Partly Cloudy with a Chance of Zarr

A Virtualized Approach to Zarr Stores from ECMWF's Fields Database

FOSDEM'26

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ECMWF

WARM WORLD

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Who Am I?

Tobias Kremer

- Research Software Engineer @ ECMWF
- Former cloud backend engineer
- Working in WarmWorld Easier with colleagues from
  - Forschungszentrum Jülich (JSC)
  - Deutsches Klimarechenzentrum (DKRZ)
  - Max-Planck-Institut für Meteorologie (MPI-M)
  - Climate Service Center Germany (GERICS)
  - Karlsruher Institut für Technologie (KIT)
  - Universität zu Köln
- ECMWF – MARS ecosystem
  - Fields Database (FDB)
  - Python Interface for the FDB (PyFDB)
  - Zarr Interface for the FDB (ZFDB)

What is ECMWF?

Established in 1975, Intergovernmental Organisation

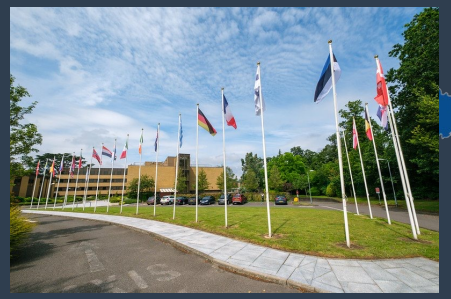
- 23 Member States | 12 Cooperating States
- 500+ staff

24/7 operational service

- Operational NWP – 4x forecasts / day
- Supporting NWS (coupled models) and businesses

Research institution

- Experiments to continuously improve our models
- Reforecasts and Climate Reanalysis



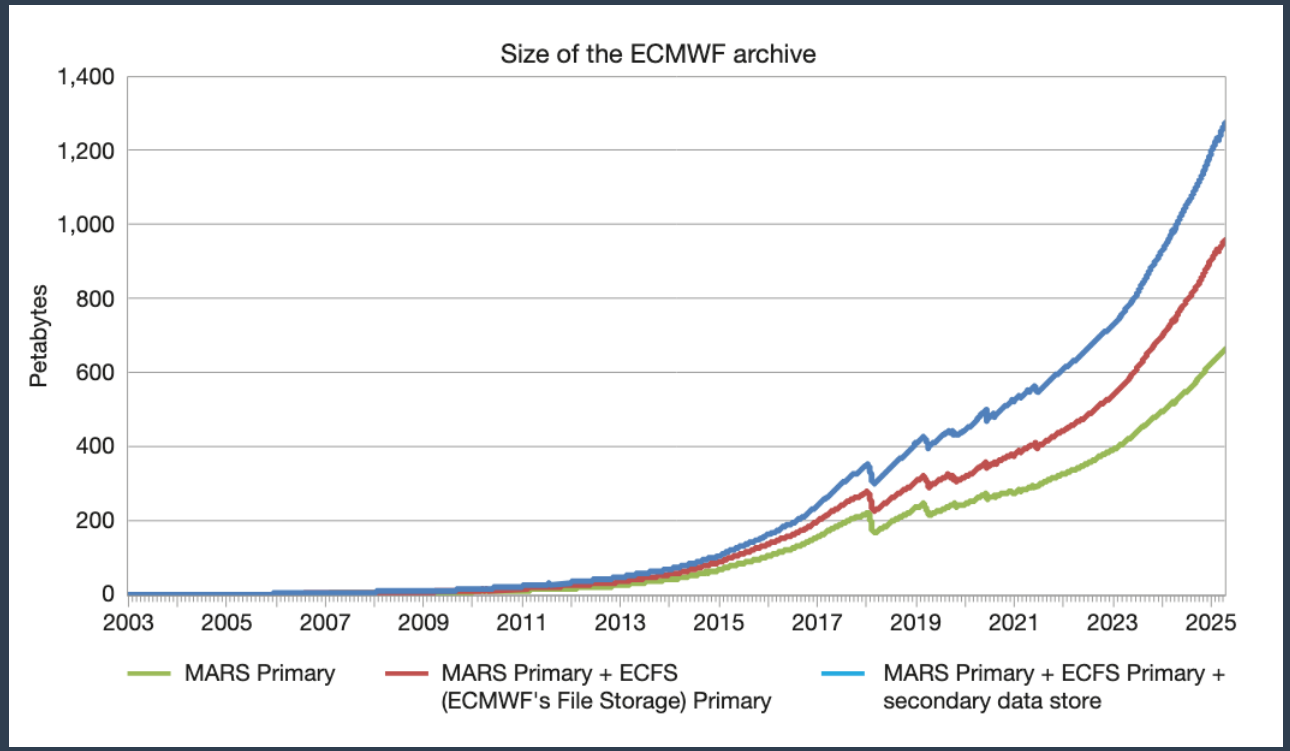
Reading, GB

Bonn, DE

Bologna, IT

Why are we talking about Zarr?

- Explosion of scientific data
  - ECMWF produces ~360 TiB of forecast data per day (projection 2027: 1 PiB)
  - Need for scalabitility and open formats
- Increasing pool of target users
  - Social Science
  - Geologists
  - …
- Many new use cases in the Python / Machine Learning domain



https://www.ecmwf.int/sites/default/files/elibrary/072025/81670-ecmwfs-improving-data-services-in-the-era-of-cloud-computing-and-machine-learning.pdf

Why are we talking about Zarr?

Traditional HPC use-cases:

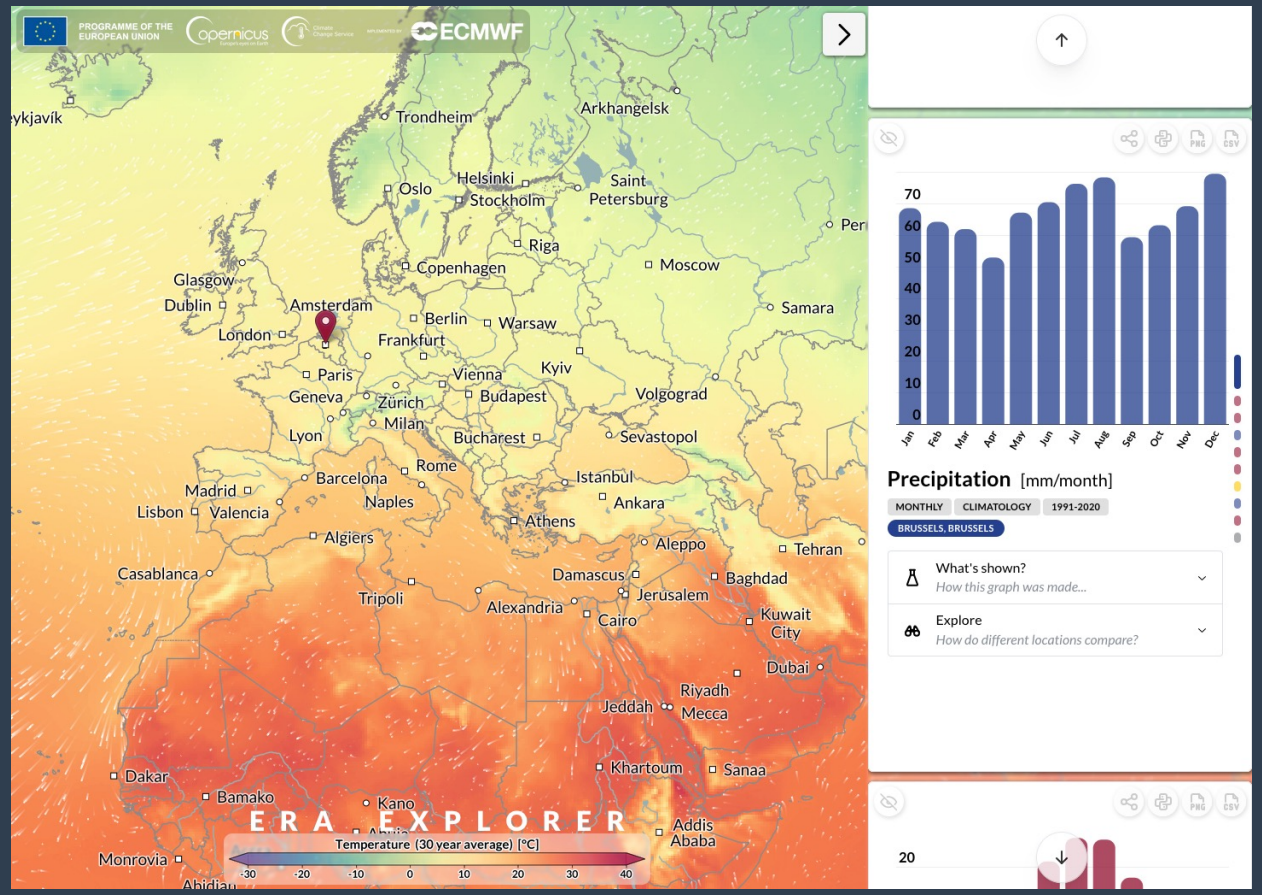
- NWP workflows writing/reading on parallel FS
- Analysis of forecasts in weather and climate

Shift in interest in recent years:

- Hybrid workflows (HPC + cloud)
- Semantic data storage on the cloud
- Interactive analysis / ML training on large datasets
- **A**nalysis-**R**eady **C**loud-**O**ptimized Datasets

Can we give flexible access to data?

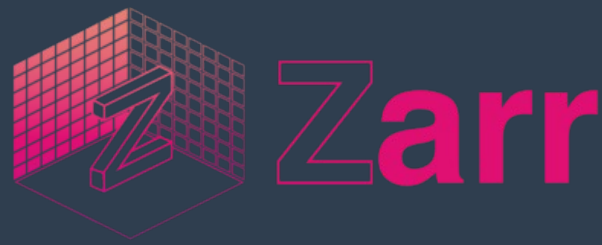
(even without prior domain knowledge?)



https://era-explorer.climate.copernicus.eu/?lat=50.86&lng=4.35&plot=0

Goal of the talk

- Show how Zarr fits into HPC and open-source ecosystems
- Bridge the gap between classical HPC and modern cloud based solutions



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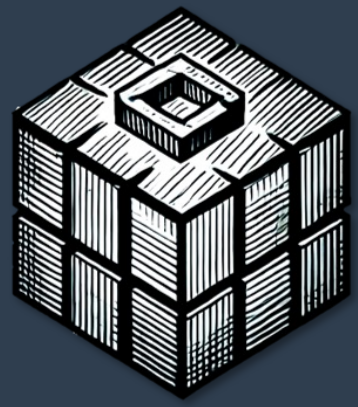


FDB

What is the FDB?

Short:

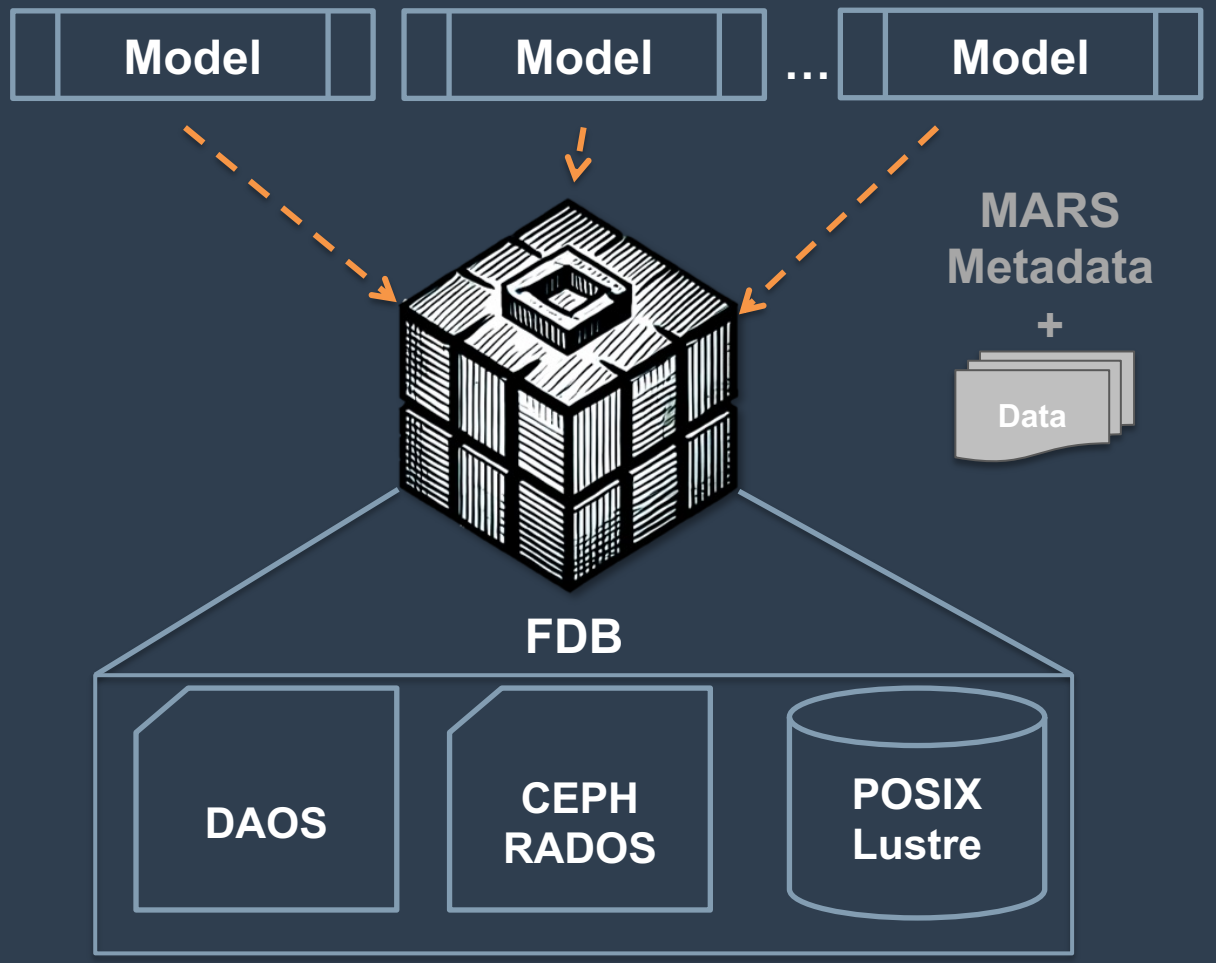
Domain specific high-performance object store
(Transactional, No explicit synchronization, No MPI)

Key-value store

- Keys are scientific meta-data (MARS Metadata)
- Values are byte streams (GRIB, ODB)

Based on data semantics e.g:

```
param=temperature/humidity,
steps=0/to/240/by/3,
date=19990101/to/20251231,
```



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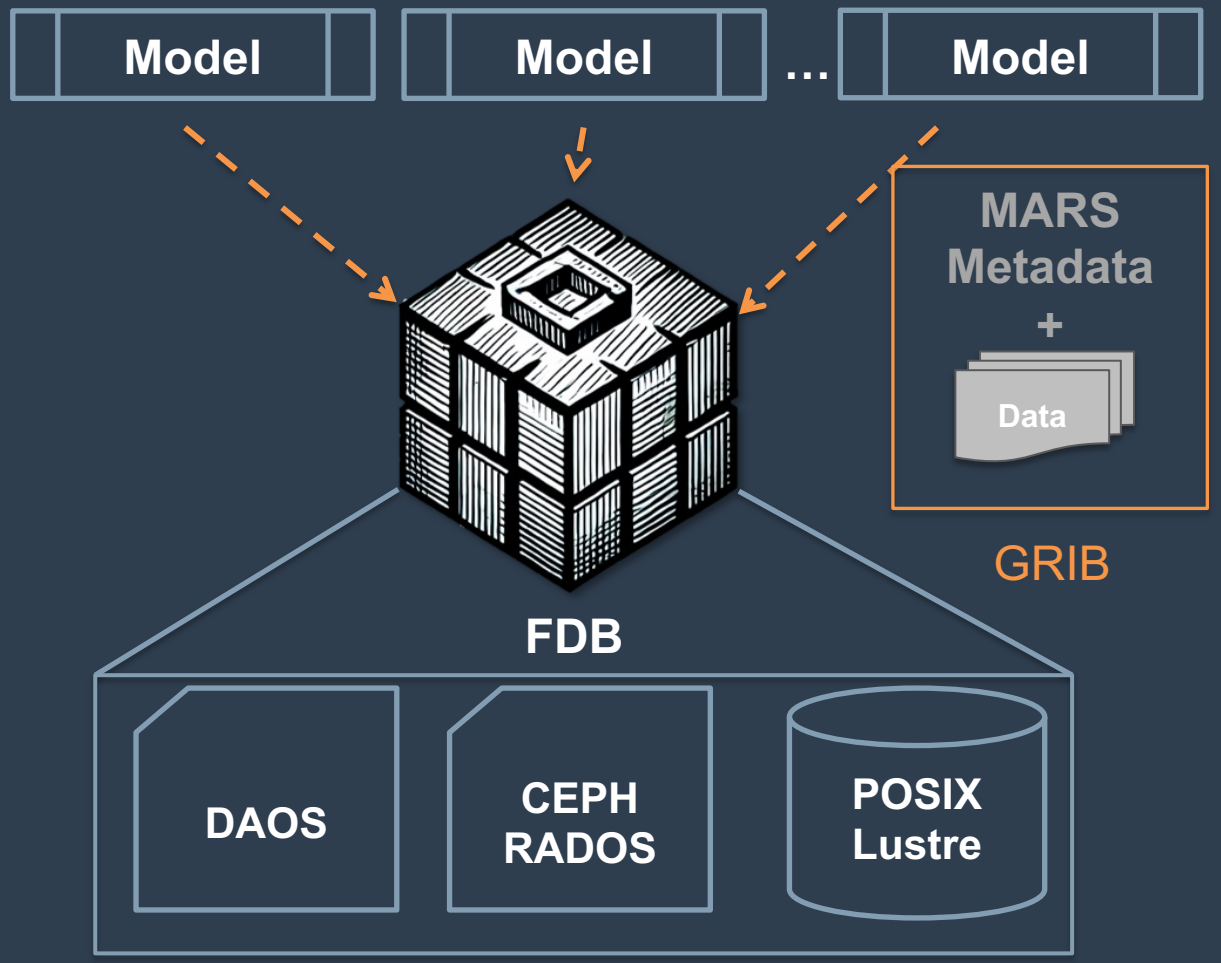
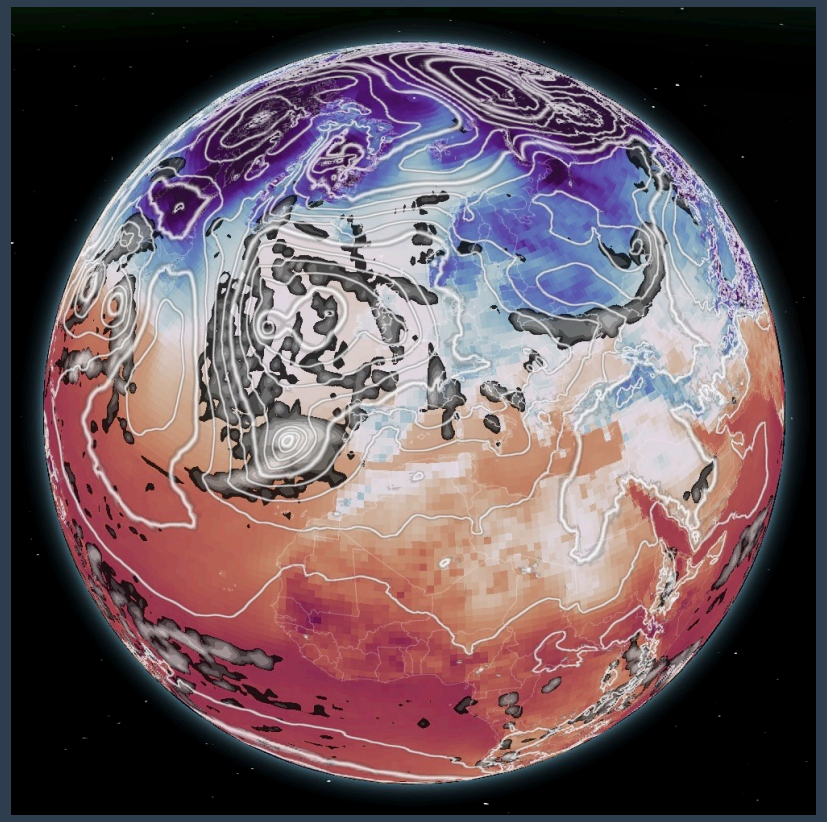


What is GRIB?



GRIB - **G**eneral **R**egularly-distributed **I**nformation in **B**inary form

- Stores gridded fields e.g., temperature, pressure
- Standardized by WMO for meteorological data exchange
- Binary, compact, and efficient for large NWP datasets
- Optimized for archival workflows:
    - Sequential access
    - Minimal overhead for operational pipelines
    - Self-describing
- But:
    - Complex structure (requires external tables)
    - Not cloud-native

Grib File Structure on Disk

Section 0 Indicator	Section 1 Identification	Section 2 Local Use	Section 3 Grid Definition	Section 4 Product Definition	Section 5 Data Representation	Section 6 Bitmap	Section 7 Data	Section 8 End

What is Zarr?

Short:

A Library and a ***Format***

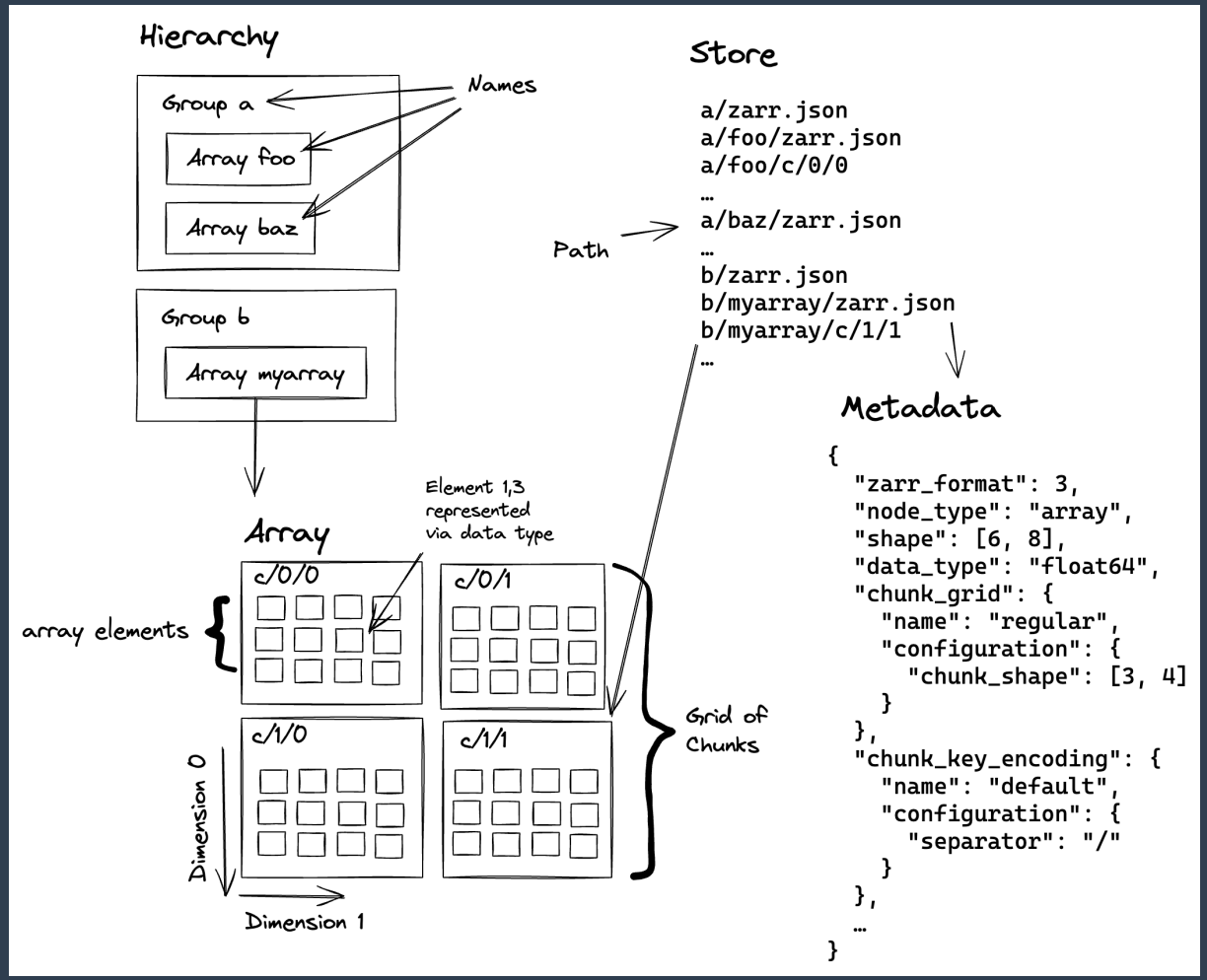
(An Interface and a behavioural contract)

Definition:

Chunked, compressed, N-dimensional arrays

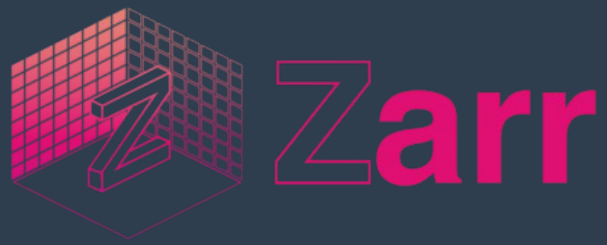
Key features:

- Storage agnostic
- Language interoperability
- Chunking for performance
- Maps onto directories and files:
  - Groups map to Directories
  - Arrays map to Set of Files
  - Chunk map to File



https://zarr-specs.readthedocs.io/en/latest/_images/terminology-hierarchy.excalidraw.png

How to bridge the gap between GRIB and Zarr



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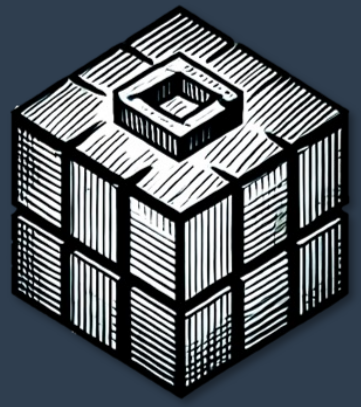
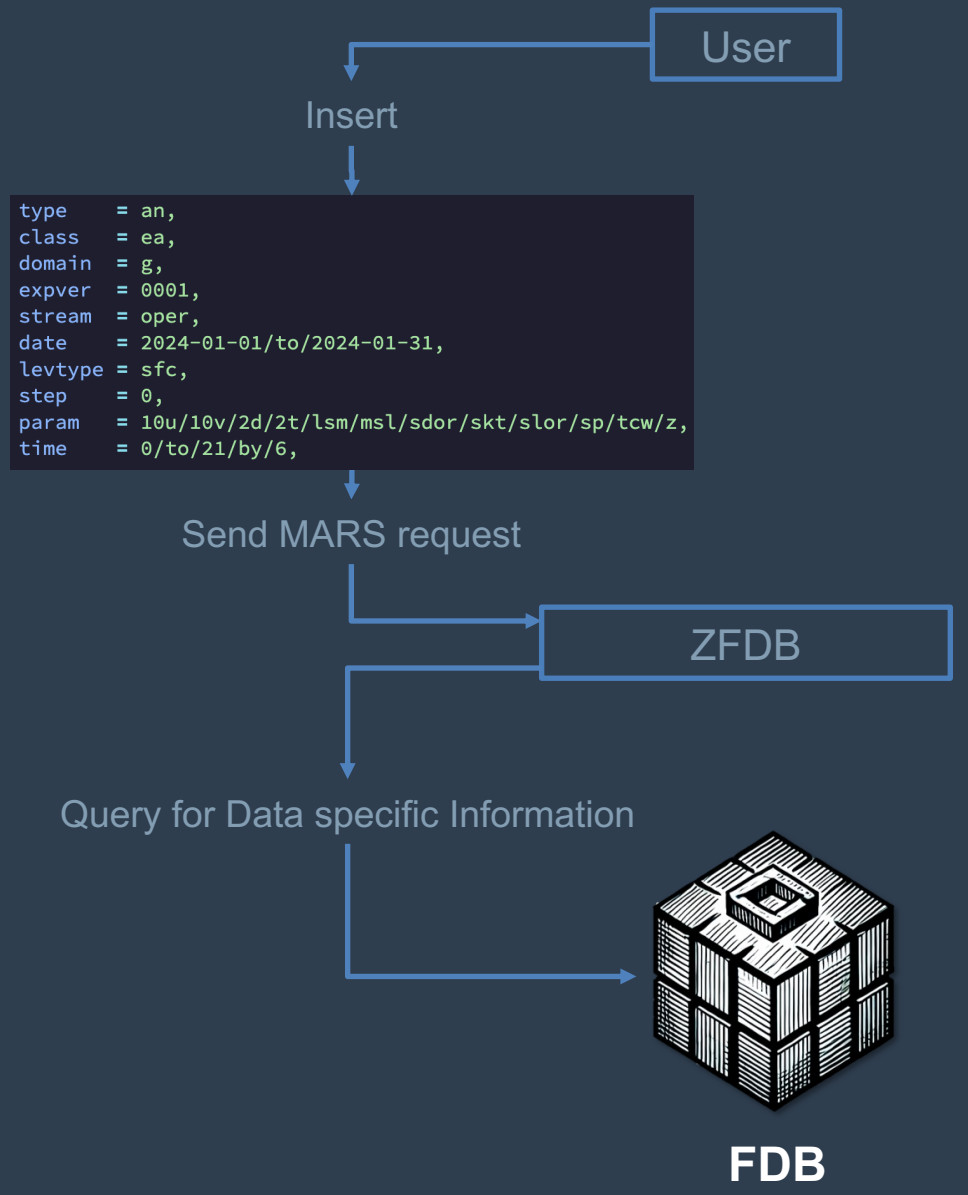


FDB

Local

Local - Creating a Lazy View

- Define a view onto GRIB data stored in a FDB
- Retrieve a Zarr-Store
- Zarr's chunking maps to FDB chunking
- View is cached and reused



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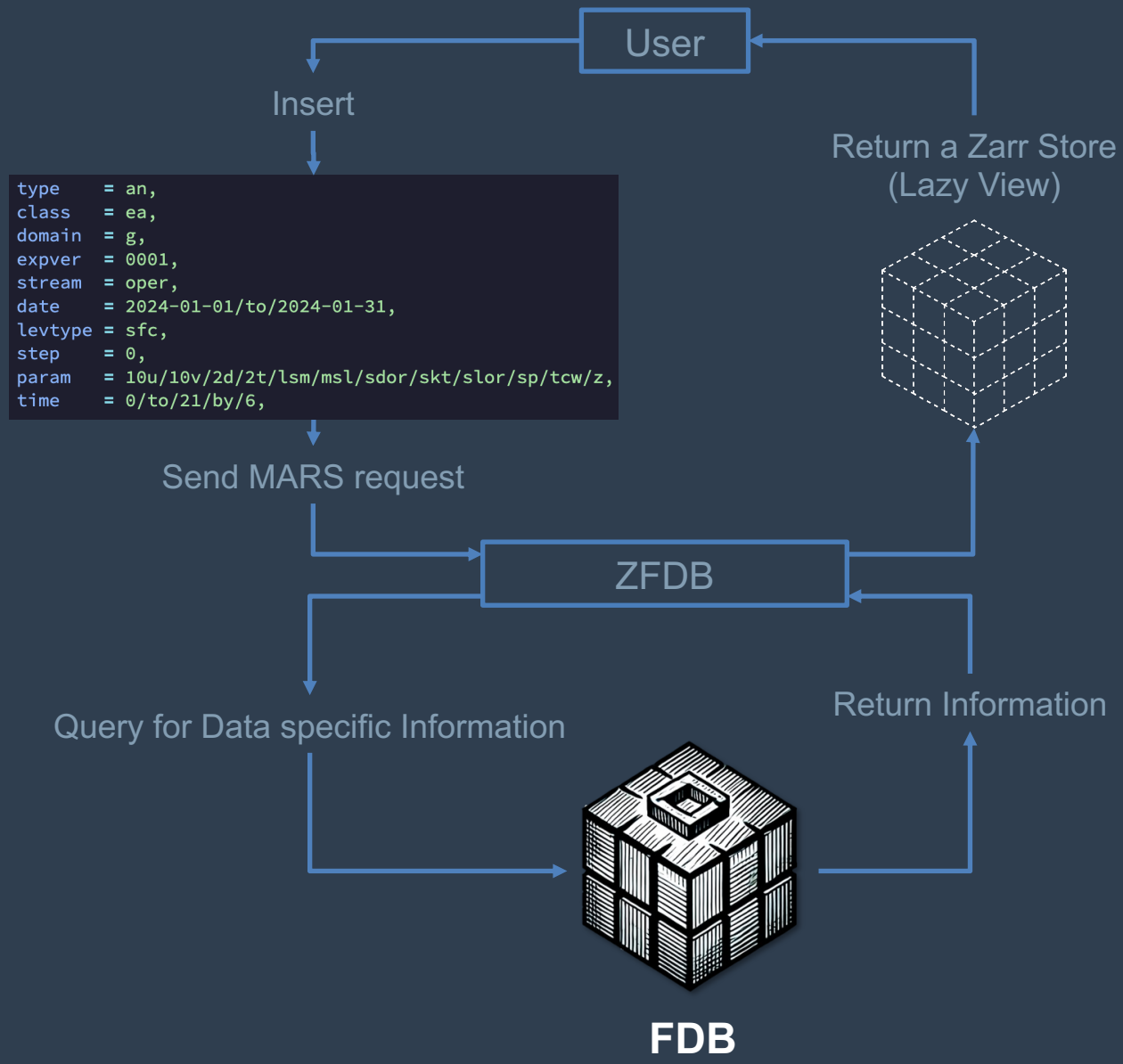
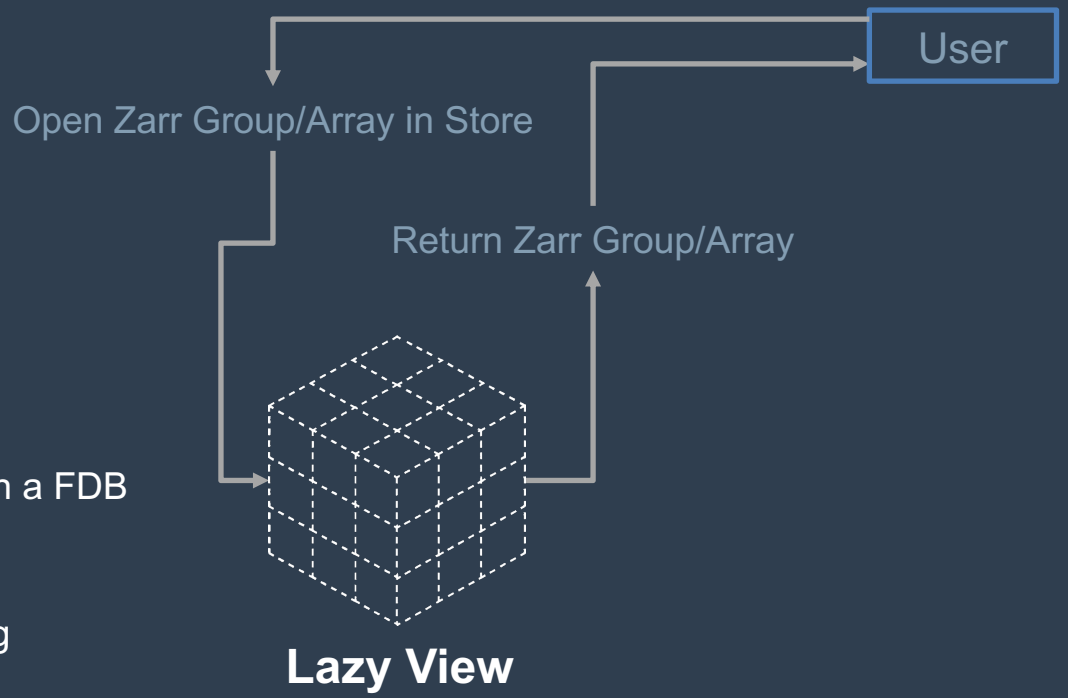


Local - Query View / Zarr Chunk



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--- Non-read path
--- Read paths

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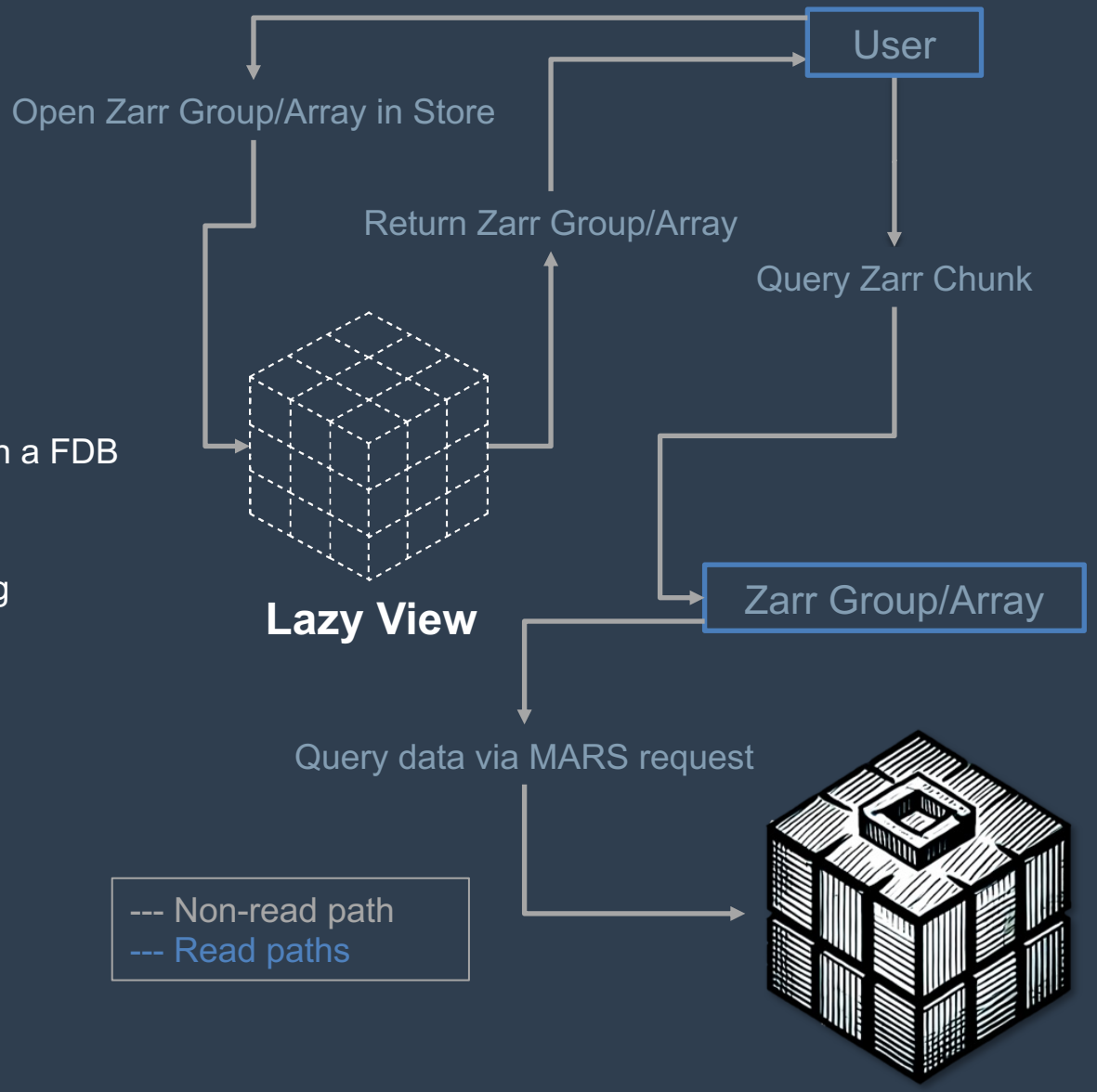

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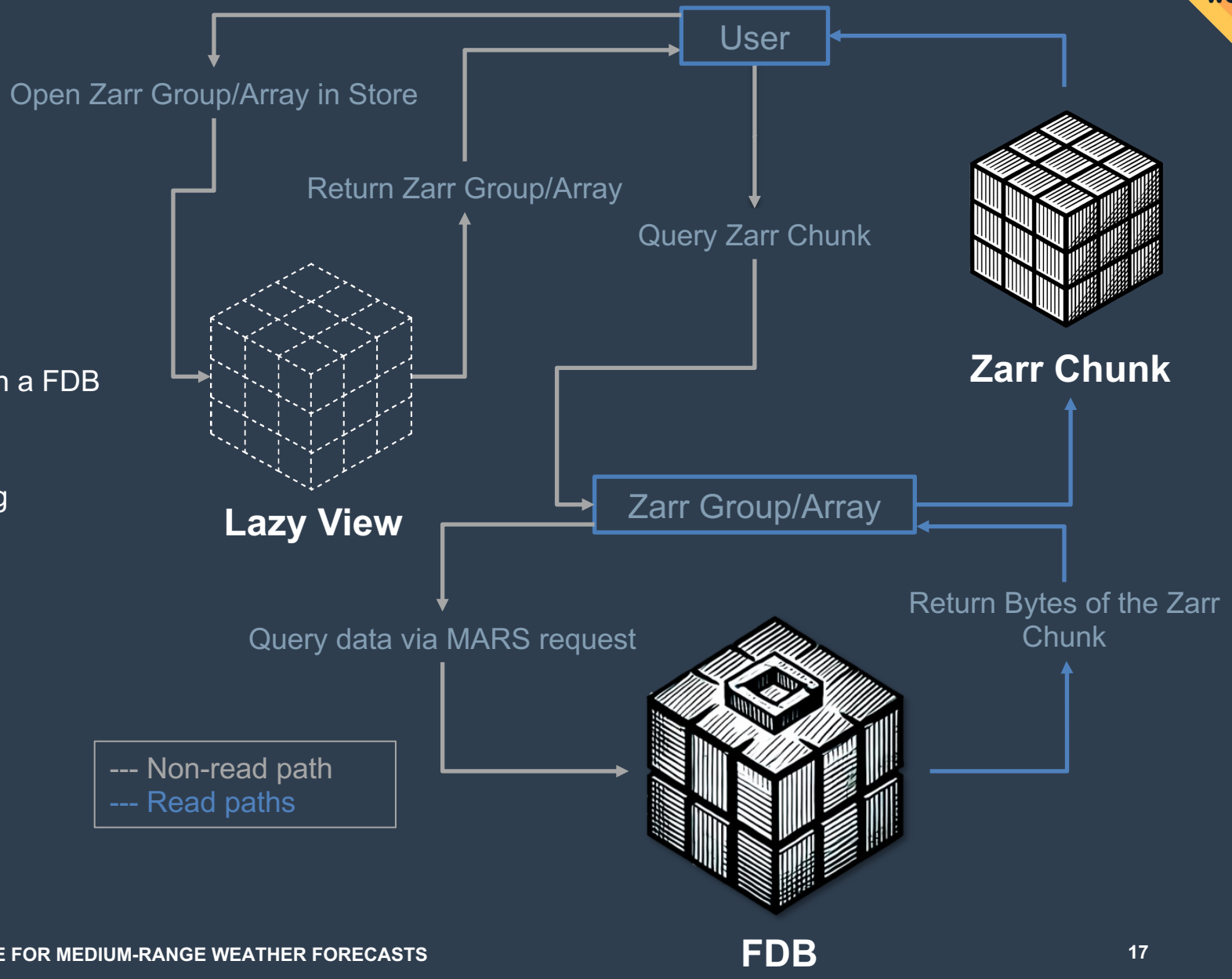


```python
def store_creation(fdb_config_path: pathlib.Path) -> zarr.ABC.store.Store
  builder = SimpleStoreBuilder(fdb_config_path)
  builder.add_part(
    "class=ea,type=an,stream=oper,date=2024-01-01/to/2024-01-31,time=0/to/21/by/6,step=0,domain=g,expver=0001,"
    "param=10u/10v/2d/2t/lsm/msl/sdor/skt/slor/sp/tcw/z,"
    "levtype=sfc,"
    [
      AxisDefinition(["date", "time"], True),
      AxisDefinition(["param"], True)
    ],
    ExtractorType.GRIB,
  )
  builder.add_part(
    "class=ea,type=an,stream=oper,date=2024-01-01/to/2024-01-31,time=0/to/21/by/6,step=0,domain=g,expver=0001,"
    "param=q/t/u/v/w/vo/d,"
    "levtype=ml,"
    "levelist=48/60/68/74/79/83/90/96/101/105/114/120/133,"
    [
      AxisDefinition(["date", "time"], True),
      AxisDefinition(["param", "levelist"], True)
    ],
    ExtractorType.GRIB,
  )
  builder.extendOnAxis(1)
  store = builder.build()
  return store
```

results in

Zarr

Store with Numpy Array like Zarr Cube
Size = (32 * 4, 12 + 7 * 13, 40320)

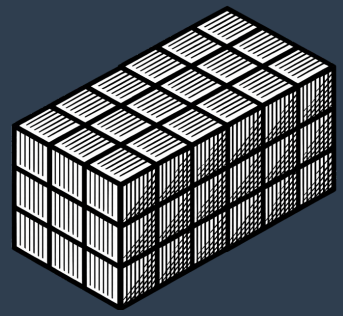
[#Datetime, #Parameter_Levelist, #Implicit Field Entries]

Lazy View

+

Lazy View

results in

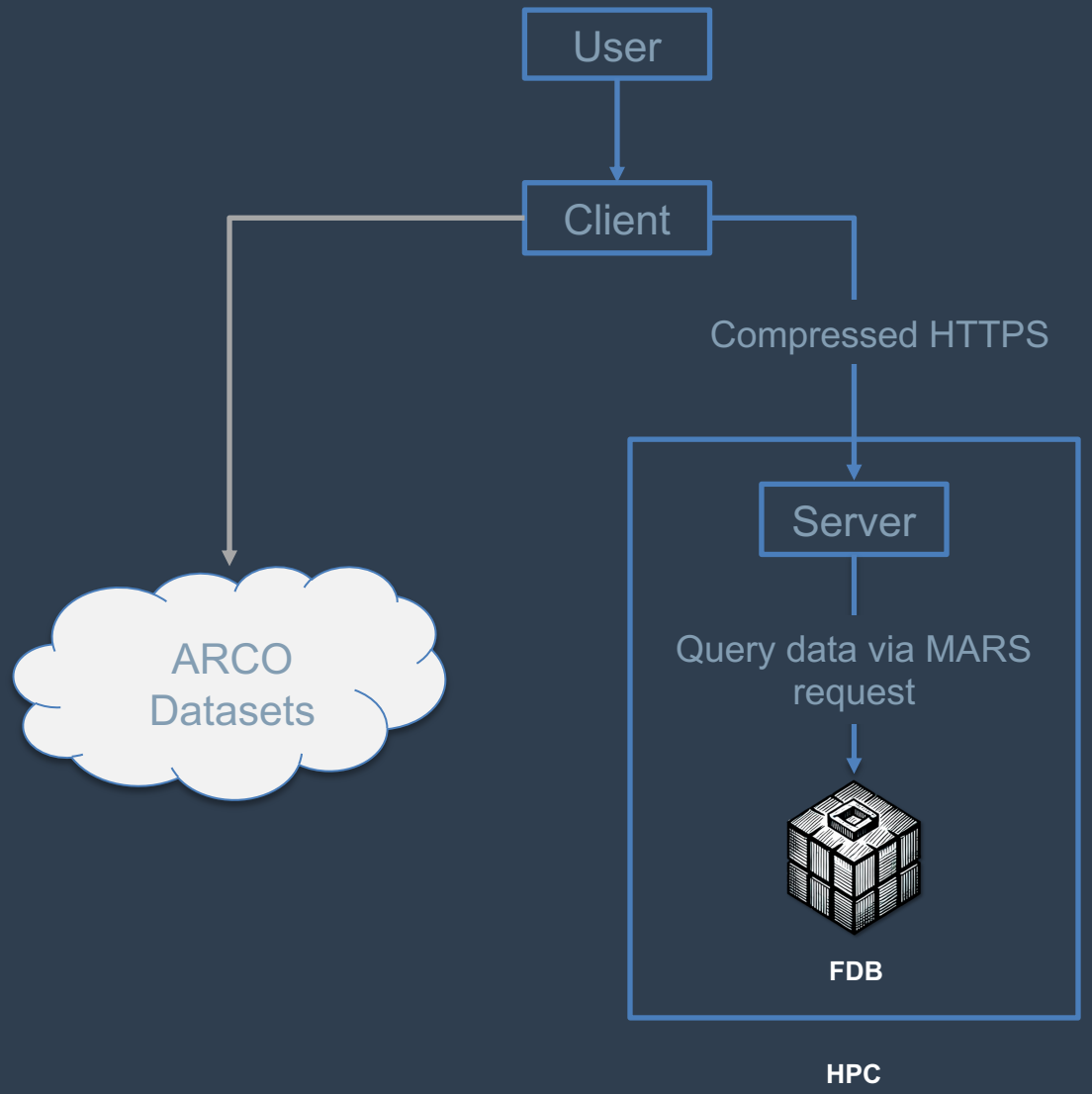


Zarr Array

ECMWF EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

Remote

Remote - Zarr via HTTPS



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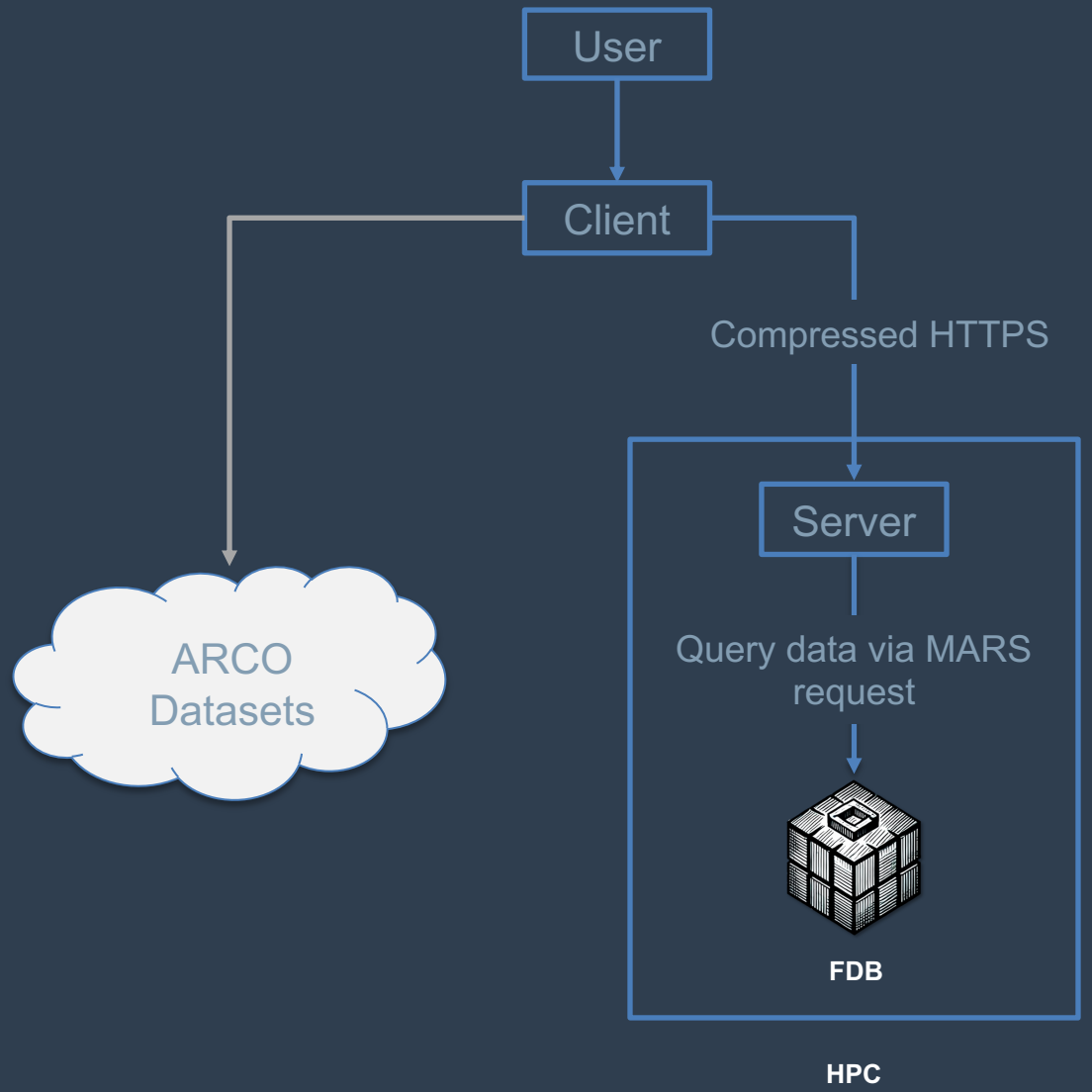
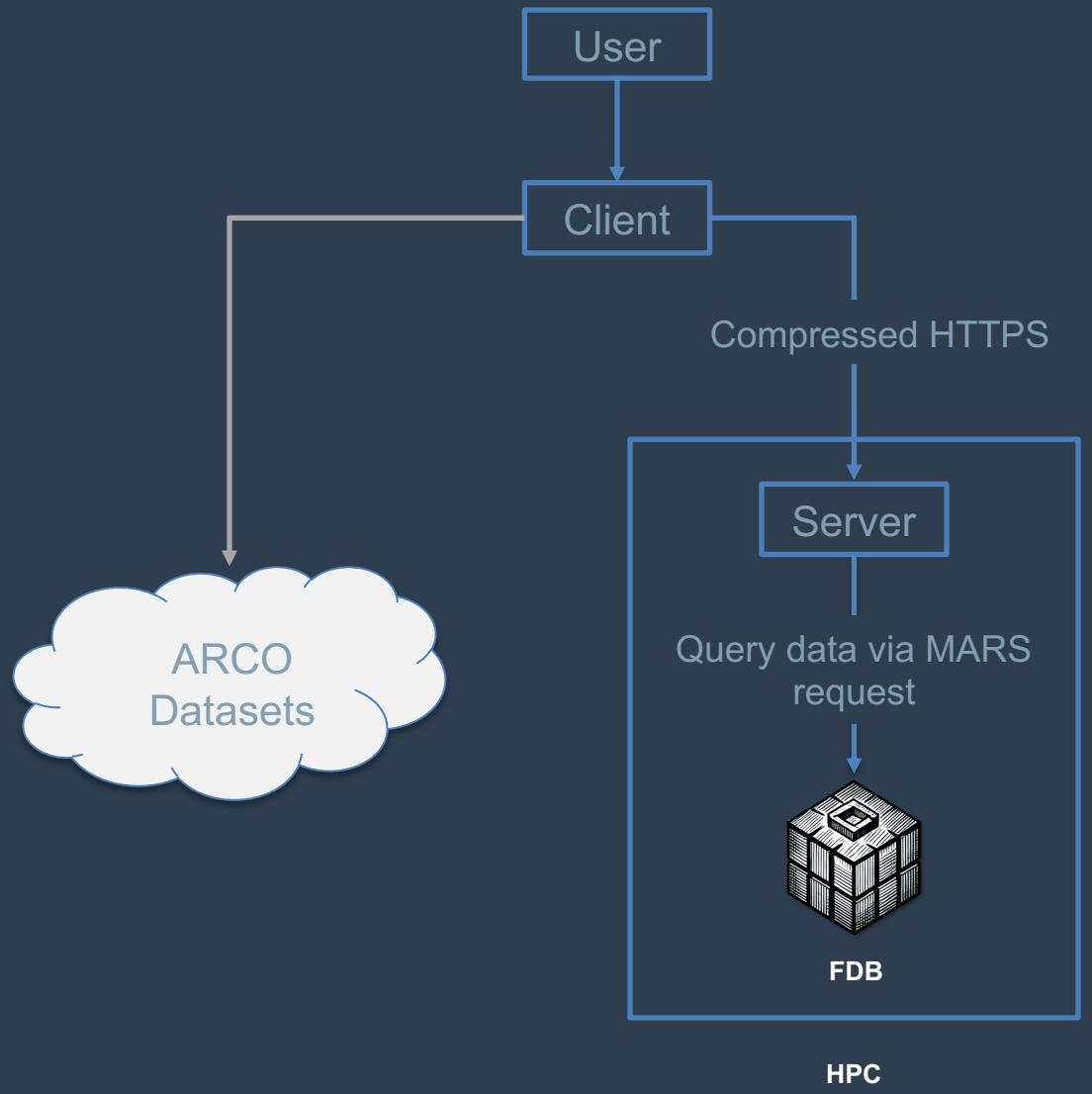


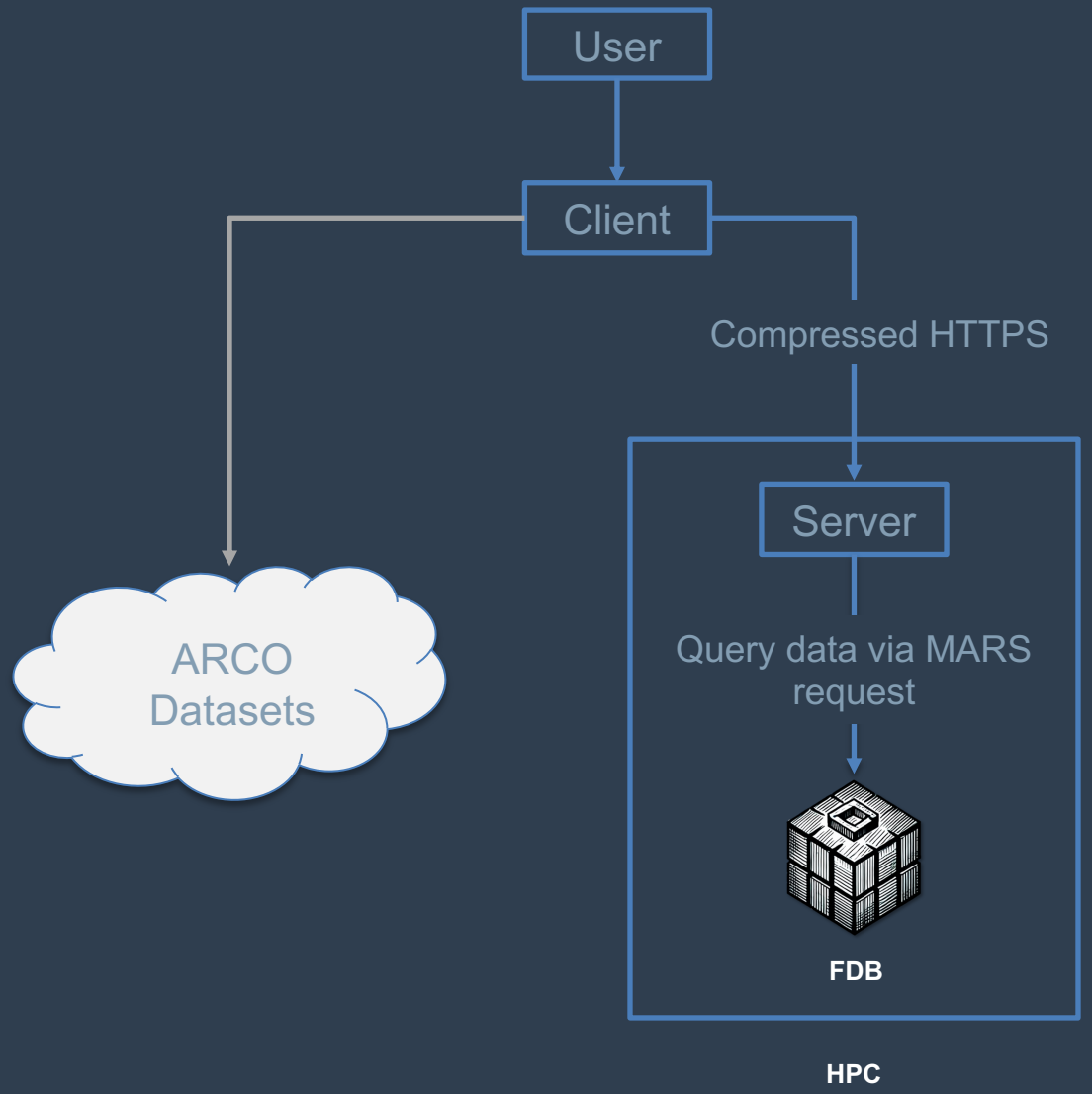
1. Client
   - Triggers creation of a virtual view

Remote - Zarr via HTTPS



1. Client
   - Triggers creation of a virtual view
2. Server
   - Creates virtual view of FDB data

Remote - Zarr via HTTPS



1. Client
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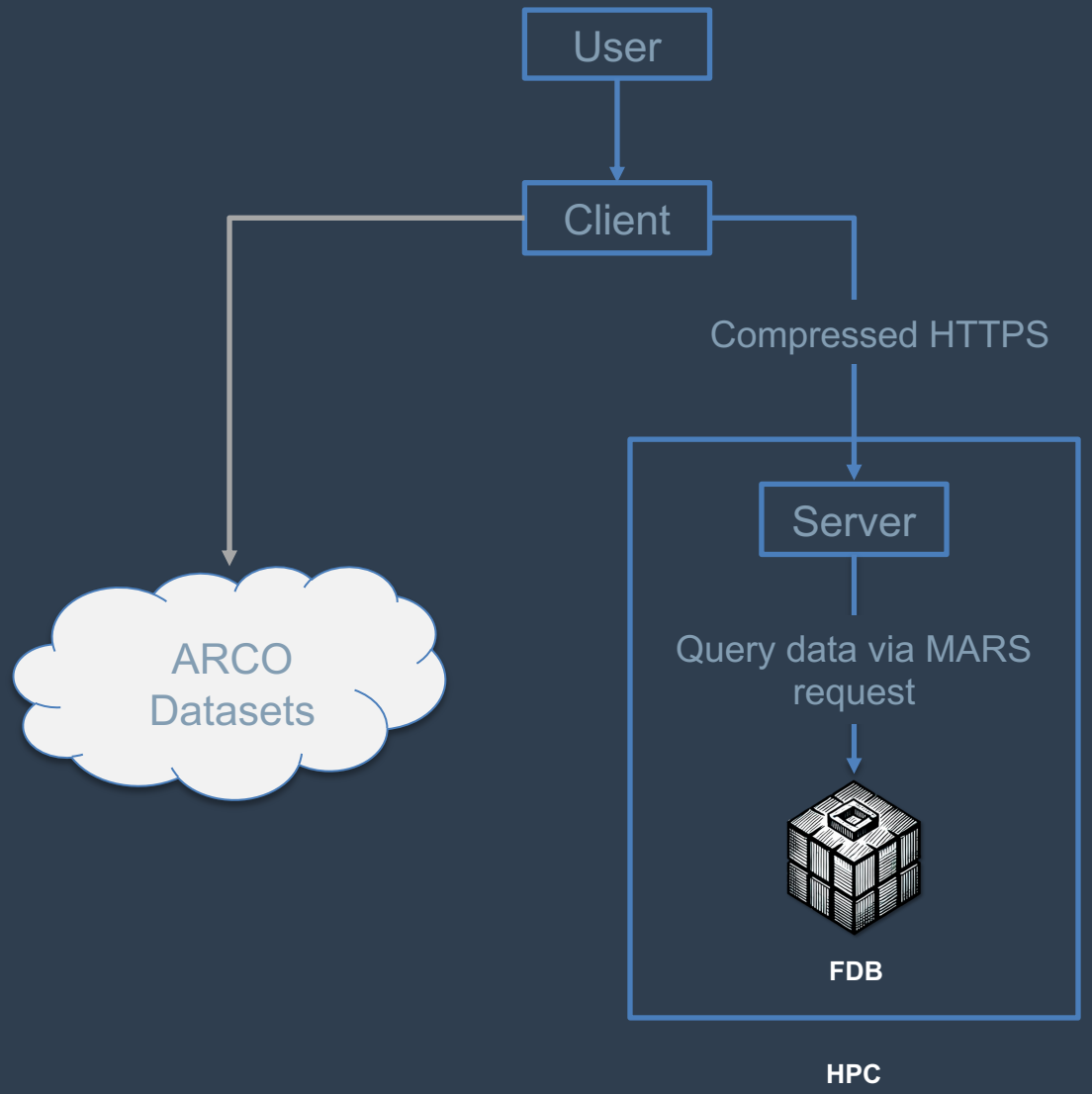
2. Server
   - Creates virtual view of FDB data
3. Client
   - Opens virtual view via FSSpecStore
   - Send chunk request to Server

Remote - Zarr via HTTPS



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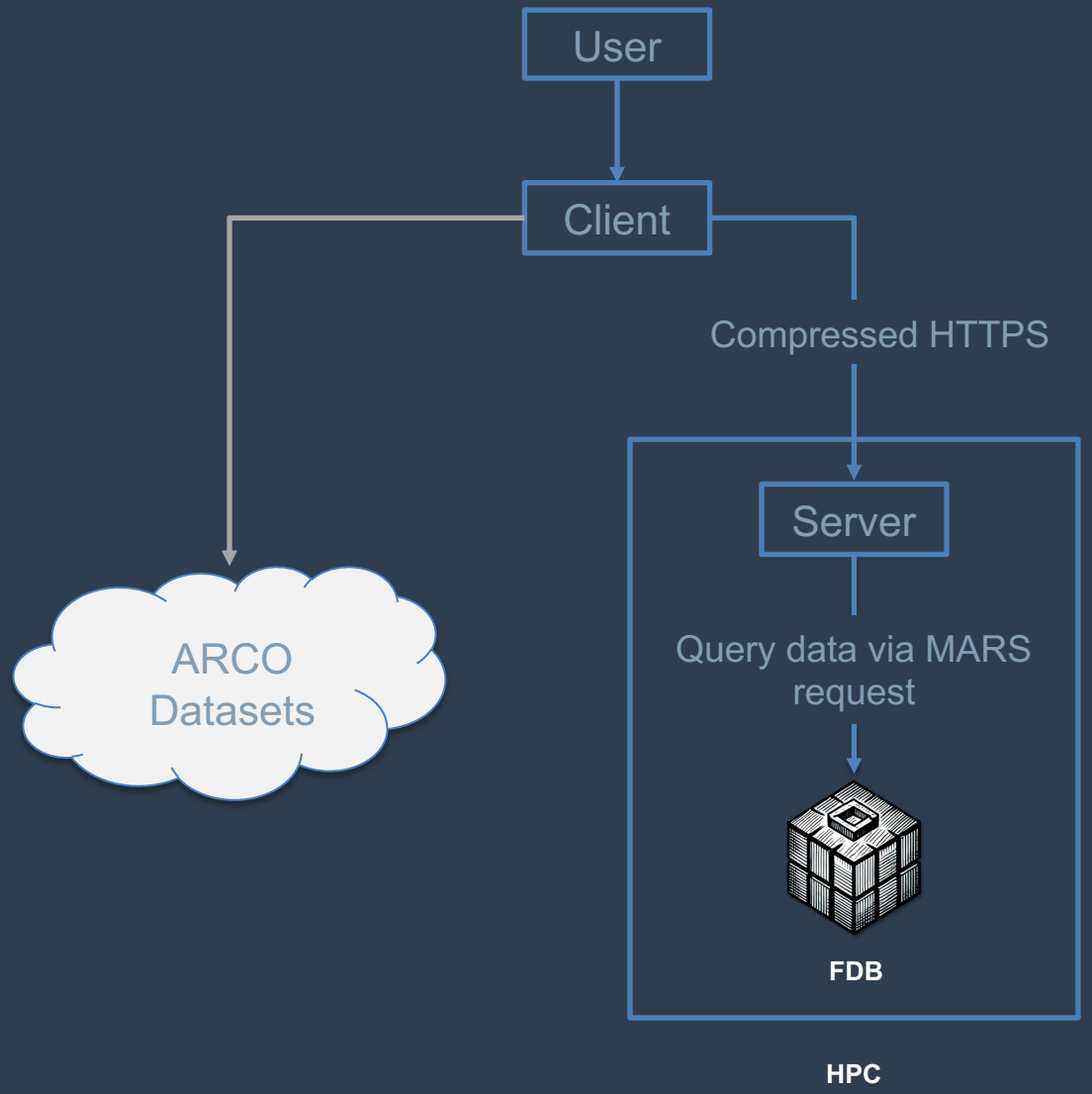

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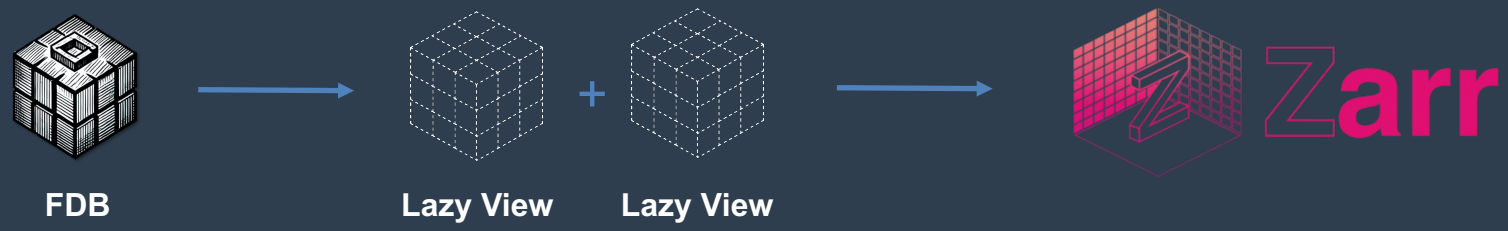
   - Chunk is send via compressed HTTPS to Client
5. Client
   - Return the data as part of the Array access

Summary / Acknowledgments

Mapping between metadata driven GRIB and Zarr via lazy views to support shifting user requirements towards cloud use-cases



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- Carsten Hinz @JSC
- Colleagues @WarmWorld Easier
- Data Mangagment and Service Team @ECMWF

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FDB Documentation	https://fields-database.readthedocs.io/en/latest/
Zarr Python	https://github.com/zarr-developers/zarr-python
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