DATA-CENTRIC WORKFLOWS IN EXASCALE WEATHER FORECASTING

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ABOUT ECMWF

Established in 1975, Intergovernmental Organisation
- 23 Member States | 12 Cooperating States
- 350+ staff

24/7 operational service
- Operational NWP – 4x HRES+ENS forecasts / day
- Supporting NWS (coupled models) and businesses

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

Operate 2 EU Copernicus Services
- Climate Change Service (C3S)
- Atmosphere Monitoring Service (CAMS)
- Support Copernicus Emergency Management Service CEMS

Destination Earth
- Operates two Digital Twins
- Operates the DestinE Digital Twin Engine (DTE)
WHAT IS A DIGITAL TWIN?

Driven by high-performance computing, advanced Earth-system simulations are fused with a continuous flow of observations to create the most accurate digital replica.
HOW DOES A DIGITAL TWIN WORK?

Two different technologies drive Earth’s digital twin: rich real-world observations and sophisticated computer simulations.

**OBSERVATIONS**
Real-world data is gathered...

- Satellites
- Targeted drones
- Crop-field sensors
- Seismic sensors

**SIMULATIONS**
...and Earth’s systems are modelled

- Global weather and climate
- Streets, buildings and green areas in cities
- Vegetation, soil, water, weather on farms
- The planet’s crust and mantle
Fed by real-world observations, these digital twins let us understand what has happened on Earth – and what will happen in the decades ahead.
DIGITAL TWIN, REAL IMPACT

Giving us new insights on days or entire decades, digital twins of the Earth can provide huge benefits to many sectors.

CITIES
Smart cities can harness the digital twin for everything from traffic management to construction planning.

FARMING
The digital twin can aid agriculture’s key functions (irrigation, fertilisation, harvest) and its response to extreme weather.

ENERGY
We will have new knowledge to enable ambitious projects like harvesting Earth’s inner heat, converting this geothermal energy and storing it.

CLIMATE CHANGE
The digital twin’s unique insights will help drive Europe’s efforts to become the world’s first climate neutral continent by 2050.
Funded by the European Union

ECMWF / ESA / EUMETSAT
EuroHPC Centres
Horizon Europe R&I
Partnerships across Europe and beyond
Part of EU Green Deal and Digital Strategy
ECMWF’S ROLE

Digital Twin: Weather-induced and Geophysical Extremes
• Capabilities and services for the assessment/prediction of environmental extremes (km-scale)

Digital Twin: Climate Change Adaptation
• Capabilities and services for Climate change adaptation policies and mitigation scenarios

Digital Twin Engine (DTE):
• Framework for execution of Digital Twins on HPC and beyond
• Allows modular construction of data-centric workflows
  • Built upon a data management strategy
  • Maximum re-use of software through common interfaces
  • Maximum re-use of data through data curation
• Bringing ECMWF expertise to Open Science
ECMWF’S PRODUCTION WORKFLOW

Acquisition

Earth System Model

Product Generation

Product Dissemination

Global Observations

200M obs/day

9km resolution

120TiB/day

30TiB in 1 hour

45TiB/day

~350 world destinations

Member States & Customers

Archive

Perpetual Archive

Obs

Fields

Products

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Obs

Fields

Products
ECMWF’s Production Workflow

- **Earth System Model**
- **Product Generation**
- **Product Dissemination**

**Fields**
- Raw Output
- Parallel Filesystem Storage (Lustre)
- 30 TiB
- 70% Read

**Products**
- Member States & Customers

Time critical path = 1 hour window
ECMWF’S PRODUCTION WORKFLOW

Observations → Acquire → Storage Parallel FS → Modify → Produce Earth System Model → Product Generation

Data is Central!

Acquisition

Product Dissemination

Member States & Customers

Acquire → Disseminate

Archive

Perpetual Archive
Data is indexed by its scientific metadata, according to a hierarchical schema.

The key used to index data carries scientific meaning:
- Not just a UUID
- Not just storing metadata with data
- The metadata is used to index and uniquely identify the data

ECMWF archive from 1975-2022 (>400PiB) is all addressed with the same data language.

Data is implicitly discoverable and findable (FAIR) when you know the domain schema.
The most basic semantic data access can be done with files...

/.../20210112/1200/24/0/T/...

... but a proper implementation decouples the scientific identification from the storage resource...

... and the applications don’t need to care how the objects are stored.
SEMANTIC DATA ACCESS ➔ FLEXIBLE DATA STORAGE

- Observations
- Acquisition
- Product Dissemination
  - Acquire
  - Disseminate

Earth System Model

- Produce
- NVRAM
- PFS
- Archive
  - Perpetual Archive

- Modify
- Product Generation

Seamlessly distribute data between storage tiers and explore novel storage technologies

Member States & Customers
SEMANTIC DATA ACCESS ➔ FLEXIBLE DATA ROUTING

Acquisition ➔ Product Dissemination

Observations ➔ Acquire ➔ Disseminate ➔ Member States & Customers

Earth System Model ➔ On-the-fly Post-processing ➔ Product Generation

NVRAM ➔ PFS ➔ Perpetual Archive

Avoid write-read altogether through tighter coupling of components

Parameter: T
THE DESTINATION EARTH CHALLENGE

1 PiB
(>35x increase)
How can we handle and make use of such vast amounts of data?
ECMWF will build a **framework of components** for Earth System Digital Twins

Lower the barriers to entry:

- For **creation** of high-resolution Digital Twins
- For **interaction** with Digital Twin output

Encourages and simplifies collaboration with R&I programmes and Open Science

Built on our own operational experience and will improve our own forecast handling!
THE DIGITAL TWIN ENGINE

- Components are modular, and solve specific problems:
  - Workflow orchestration (ecFlow)
  - Earth System Model Plugins
  - Data aggregation and post-processing (MultiO, PGen)
  - Data storage (FDB)
  - Serving and extraction of data (Polytope)
  - Data notification (Aviso)

- DTs don’t have to use every components (opt-in)
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- DTs don’t have to use every component (opt-in)

- Component interfaces are all based on semantic data access

**Semantic key**

- date: 20210112
- time: 1200
- step: 24
- parameter: T
- level: 0
MULTIO – MULTIPLEXING IO-SERVER

- Aggregation from distributed model
- On-the-fly post-processing (under development)
- User-defined post-processing actions (under development)
- Routing of data based on semantic metadata

WWW.GITHUB.COM/ECMWF/MULTIO
FDB – DISTRIBUTED OBJECT STORE

- Transactional, no synchronization
- Key-value store
  - Keys are **scientific metadata**
  - Values are byte streams
- Support for multiple back-ends
  - POSIX file-system (currently on Lustre)
  - Intel DAOS (under development)
  - CEPH/RADOS (Cloud object store)
- Actual storage layout abstracted from application
- Supports wild card searches, ranges, etc., **based on data semantics**:

  ```
  date: 20210112
  time: 1200
  step: *
  level: 0 to 120
  ```

WWW.GITHUB.COM/ECMWF/FDB
Hierarchical data schema defines an n-dimensional **datacube**

```
datetime x step x parameter x level x latitude x longitude
```

**Polytope** provides a way to extract non-orthogonal data from these hypercubes

- Flight paths, tropical cyclone tracks, spatiotemporal polygons

**Polytope** shapes defined on top of the **semantic data language**

- Exposed through a REST API
- Offers massive server-side data reduction

🔗 [WWW.GITHUB.COM/ECMWF-PROJECTS/POLYTOPE](https://www.github.com/ecmwf-projects/polytope) (SOON)
AVISO – NOTIFICATION SERVICE

- Notifies of data availability
- For automating systems
- Query uses semantic keys

**When** this

- data available
- product computed
- ensemble complete

**Do** that

- my_script.py
- FDB retrieve
- HTTP POST

```
data: *  
time: *   
step: *   
parameter: T
```

```
download_data()   
produce_plot()    
```
MESSAGES TO TAKE HOME

- Digital Twins have the potential to provide **huge impact to many sectors**
- Handling and giving access the **extreme volumes of data** (1PiB/forecast) from Digital Twins is very challenging
- ECMWF is developing a **Digital Twin Engine** to facilitate creation and access to Digital Twins
- **Semantic data access is key** to ensure scalability and openness for research and collaboration