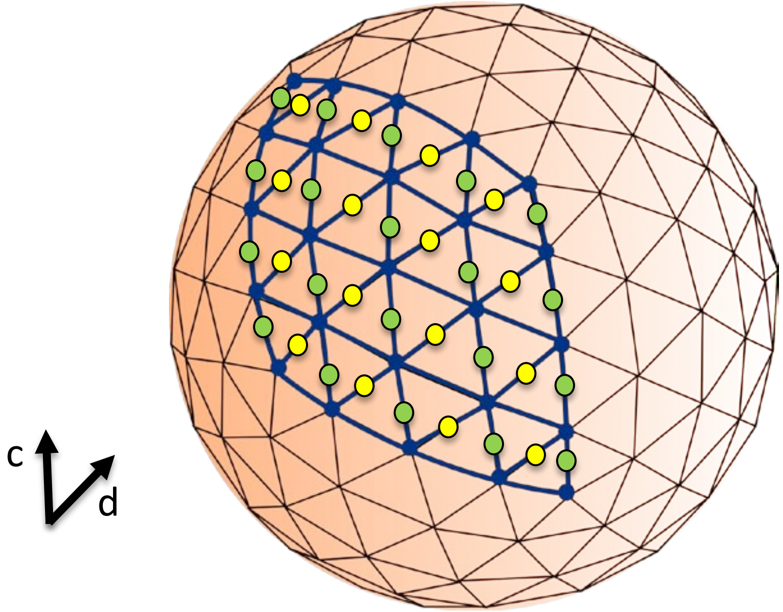

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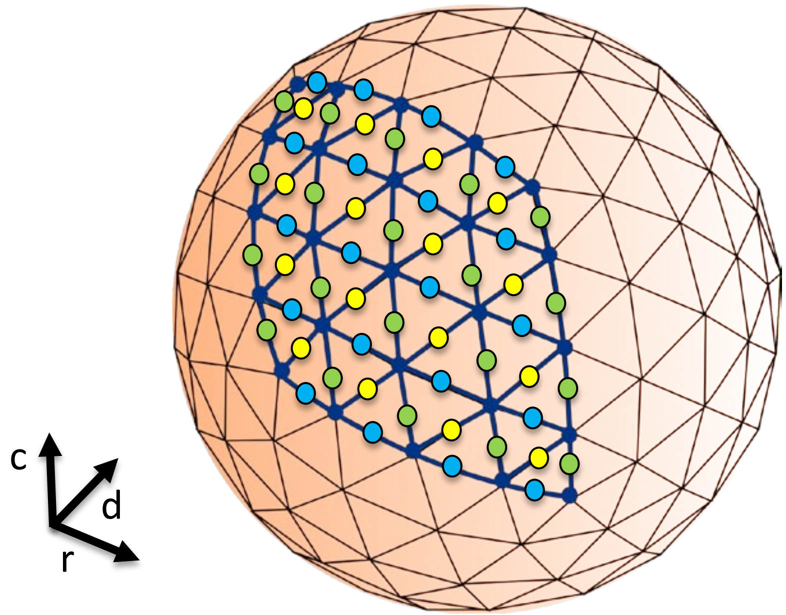

Mapping Technique

2 Mapping Centroids of Quads:

– Modified hexagonal fan.

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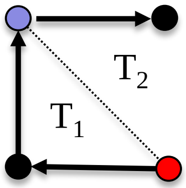
- *Example:*



2 **Mapping Centroids of Quads:**

- Modified hexagonal fan.
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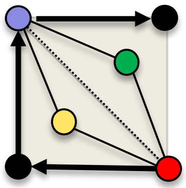

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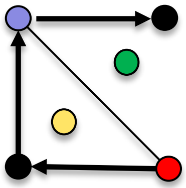

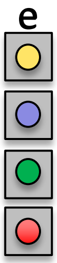

quad soup

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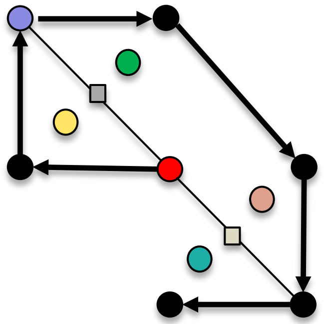
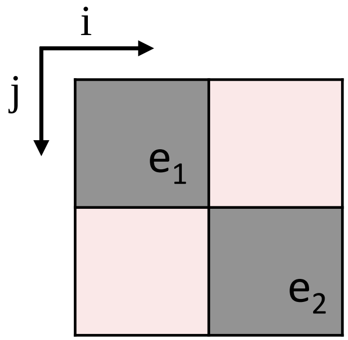
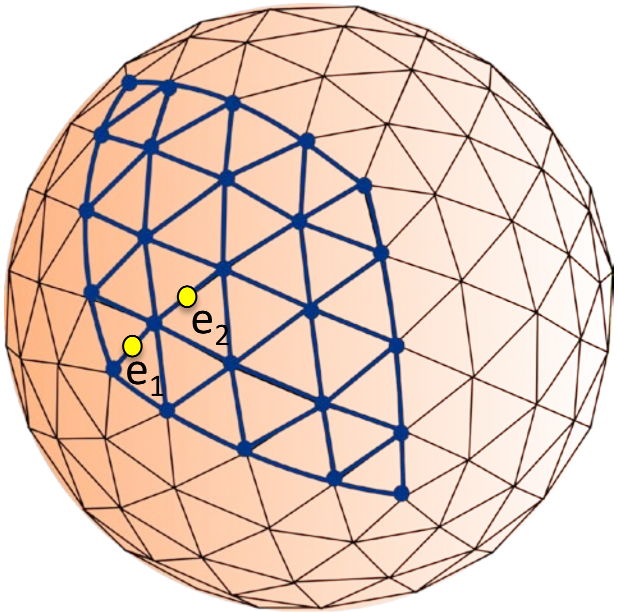


2 Mapping Centroids of Quads:

– Stored in array.



2D array



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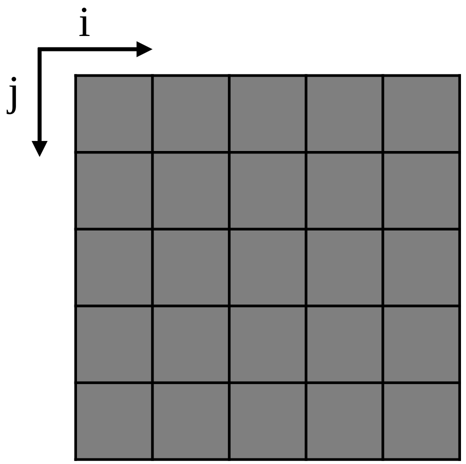
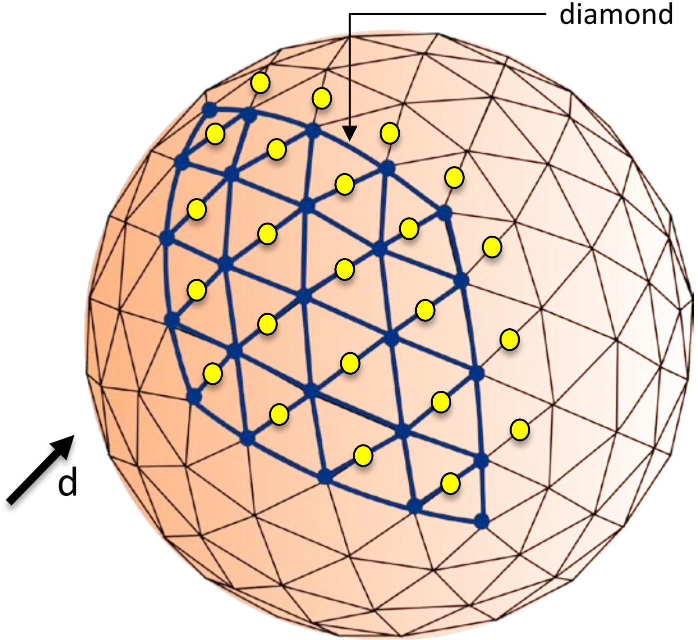
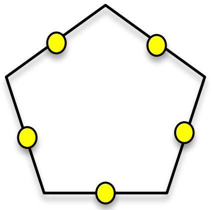


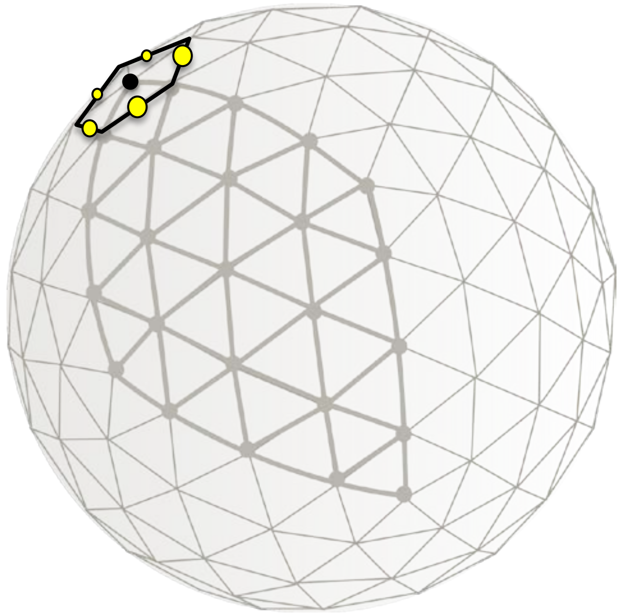
2D array



2 Mapping Centroids of Quads:

– At polar vertex :

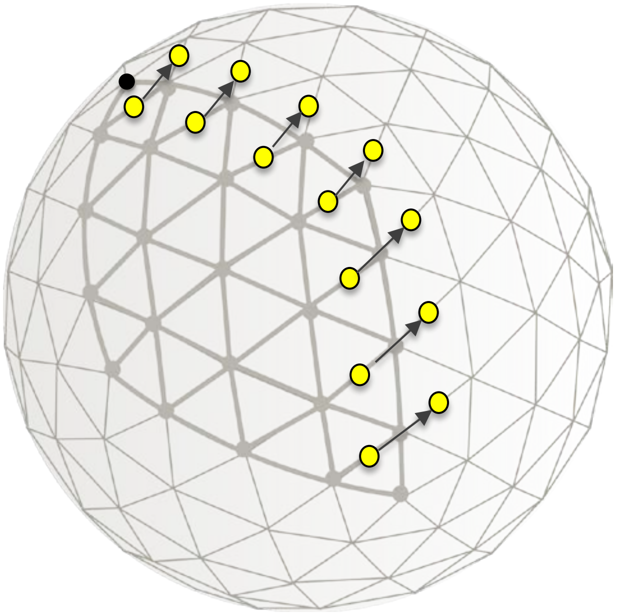




Mapping Technique

2 Mapping Centroids of Quads:

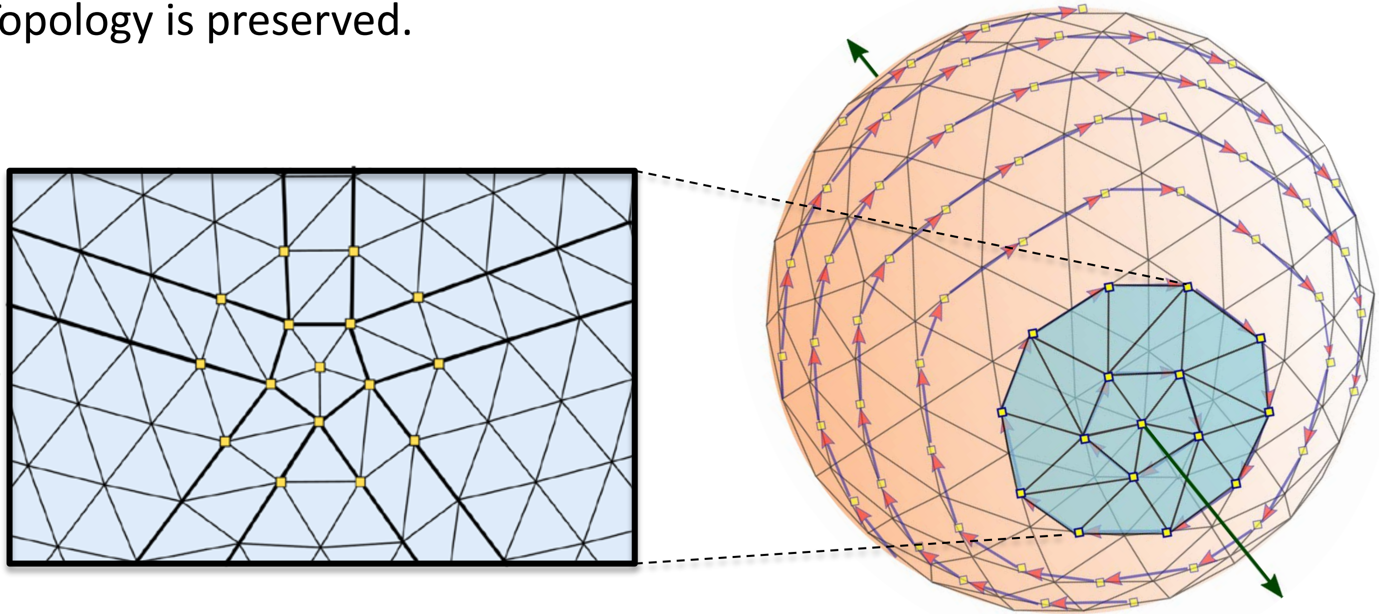
- Need to access adjacent diamond.



Mapping Technique

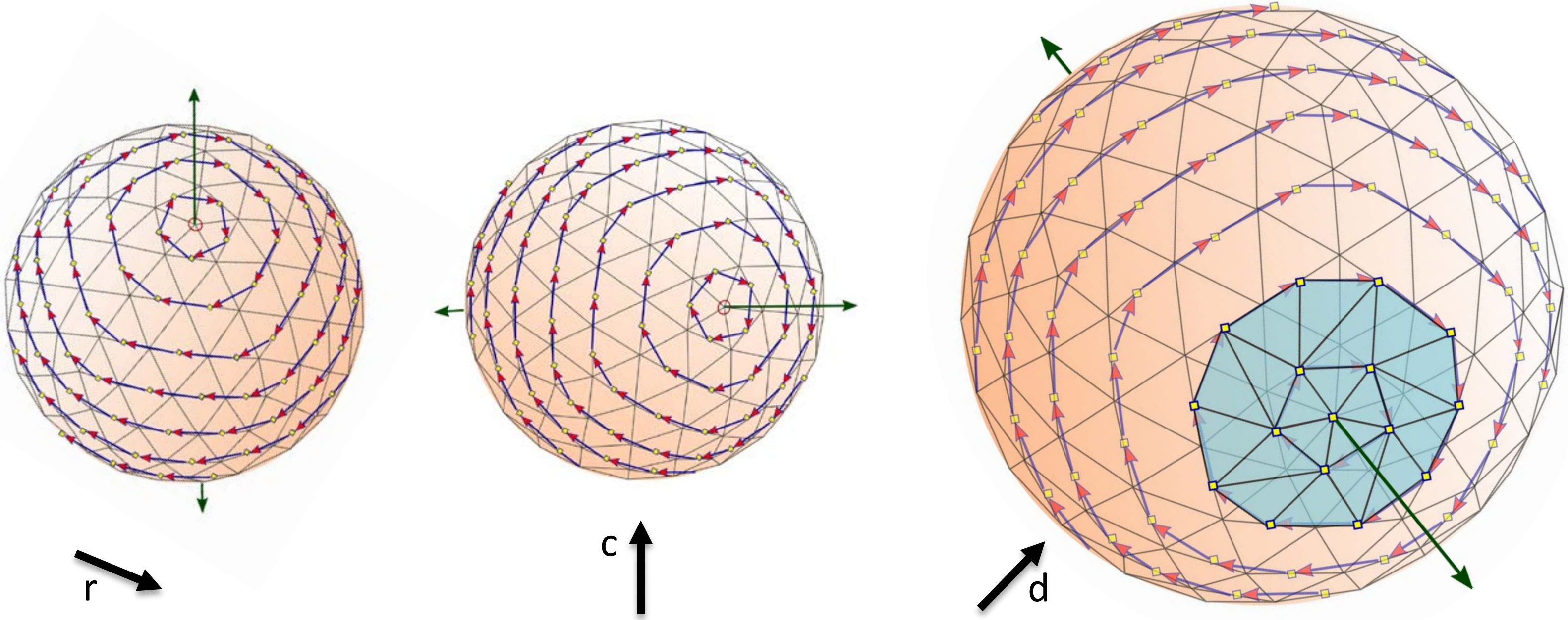
2 Mapping Centroids of Quads:

- Minor irregularity at border.
- Topology is preserved.



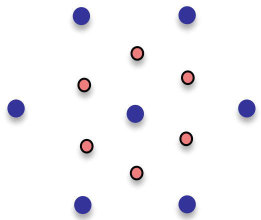
2 Mapping Centroids of Quads:

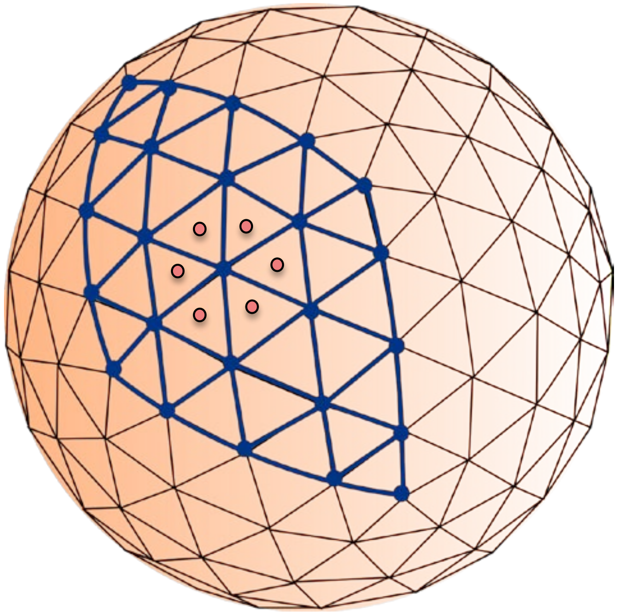
— Along other directions:



3 Mapping Centroids of Triangle:

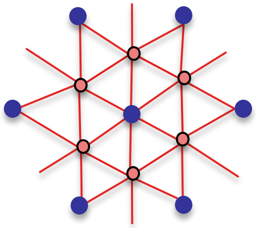
– The primal cells.

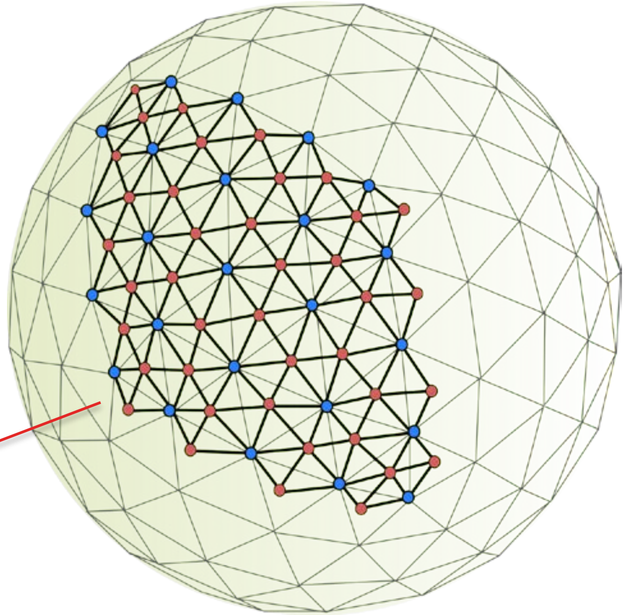




3 Mapping Centroids of Triangle:

- Connecting vertices with centroids.
- Splitting into triangle.

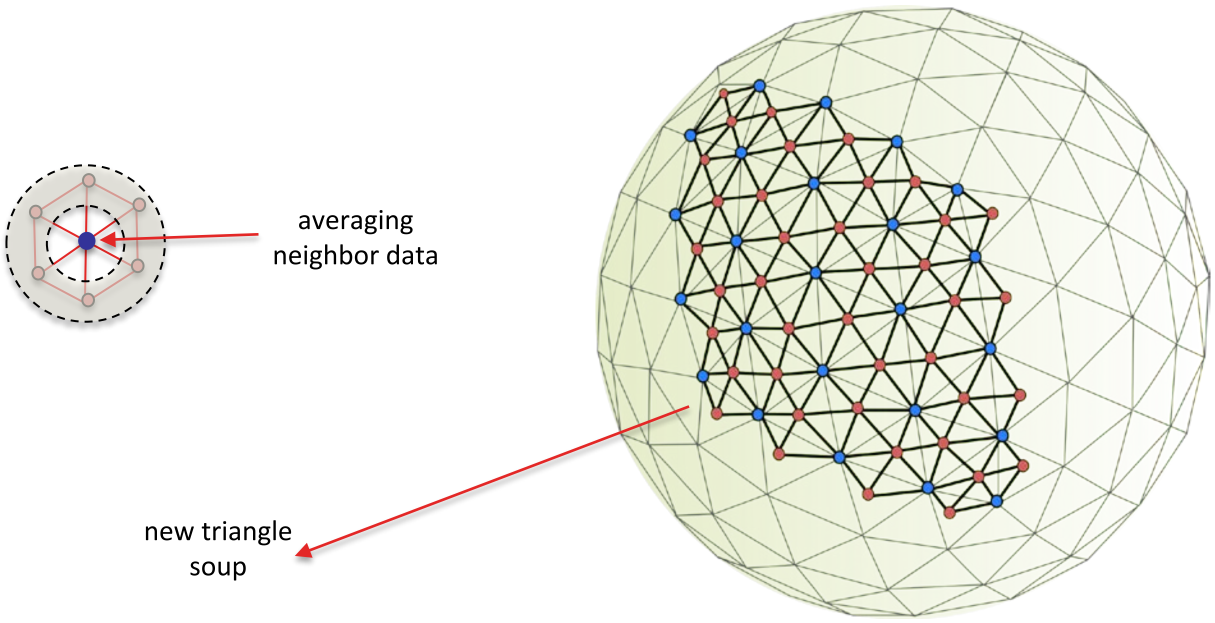




new triangle soup

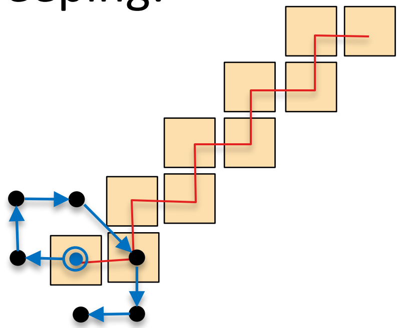
3 Mapping Centroids of Triangle:

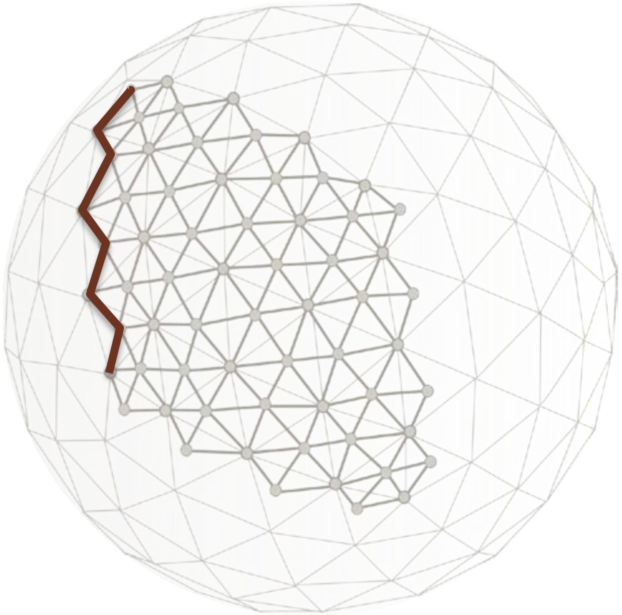
— Data at the vertices are assigned.



3 Mapping Centroids of Triangle:

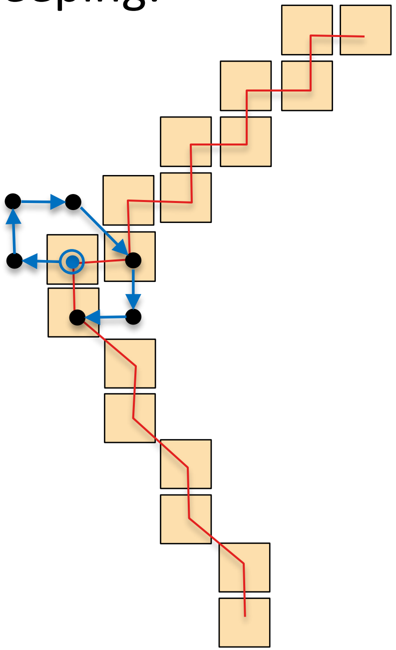
— Fan sweeping:

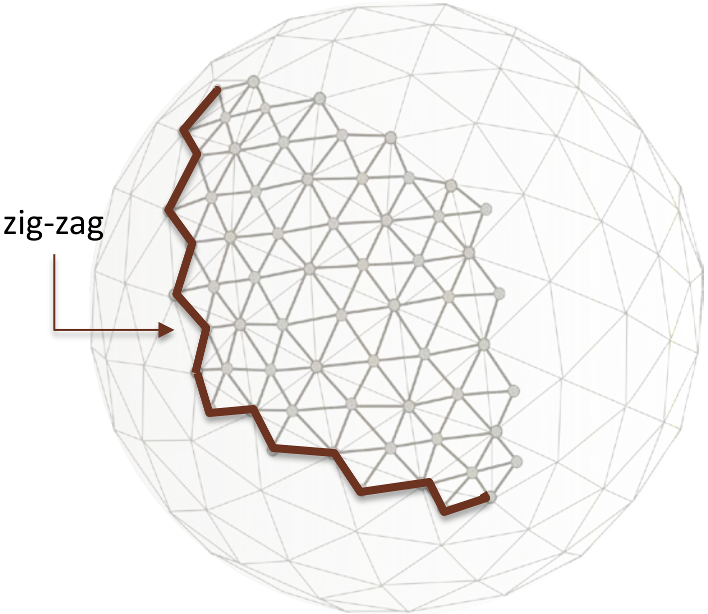




3 Mapping Centroids of Triangle:

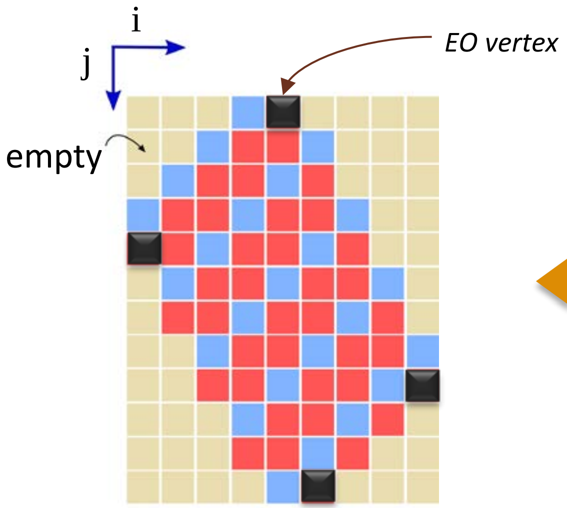
- Fan sweeping:

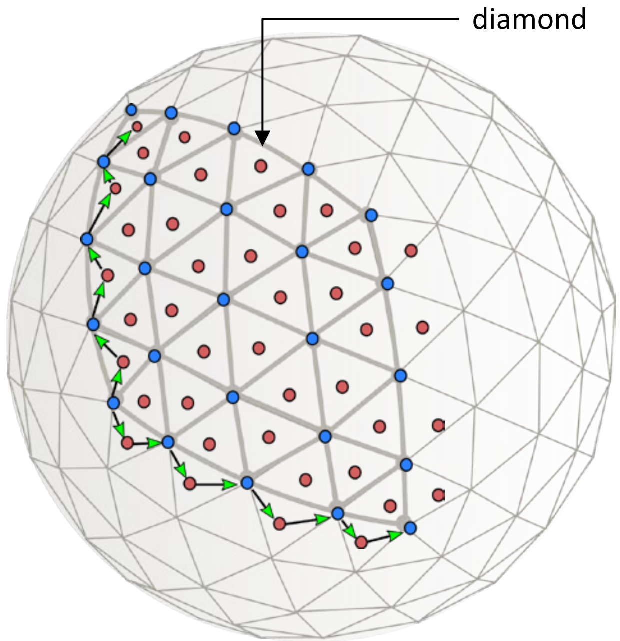




3 Mapping Centroids of Triangle:

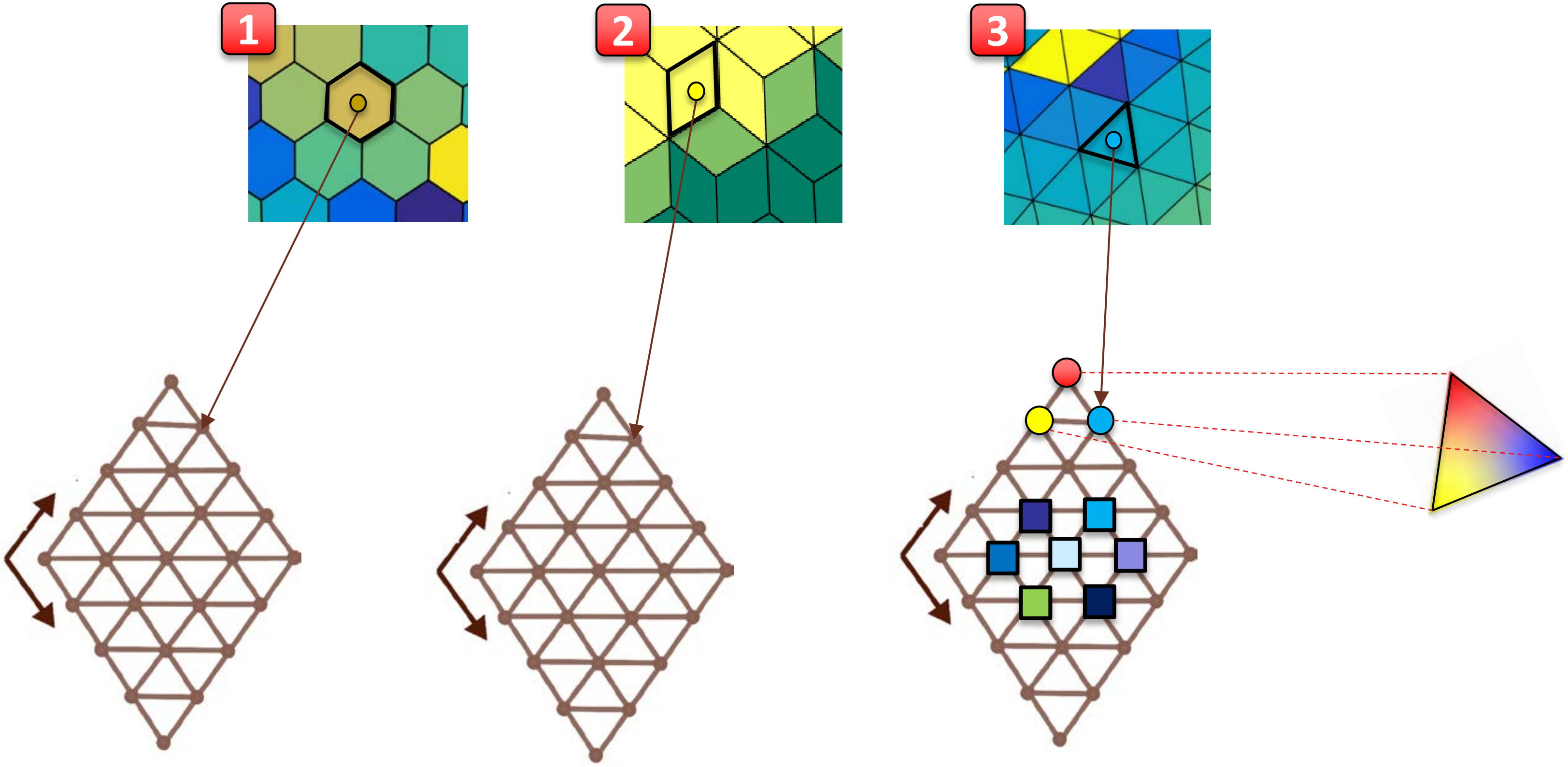
– Array has null entries.





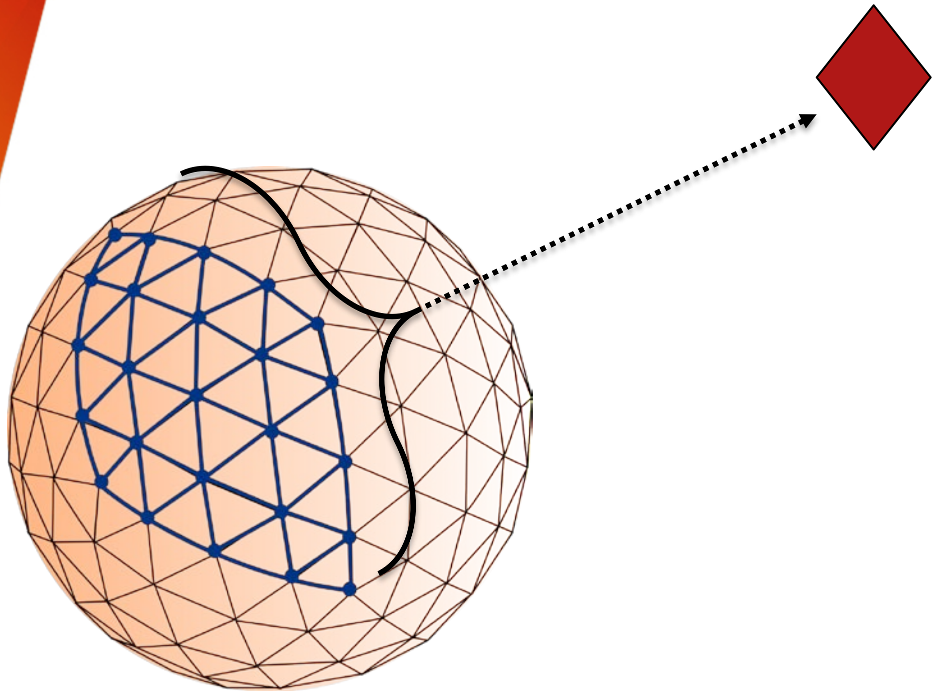
SUMMARY OF ICOSAHEDRAL MAPS

Mapping to a 2D structure



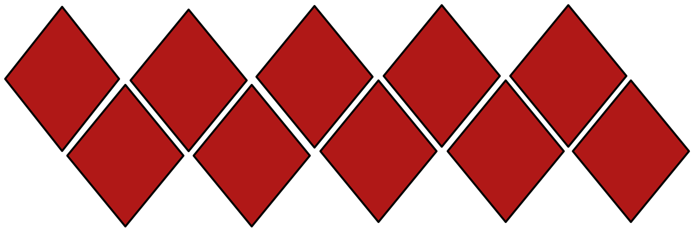
Diamonds

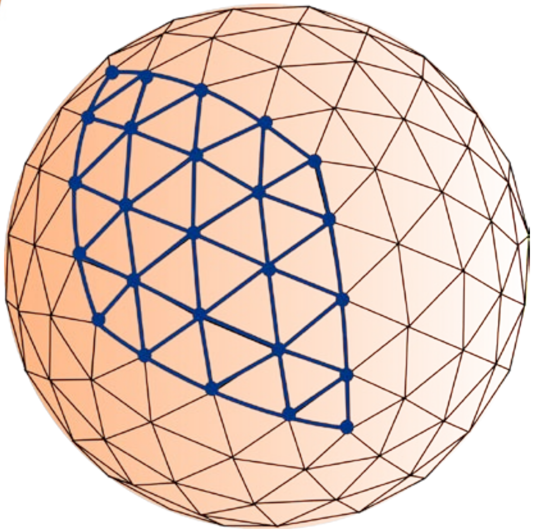
Mapping technique extract a diamond.



Diamonds

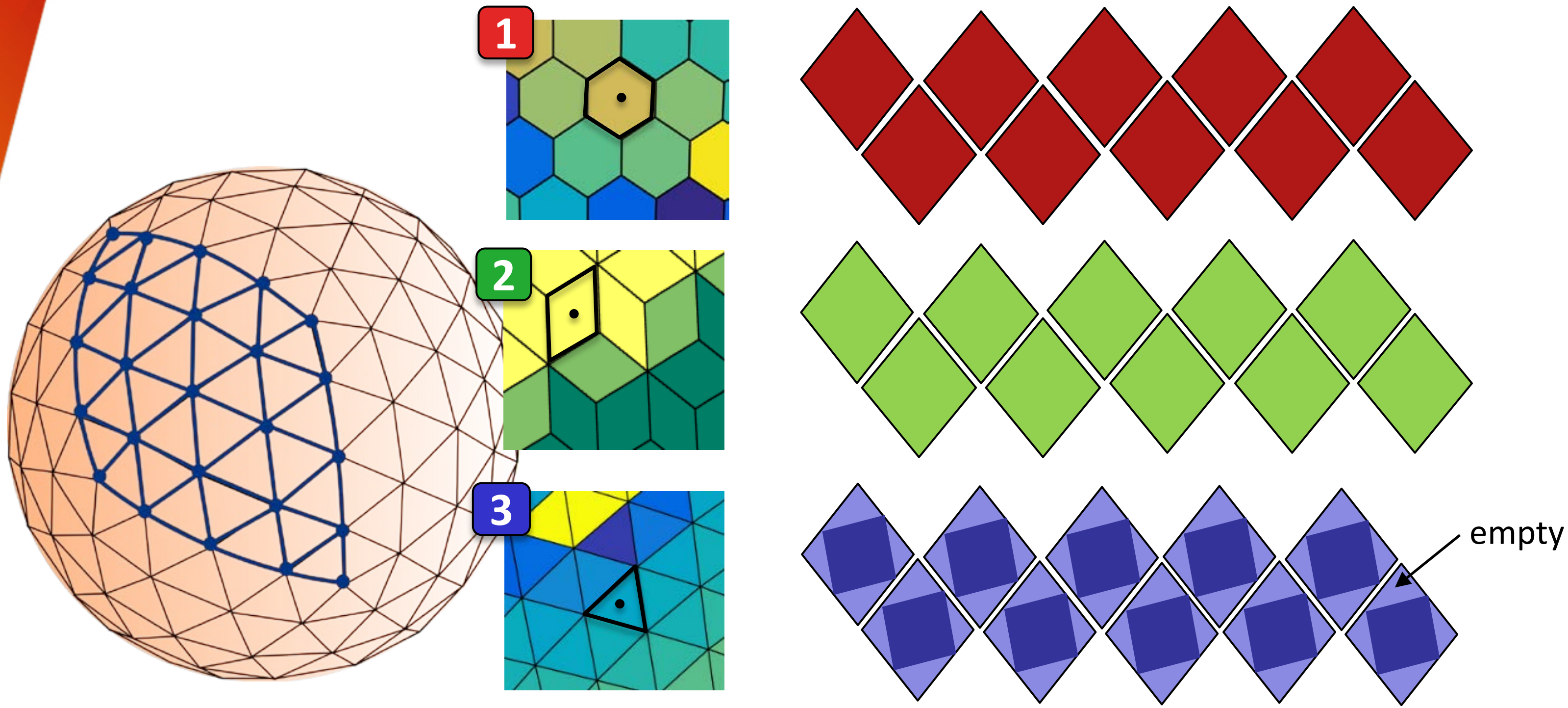
For entire Earth: total 10 diamonds.





Diamonds

For entire Earth: total 10 diamonds. [for every cell-types]



METHODOLOGY

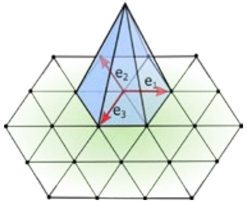
Multiresolution

Discrete Hexagonal Wavelet

- **Hexagonal Wavelet bases** [*Cohen & Schlenker '93*]

  A linear approximation of the data is obtained by linear box spline.

$$f(\mathbf{x}) = \sum_{\mathbf{k}} \overbrace{F[\mathbf{k}]}^{\text{data}} \overbrace{\varphi(\mathbf{x} - \mathbf{L}\mathbf{k})}^{\text{box spline}}$$



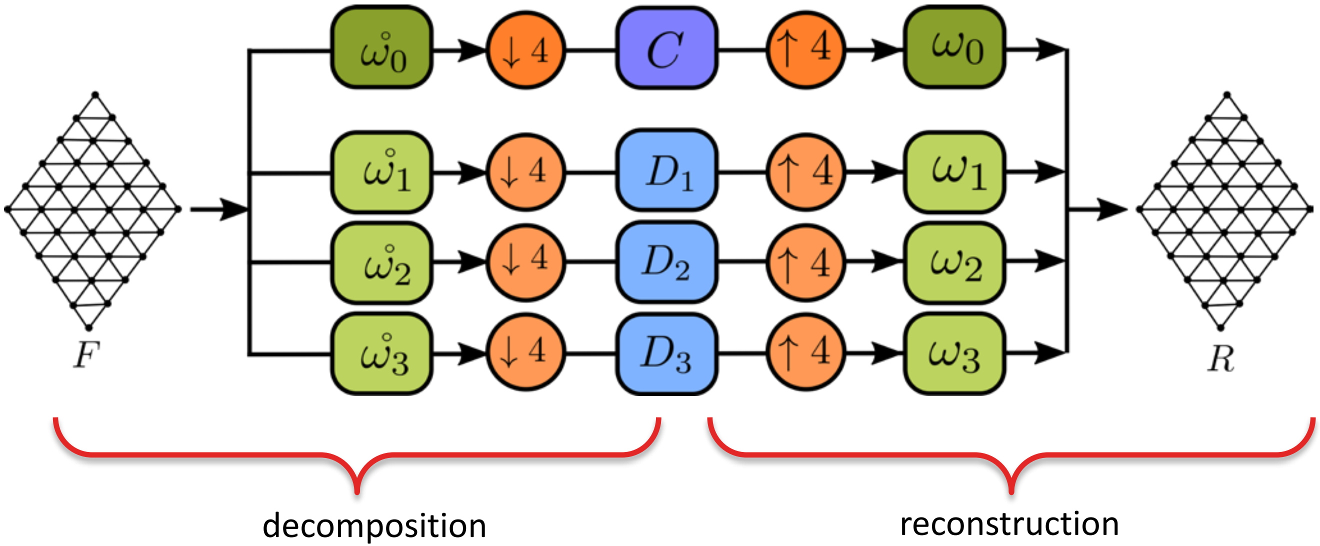
linear box spline

- Coarse-to-fine reconstruction:

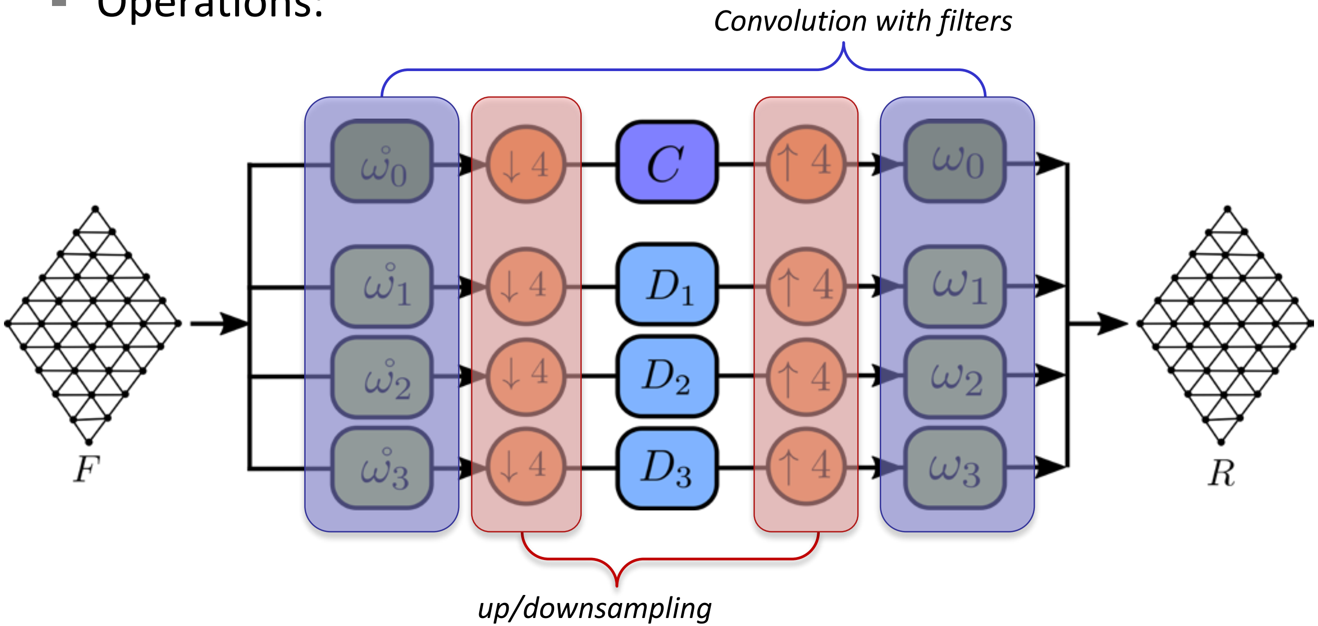
$$f(\mathbf{x}) = \sum_{\mathbf{k}} \overbrace{C[\mathbf{k}]}^{\text{coarse}} \varphi(\mathbf{x}/2 - \mathbf{L}\mathbf{k}) + \sum_{i=1}^{3} \sum_{\mathbf{k}} \overbrace{D_i[\mathbf{k}]}^{\text{details}} \underbrace{\psi_i(\mathbf{x}/2 - \mathbf{L}\mathbf{k})}_{\text{wavelet function}}.$$

MR Scheme

- **Sub-band coding scheme:**

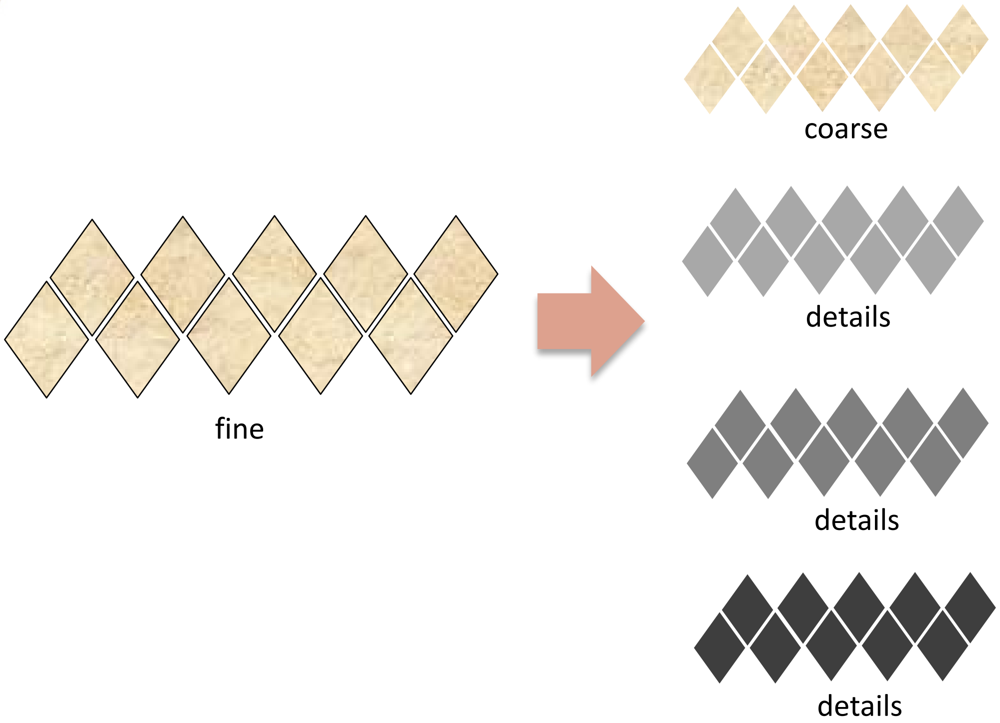


- **Sub-band coding scheme:**
  - Operations:



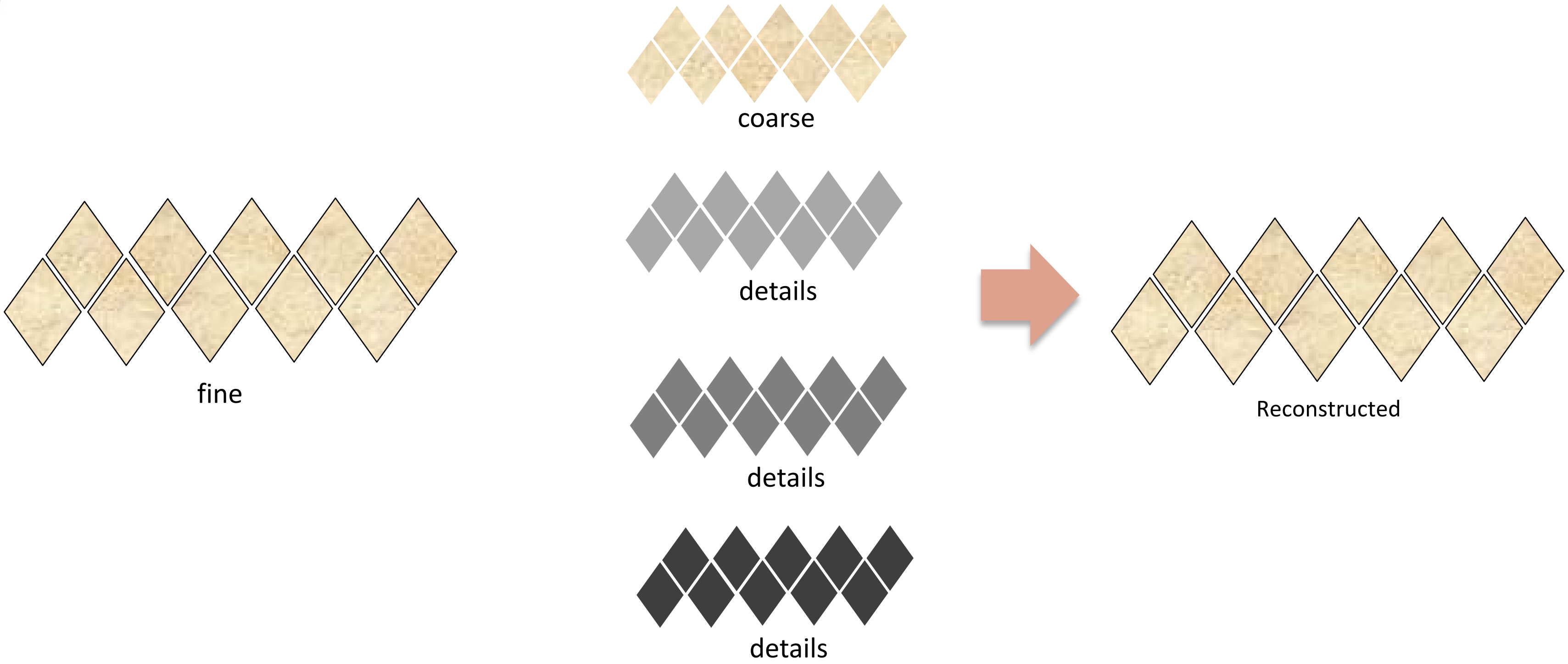
MR Scheme

- MR on icosahedral maps:



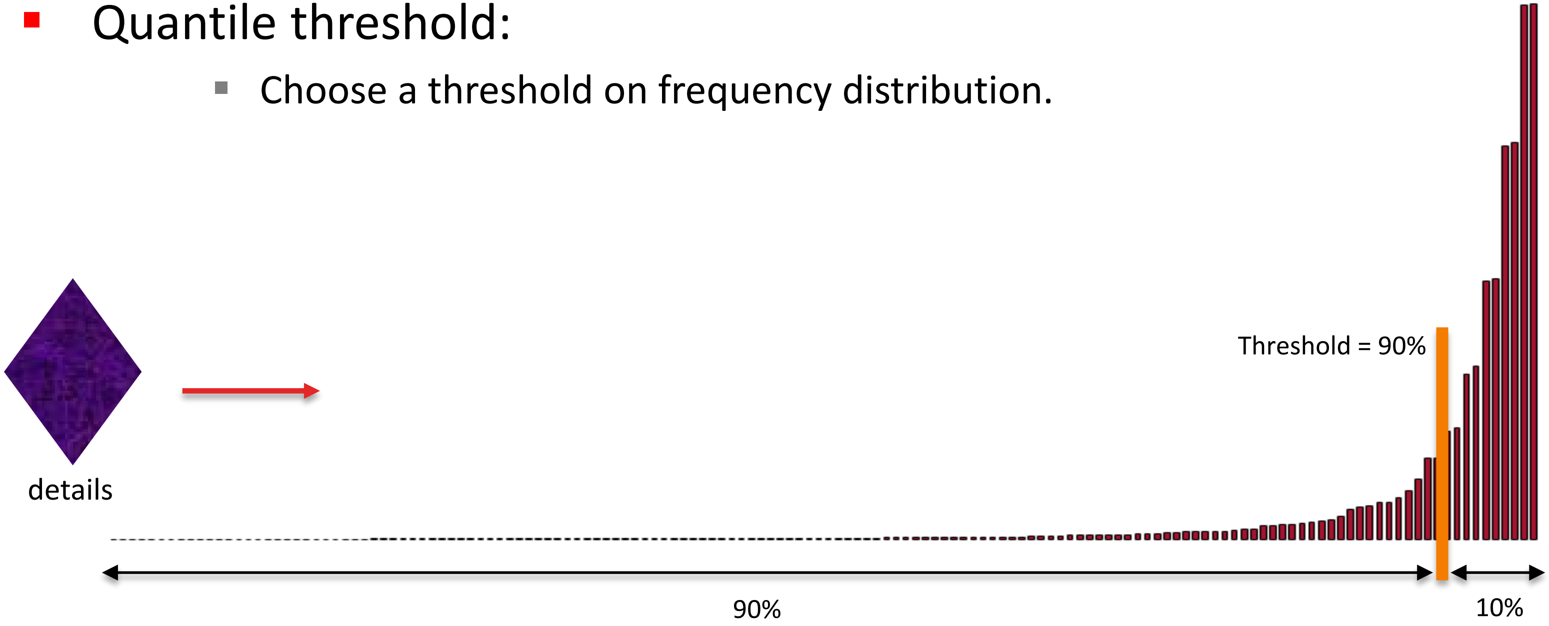
MR Scheme

- MR on icosahedral maps:



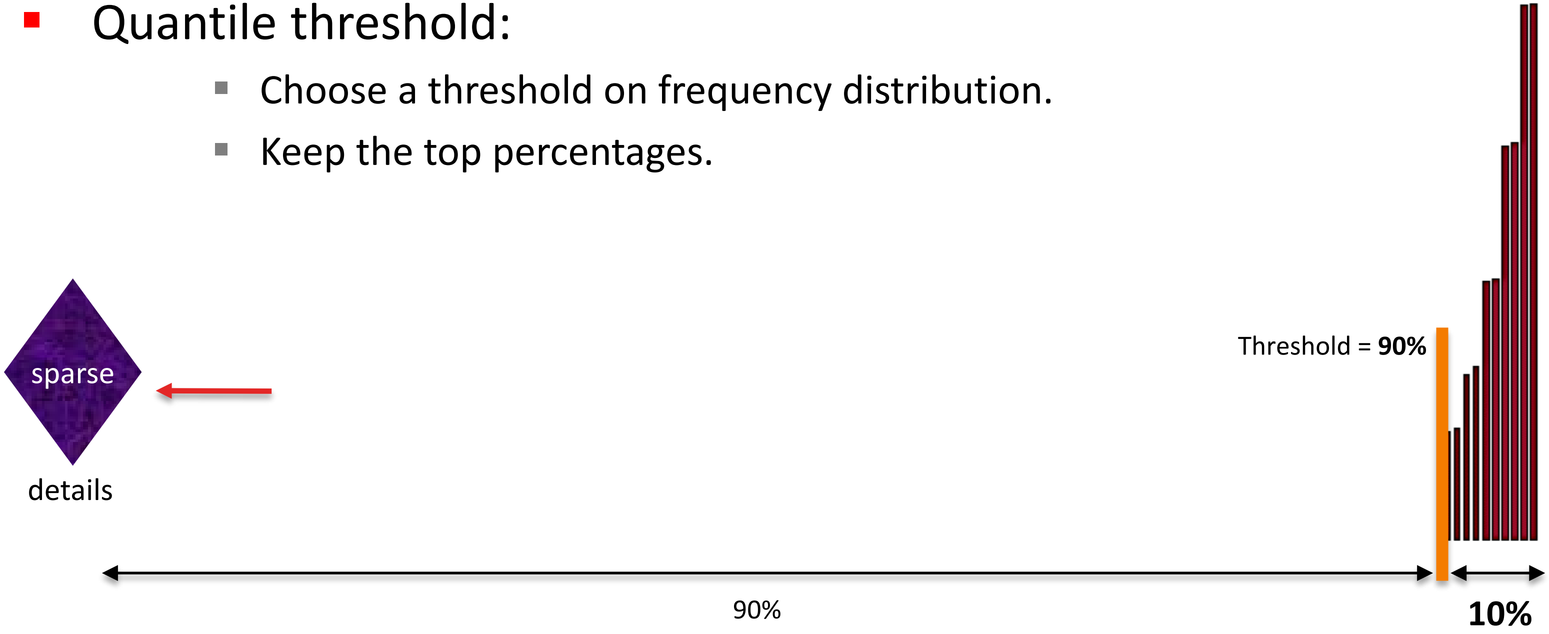
Compression

- Removing details with less energy
- Quantile threshold:
  - Choose a threshold on frequency distribution.



Compression

- Removing details with less energy
- Quantile threshold:
  - Choose a threshold on frequency distribution.
  - Keep the top percentages.

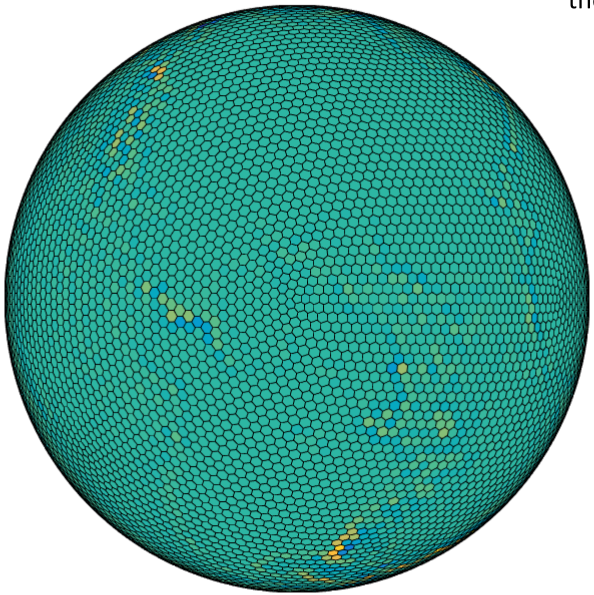


RESULTS

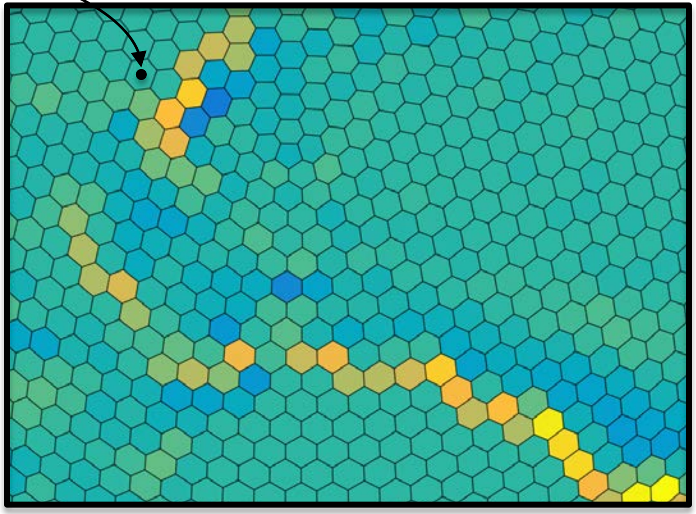
Visual Results: ICON Data

INPUT

Hexagonal cells



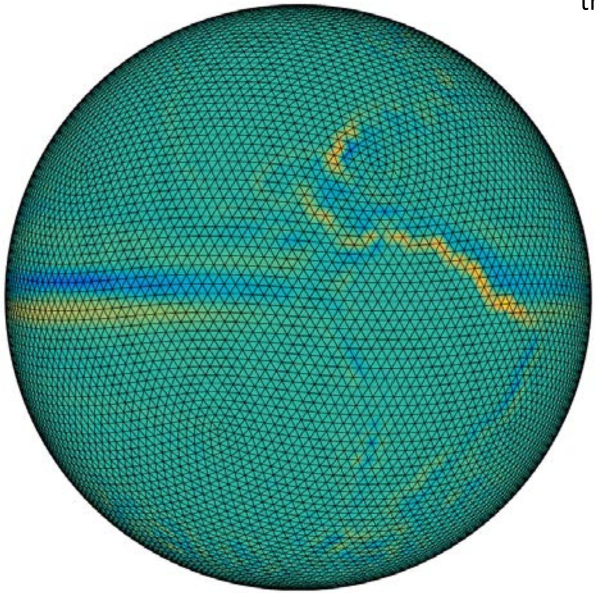
where data is at the **centroids of hexagons**



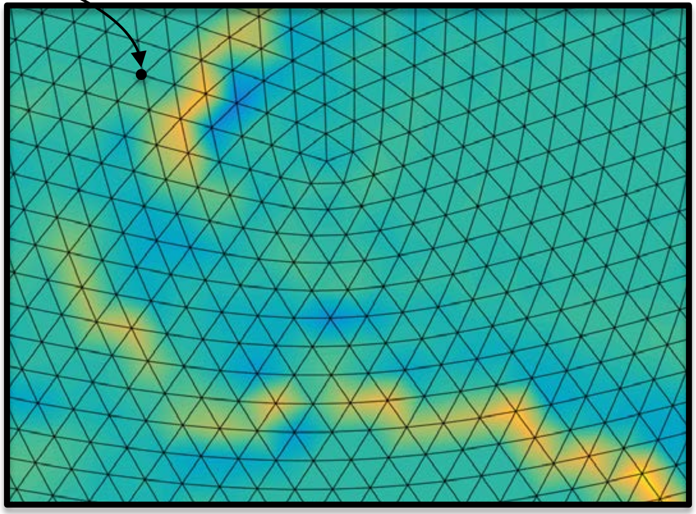
Visual Results: ICON Data

OUTPUT of ICOSAHEDRAL MAPS

Triangle Grid



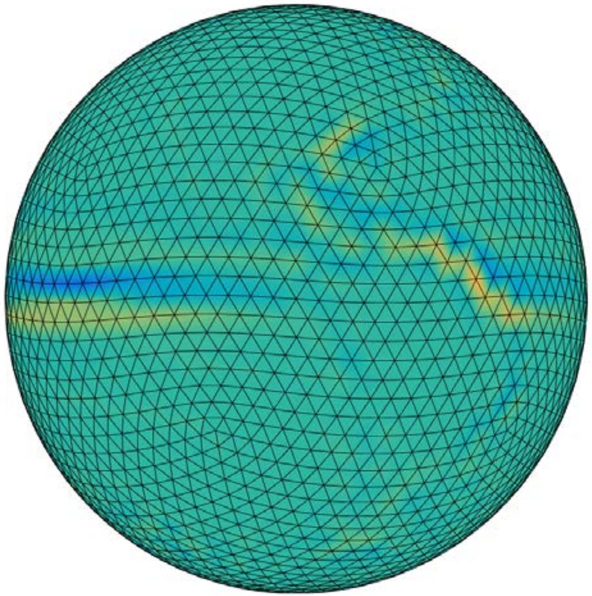
where data is at the **vertices of triangles**

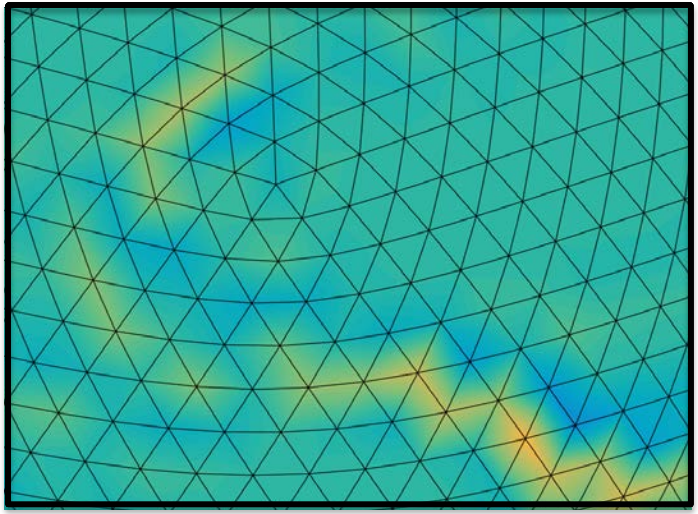


Visual Results: ICON Data

MR on ICOSAHEDRAL MAPS

Coarse Level

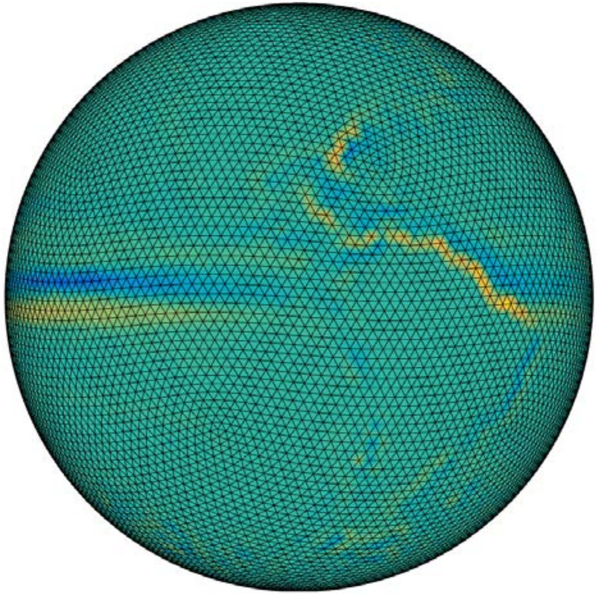


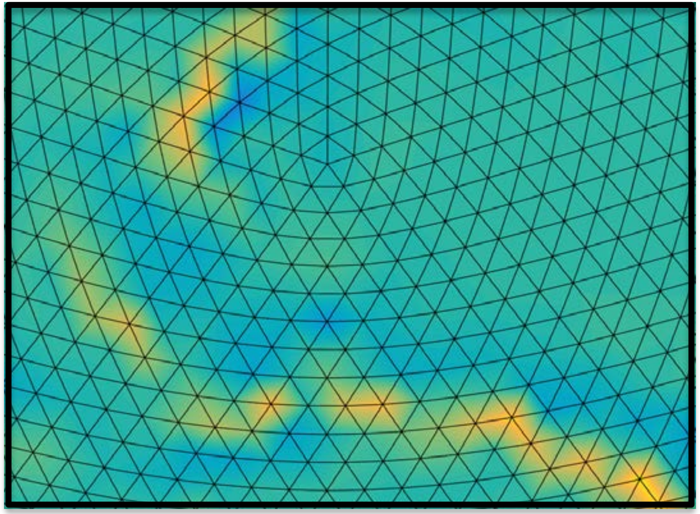


Visual Results: ICON Data

MR on ICOSAHEDRAL MAPS

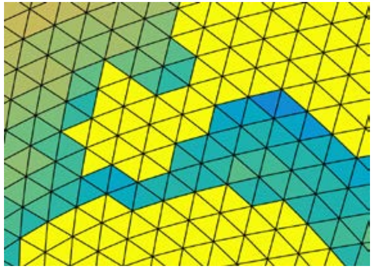
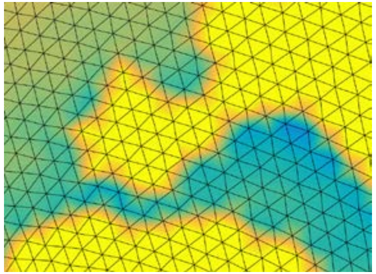
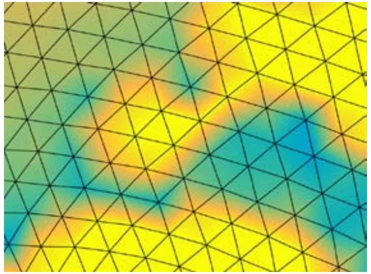
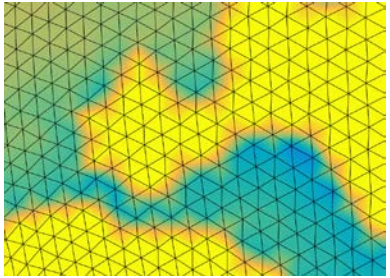
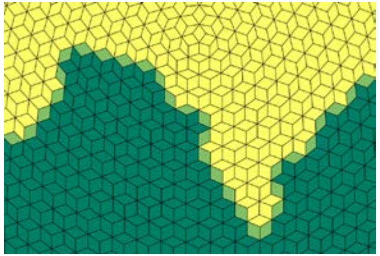
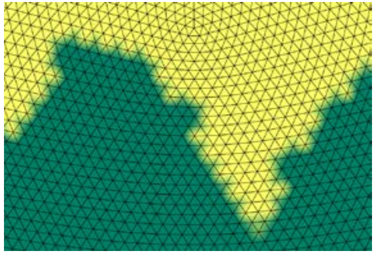
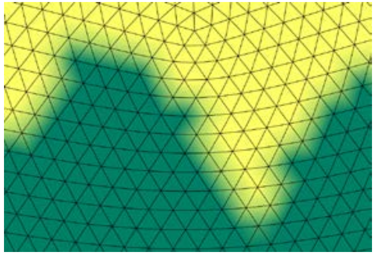
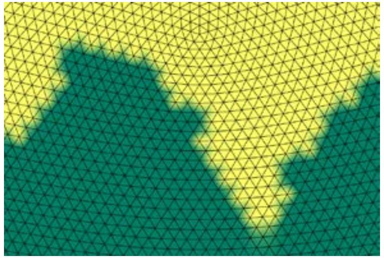
Reconstructed *(Threshold = 90%)*



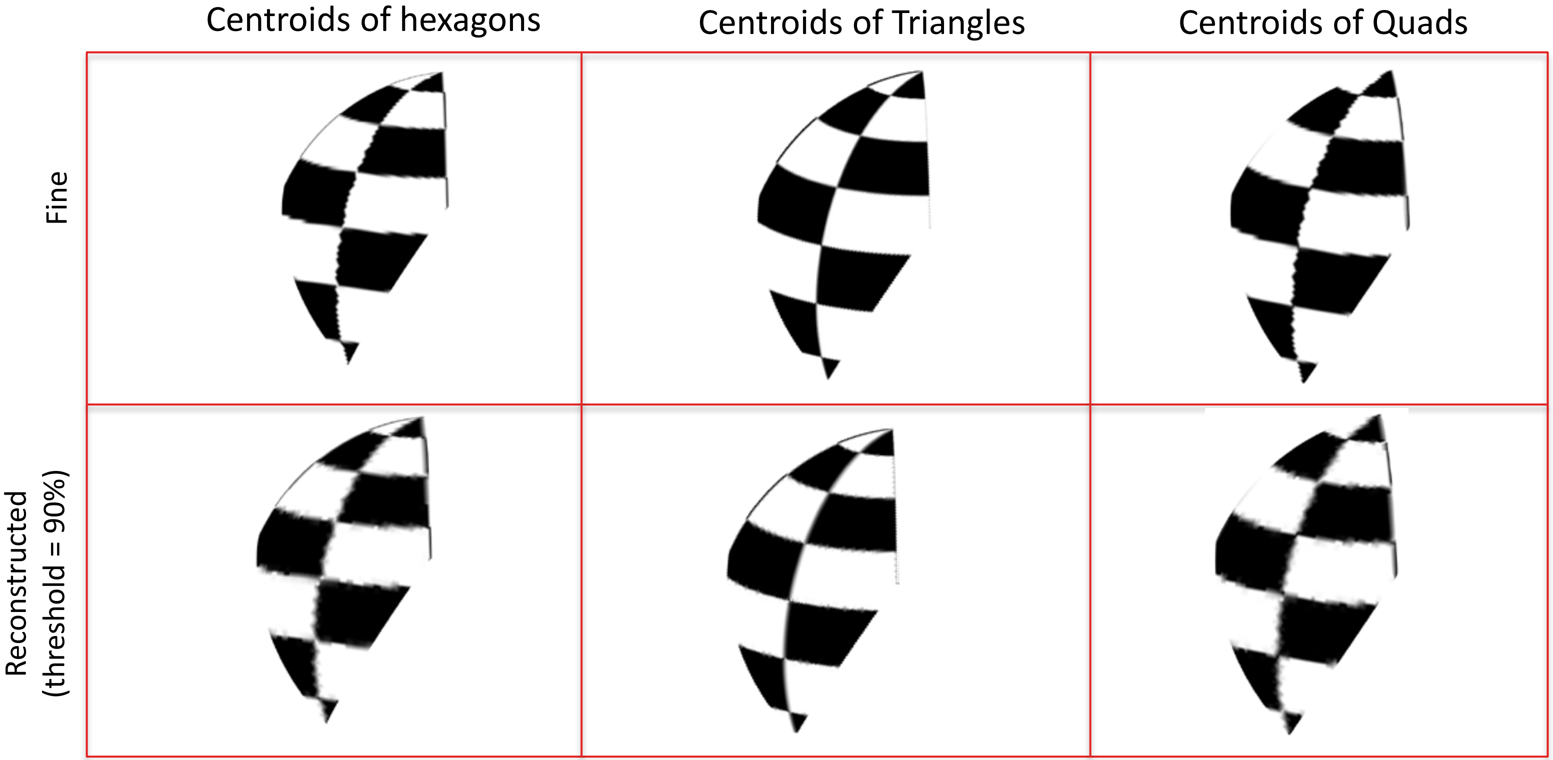


Visual Results: ICON Data

- **Other cells :**

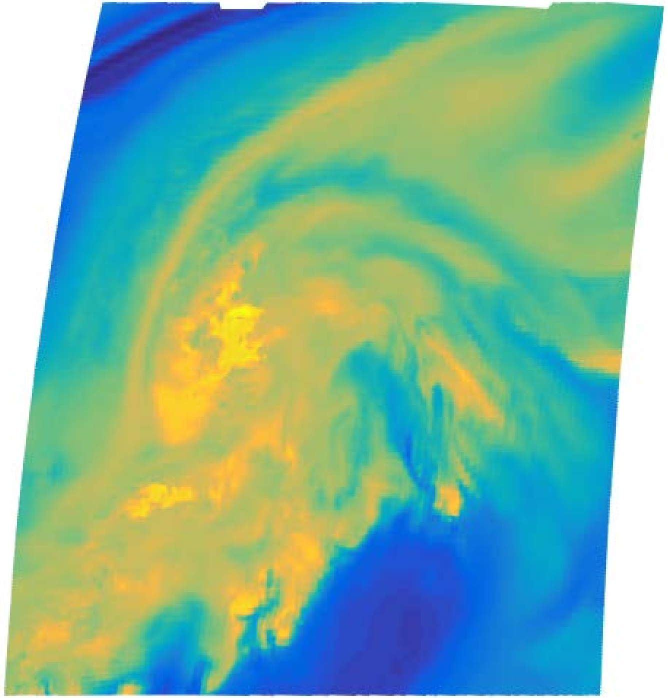
	Input cell	Icosahedral Maps: Triangle grid	MR: Coarse level	MR: Reconstructed (threshold = 90%)
Centroids of Triangles				
Centroids of Quads				

Visual Results: Synthetic Data



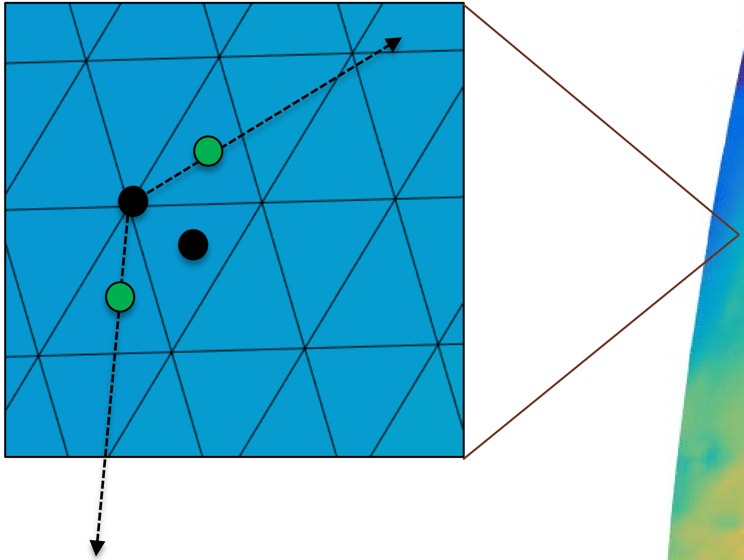
ICON Data (slice)

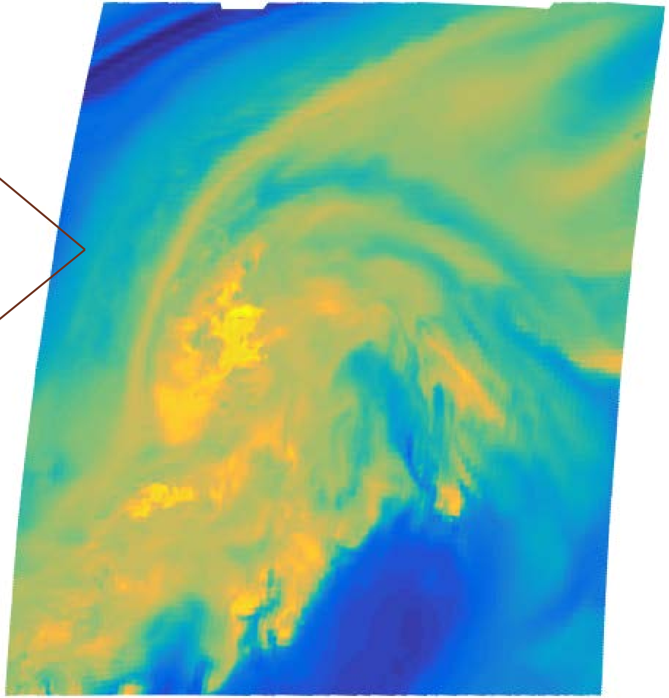
- We focused only on the centroids of the primal cells (triangles).
- **Challenges:**
  - number of EO vertices is not 12.
  - no stopping conditions for fan sweeping.



Hurricane data

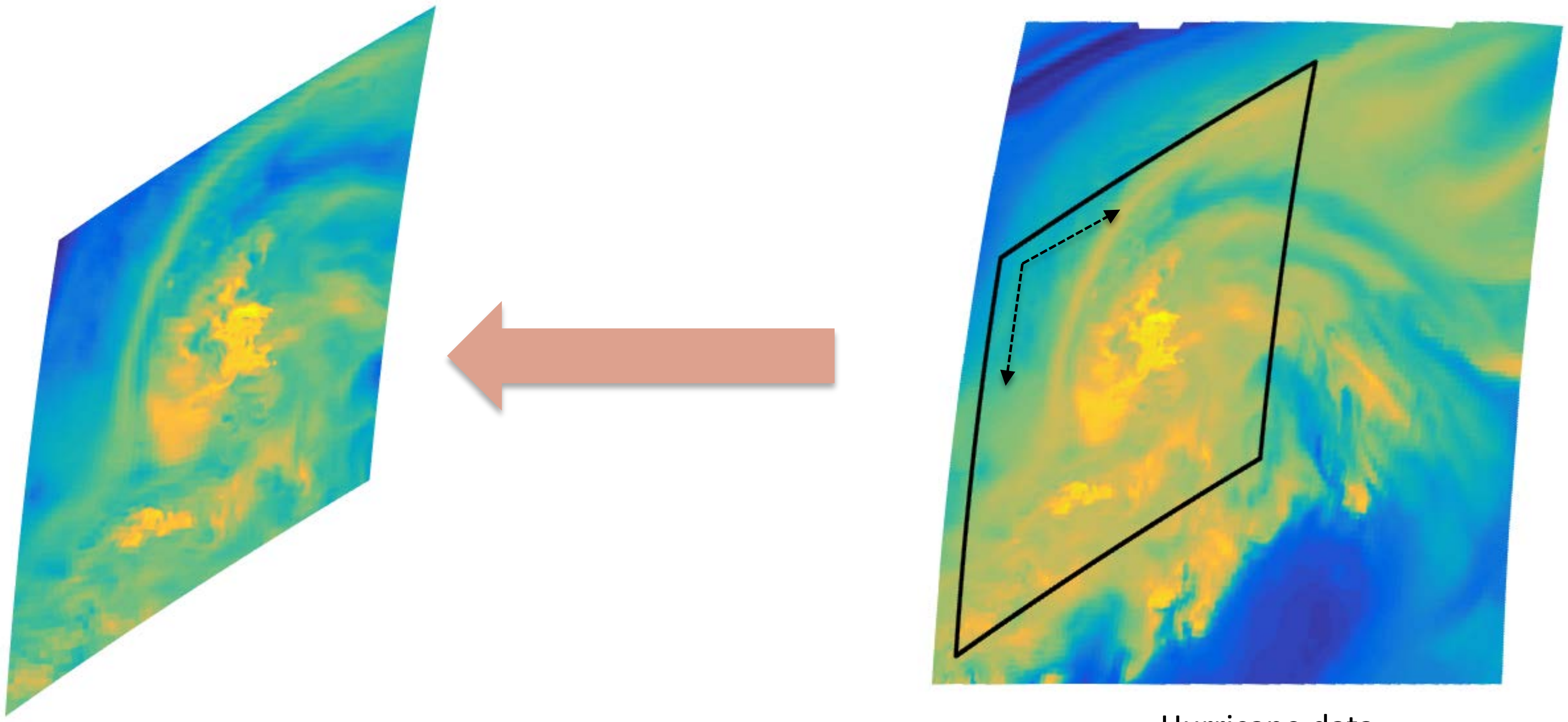
ICON Data (slice)





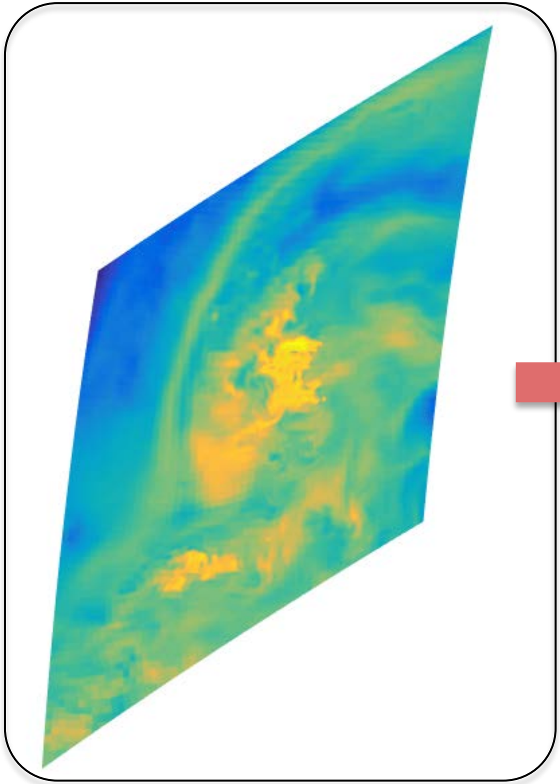
Hurricane data

ICON Data (slice)

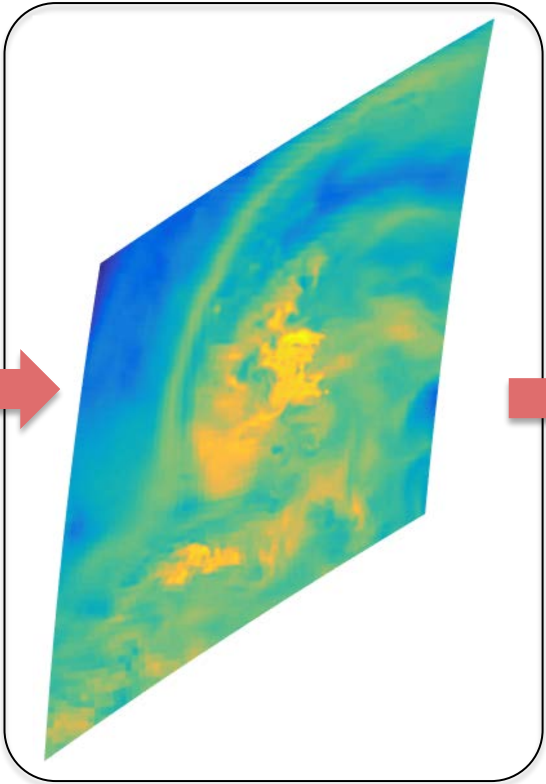


Hurricane data

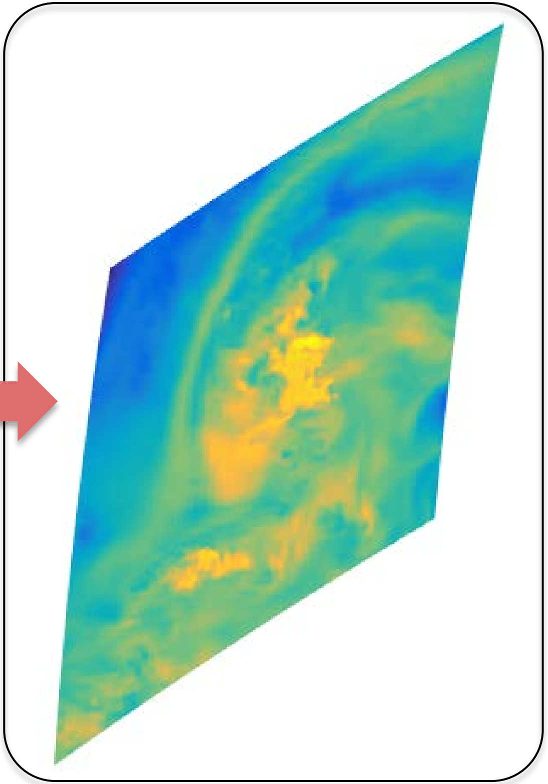
ICON Data (slice)



Fine

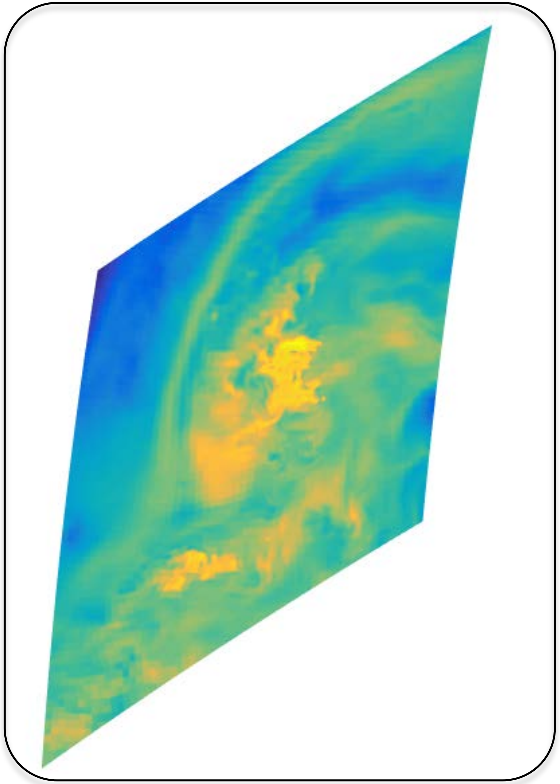


Coarse (LoD-1)

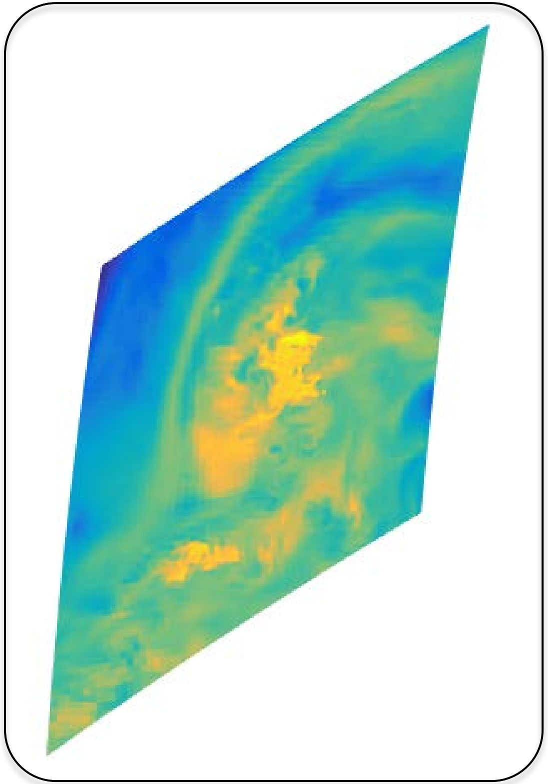


Coarse (LoD-2)

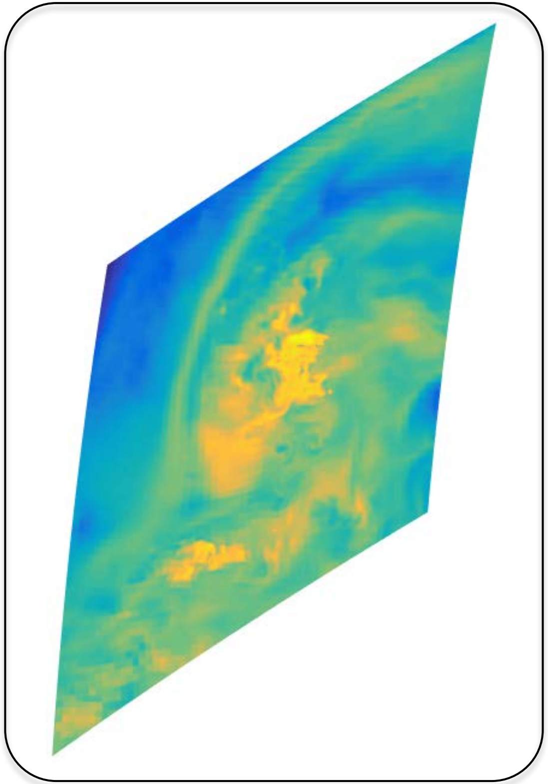
ICON Data (slice)



Fine

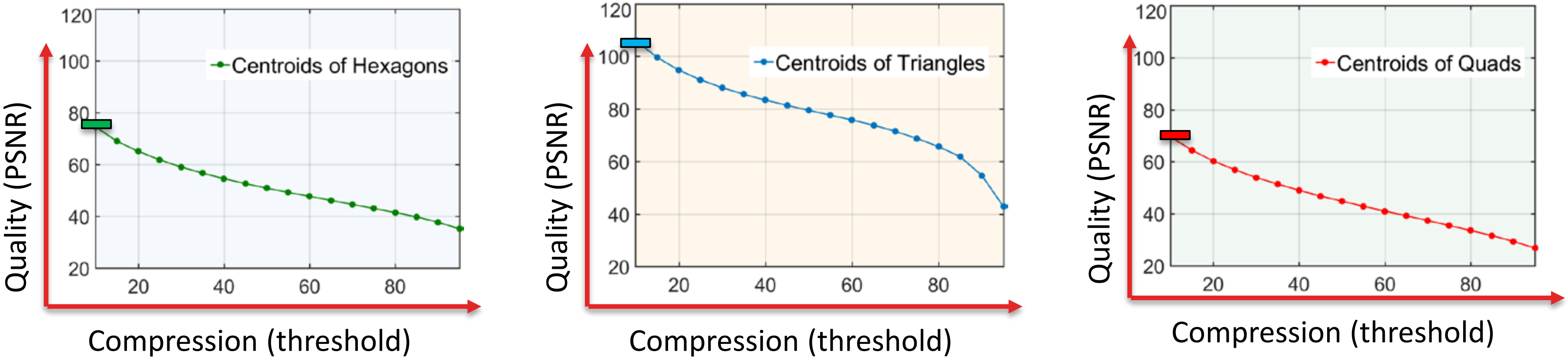


Reconstructed



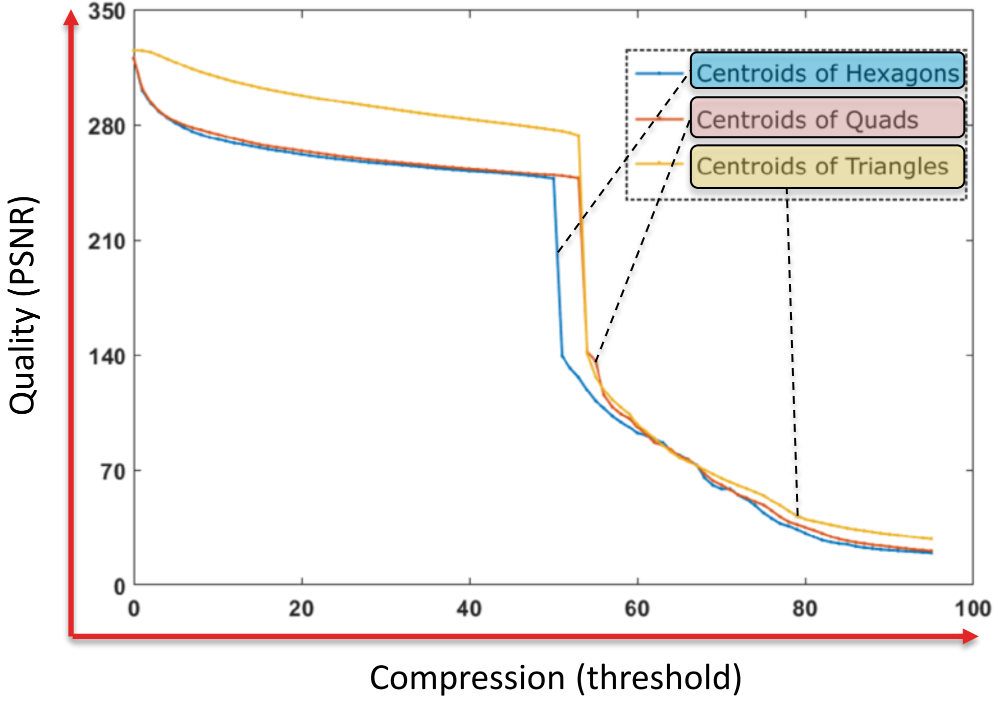
Reconstructed (90%)

- **Quality vs. Compression:** (ICON Data)



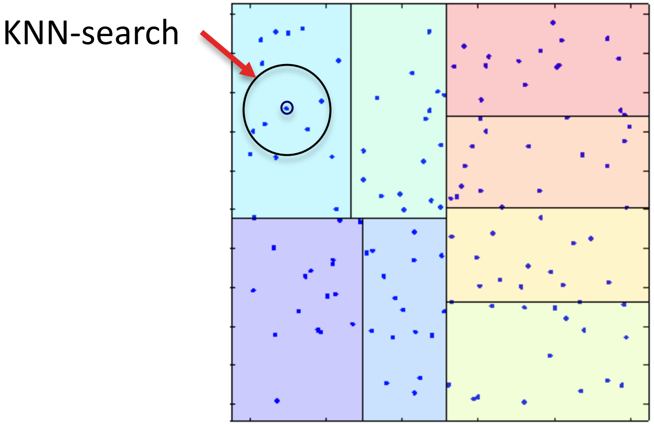
Quantitative Results

- **Quality vs. Compression:** (Synthetic Data)

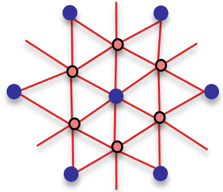


Optimization

- KD – tree.
- KNN –search.
- 1-to-3 refinement parallel.
- Hexagonal fan searches locally.



KD-tree



1-to-3 refinement

CONCLUSION

Contribution

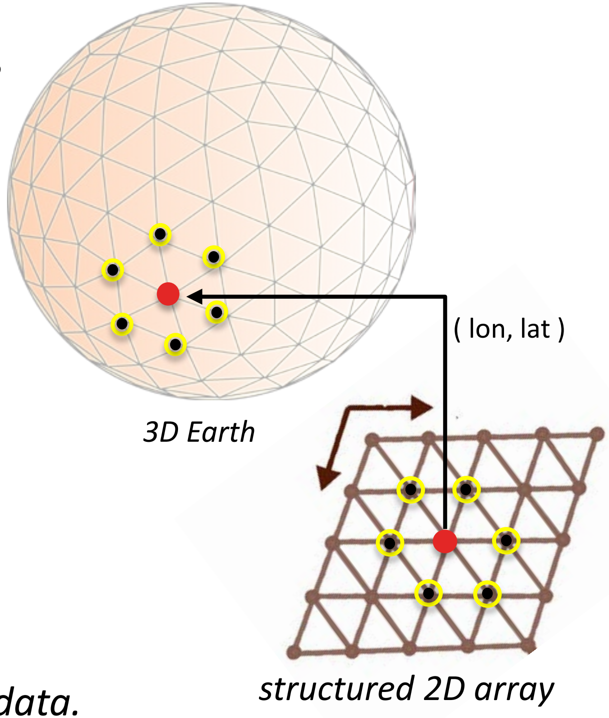
Icosahedral Maps:

Maps connectivity information for all three cell-types into to a structured grid representation.

Icosahedral Maps:

Maps connectivity information for all three cell-types into to a structured grid representation.

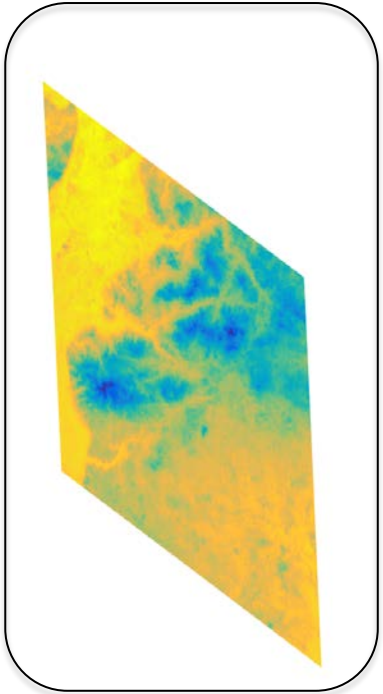
- Neighboring information is easy to access simply using indexing. Operations involved in MR is straightforward.
    - *Convolution*
    - *Downsample and Upsample*
- GPU friendly because our 2D representation -
    - ✓ *is easily fit into the GPU using textures.*
    - ✓ *allows to use barycentric interpolation for all types of data.*



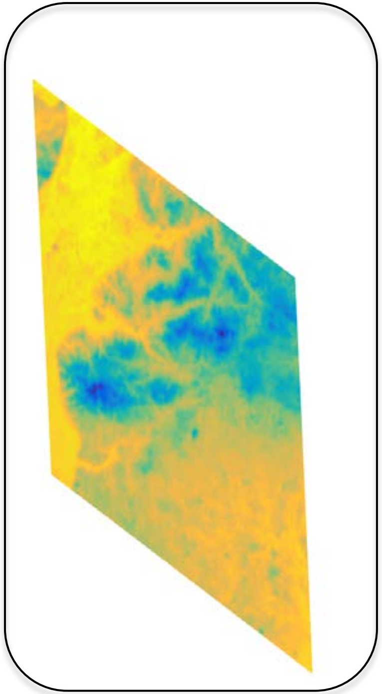
Contribution

Level-of-Detail representation of Earth data:

- Applying a hexagonal wavelet scheme on the icosahedral maps to render scalar data at a coarser resolution.
  - ✓ *save time*
- compression via thresholding.
  - ✓ *save space*



Rendered at fine level



Rendered at coarse (2nd level-of-detail)

Next Plan

- GPU Implementation.
- Mapping the whole slice into one single array.
    - This can be done by taking advantage of hexagonal fan traversal.

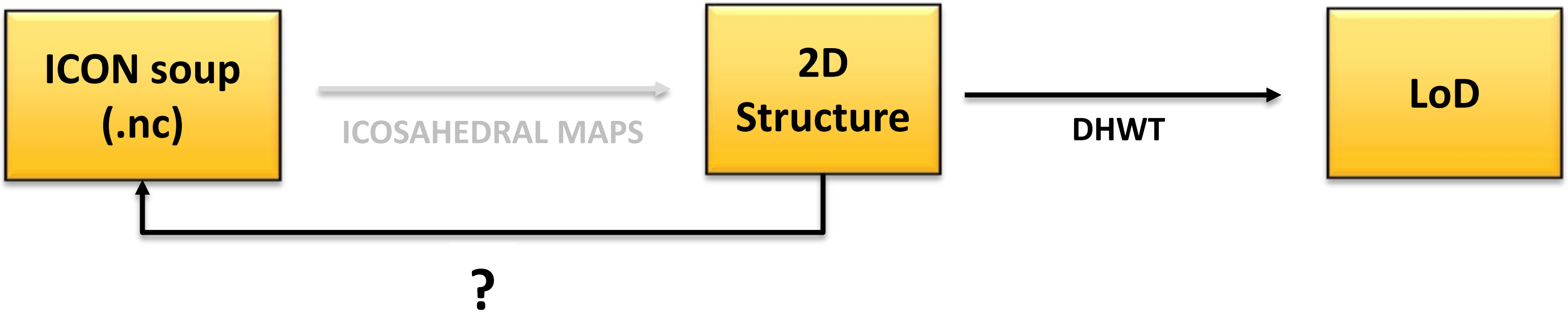
Conclusion

- Our pipeline:

$$\text{ICON soup (.nc)} \xrightarrow{\text{ICOSAHEDRAL MAPS}} \text{2D Structure} \xrightarrow{\text{DHWT}} \text{LoD}$$

Conclusion

- Question:



- Why does ICON come with soup structure?
- Is 2D structure possible? Any problem for simulation?

UNIVERSITY OF CALGARY

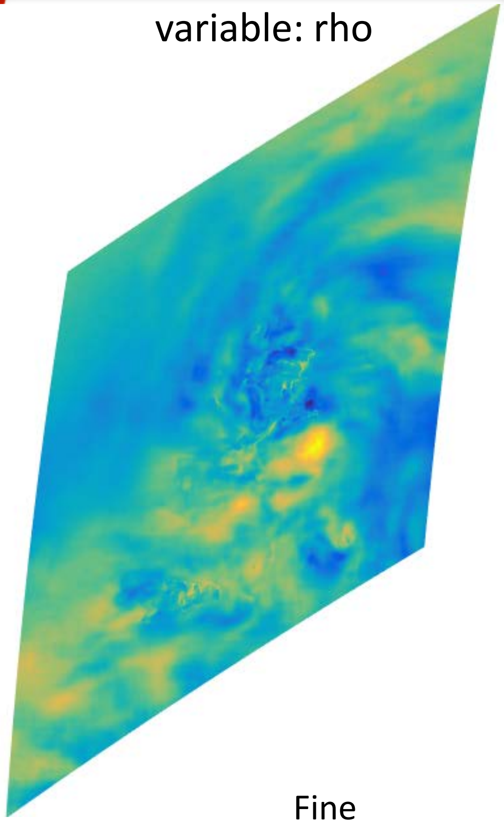
THANKS

QUESTION?

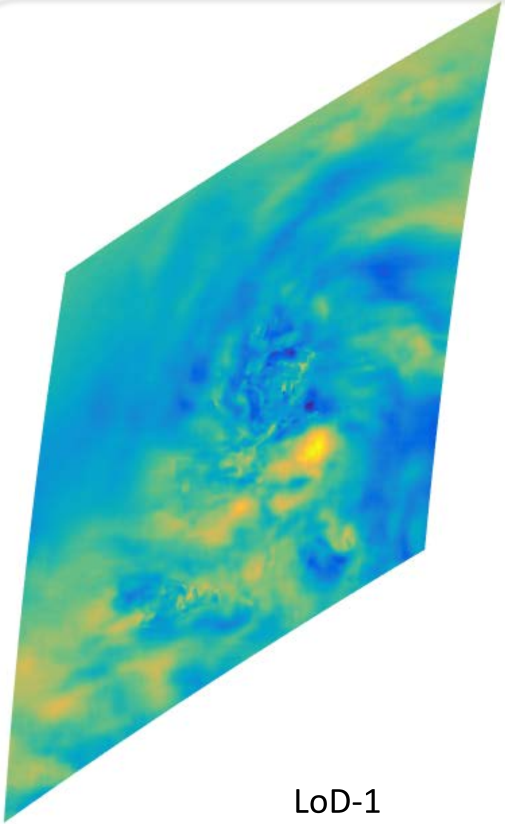
MORE RESULTS

Hurricane Data

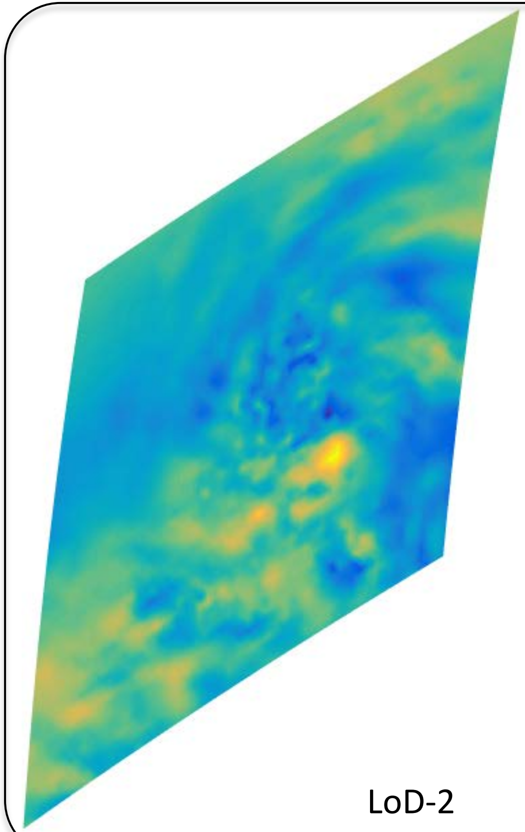
variable: rho



Fine

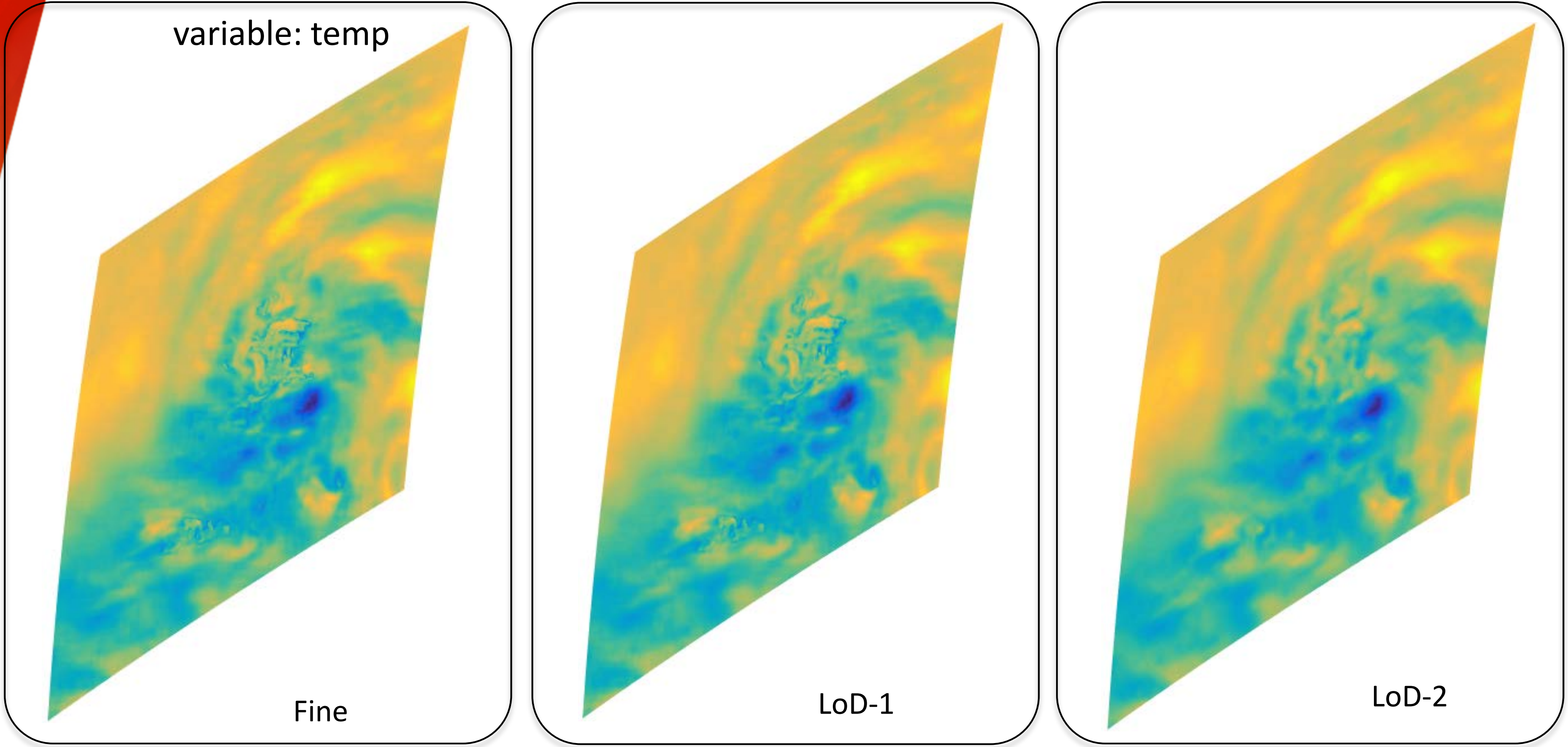


LoD-1



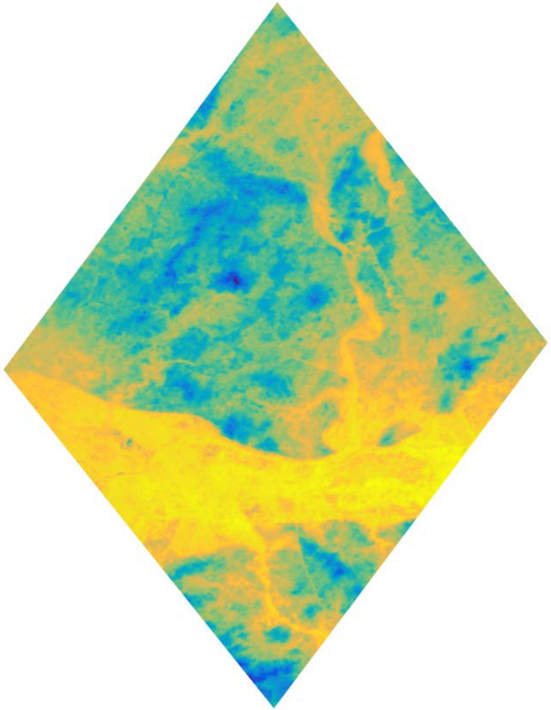
LoD-2

Hurricane Data



HD(CP)^2 Data

variable: pres



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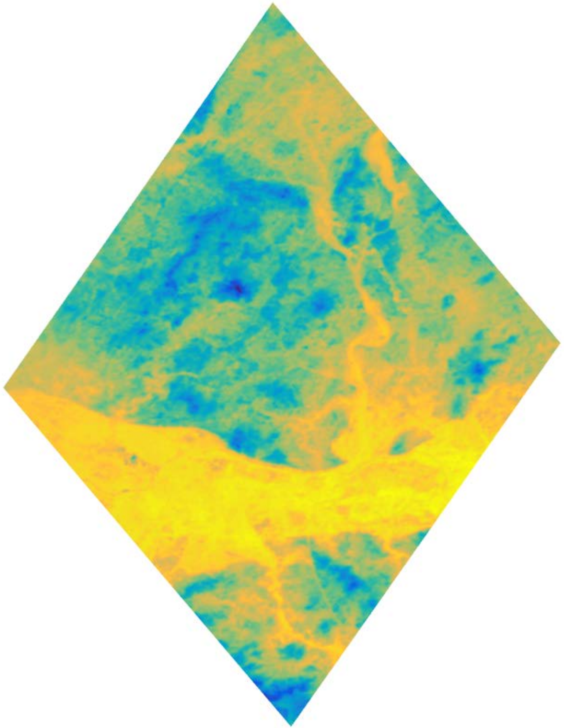
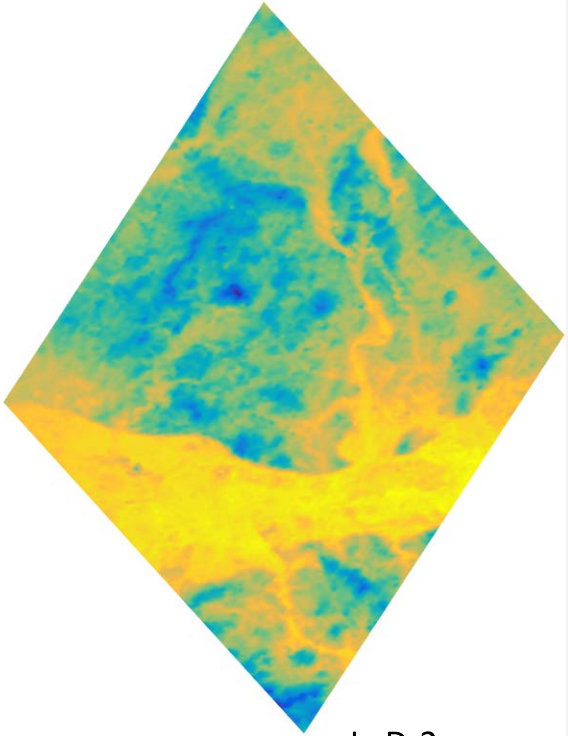


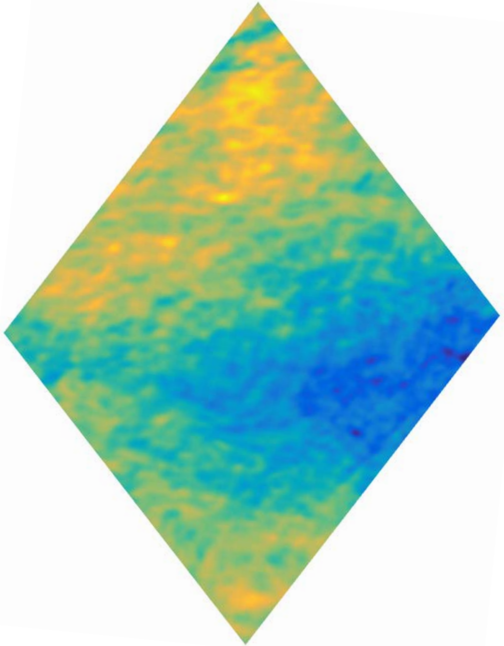
LoD-1



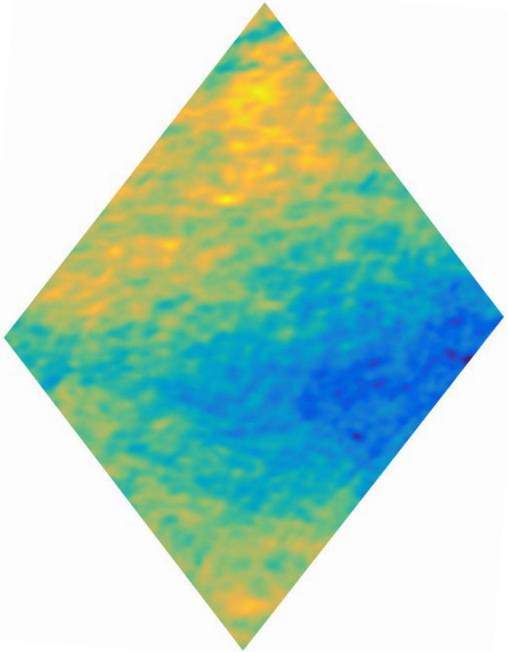
LoD-2

HD(CP)^2 Data

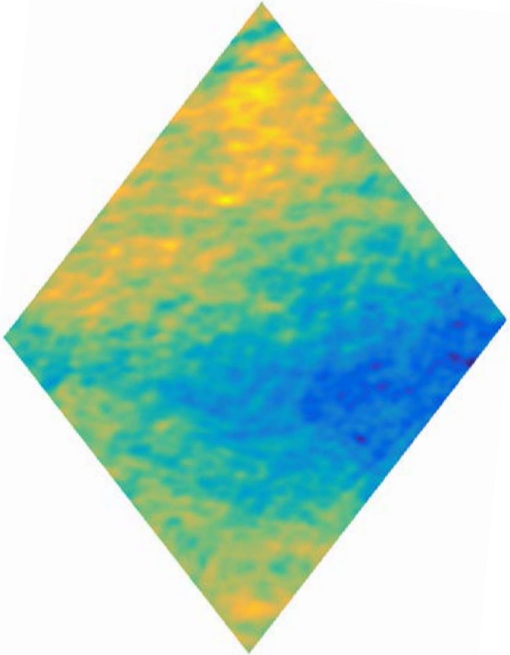
variable: va



Fine



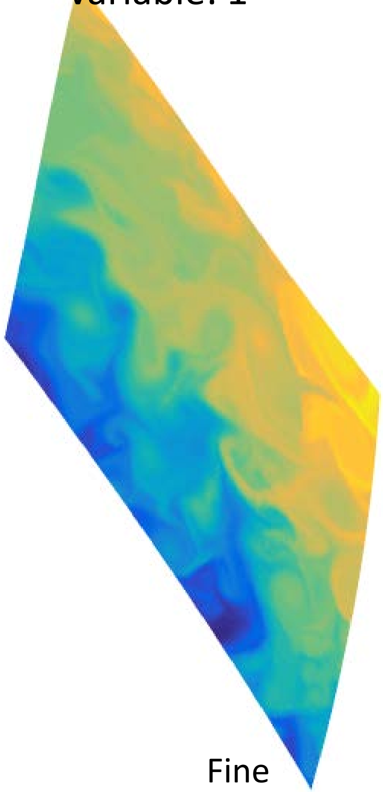
LoD-1



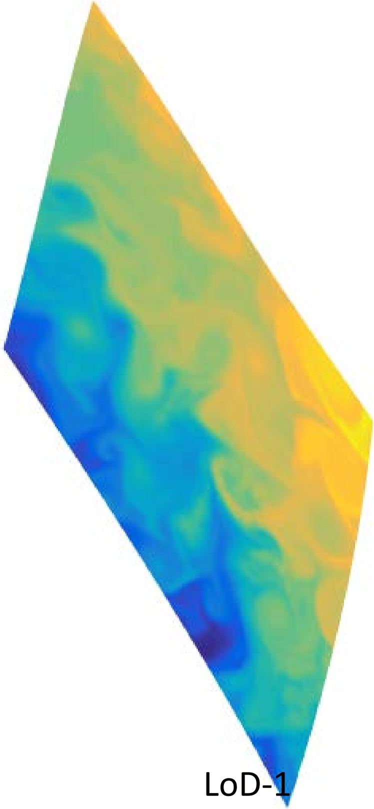
LoD-2

Agulhas Data

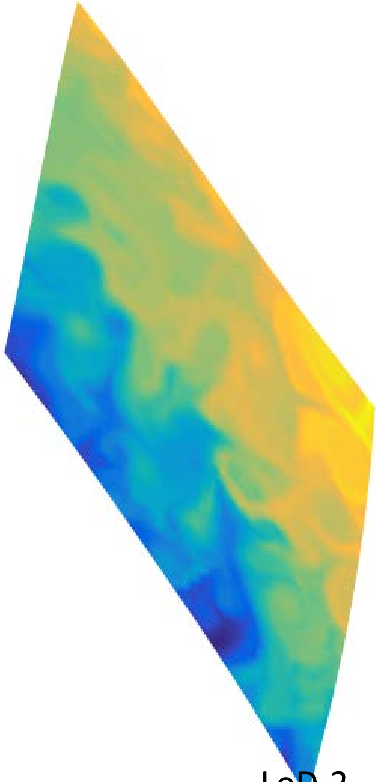
variable: 1



Fine



LoD-1



LoD-2

Agulhas Data