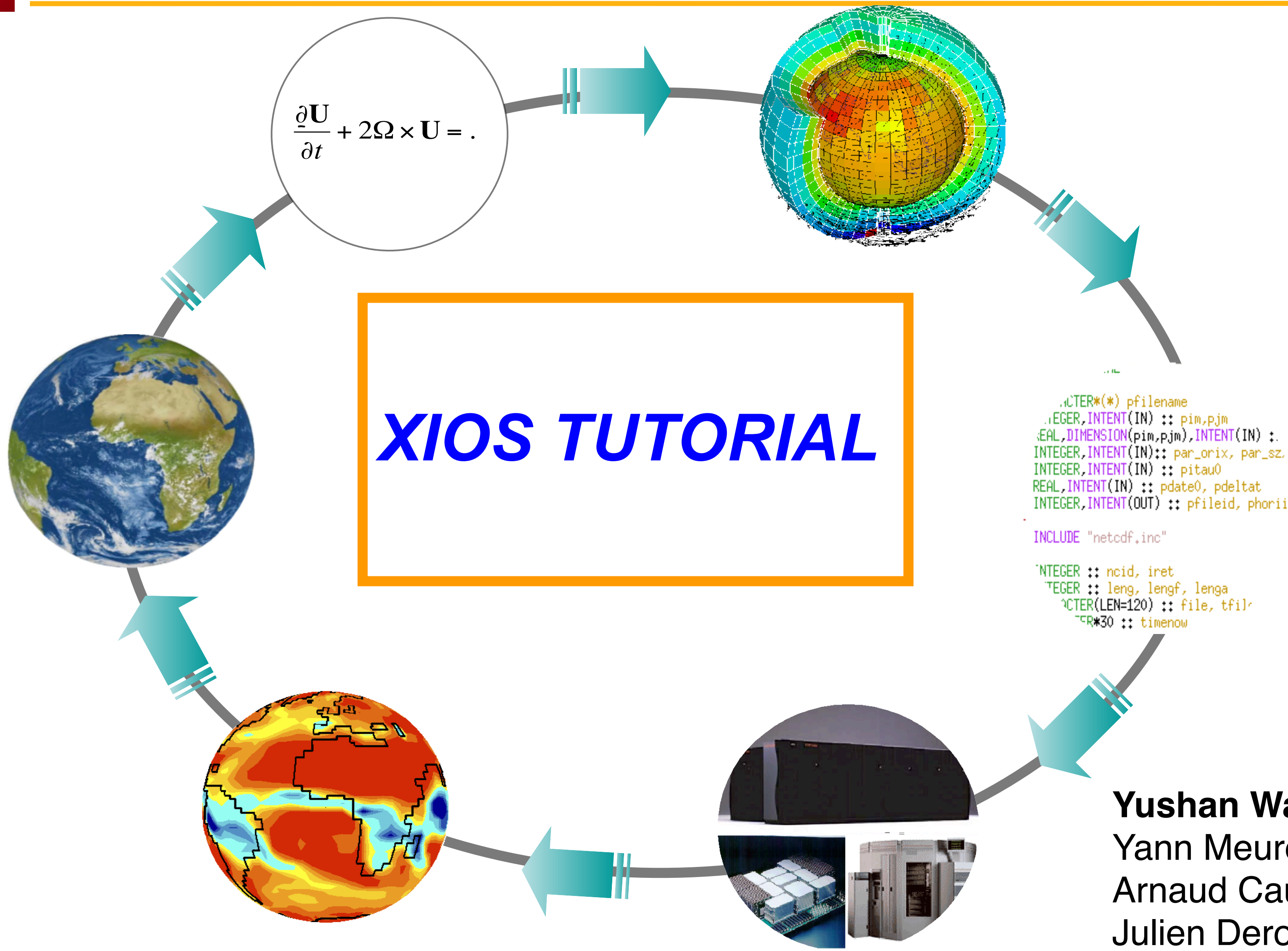


XIOS TUTORIAL

Yushan Wang
Yann Meurdesoif
Arnaud Caubel
Julien Derouillat
Olga Abramkina

Before starting the tutorial

- 9:30 to 12:30 Paris time
- 4 sessions of XIOS and 1 session of dr2xml
- Position your avatar on the orange spot to be heard
- Turn off your microphone while not speaking
- training Q&A shared document
- Groups of 2 or 3 for hands-on exercises

What will be covered in this tutorial :

LSCE

- **Background of the XIOS project**

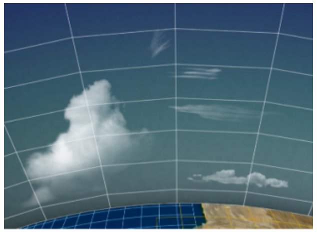
- **Get started with XIOS**
  - Install and compile XIOS
  - Use XIOS in a model
  - XML syntax
  - XIOS component (context, calendar, grid, axis, domain, file, etc.)

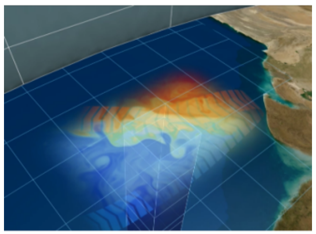
- **Get further with XIOS**
  - XIOS data distribution
  - Use XIOS to read a file
  - XIOS temporal filters
  - How to perform data transformation in XIOS
  - Activate the workflow graph in XIOS

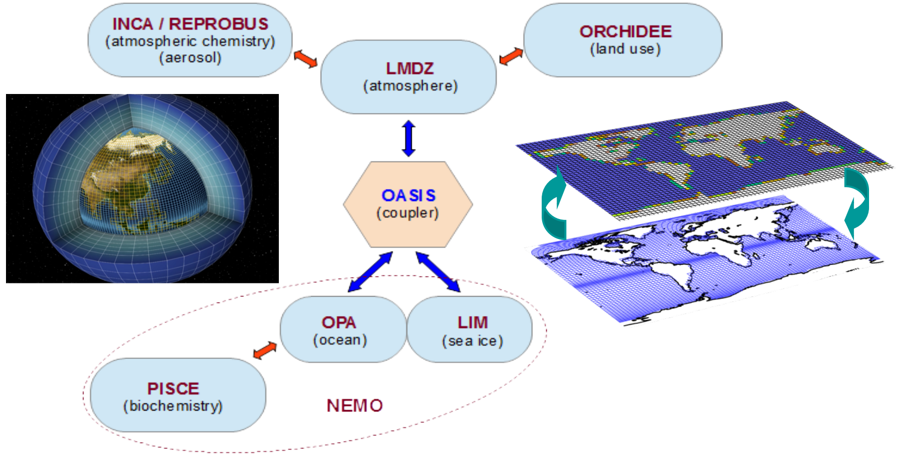
- **How to improve the performance with XIOS**
  - Client-server mode of XIOS
  - What is XIOS buffer, how it works?
  - How to understand the XIOS report?
  - How to parametrize XIOS?
  - How to debug with XIOS?

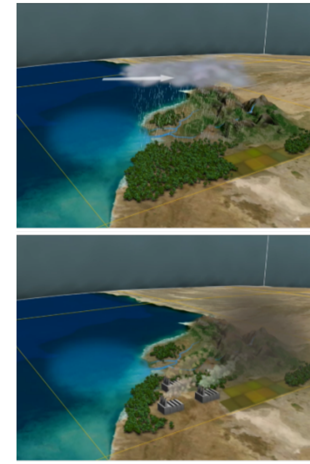
LSCE

Context : IPSL Earth System Models









- **Complex coupled model, long simulations, a lot of data generated…**
- **IPSL in the past Coupled Model Inter-comparison Project phase 6 (CMIP6)**
  - Since March 2018
  - 850 simulations (55000 model years)
  - 4 PB of data (1 PB publication ready data files)
  - High frequency files (3h, 6h, daily, ...)
  - Lots of metadata (title, description, unit, associated axis, ...)

Background of the XIOS project

LSCE

- **CMIP7 next**
  - CMIP3 : 24 models x 12 experiments = 39 TB (82 340 files)
  - CMIP5 = 50 x CMIP3
  - CMIP6 = 20~50x CMIP5

3 main challenges for climate data production

- **Efficient management of data and metadata definition from models**
  - Human cost, errors…
- **Efficient production of data on supercomputer parallel file system (HPC)**
  - 1 file by MPI process ?
    - Rebuild files (with different number of procs)
  - Parallel I/O efficiency ? (not so efficient when many procs write to same file)
- **Complexity and efficiency of post-treatment chain to be suitable for distribution and analysis**
  - Files rebuild, time series, seasonal means…
  - Mesh re-gridding, interpolation, compression…
  - Resiliency ?

LSCE

XIOS is addressing all these challenges

- **IOIPSL**

- **Efficient management of data and metadata definition from models ?**
  - Using an external XML file parsed at runtime
  - Human readable, hierarchical

- **Efficient production of data on supercomputer parallel file system ?**
  - Dedicated Parallel and Asynchronous I/O server

- **Complex and efficient post-treatment ?**
  - Integrate internal parallel workflow and dataflow
  - Managed by external XML file
  - Post-treatment can be performed "in situ "

What is XIOS

XIOS is a ~12 years old software development

- **End 2009 : « Proof of concept » : XMLIO-SERVER-V0**

- **XIOS : ~ 130 000 code lines, written in C++, interfaced with Fortran models**
  - Open Source CECILL Licence
  - Code versioning : SVN (subversion)
    - **XIOS 2.5 (stable) : forge.ipsl.jussieu.fr/ioserver/svn/XIOS/branchs/xios-2.5**
    - **XIOS trunk (dev) : forge.ipsl.jussieu.fr/ioserver/svn/XIOS/trunk**

- **Used by an increasing variety of models**
  - IPSL models : NEMO, LMDZ, ORCHIDEE, INCA, DYNAMICO
  - IGE (MAR), Ifremer (ROMS, MARS3D)
  - European NEMO consortium
  - MétéoFrance / CNRM : Gelato, Surfec, Arpège climat (CMIP6 production)
  - European models : MetOffice (HadGEM, MONC, GungHo), ECMWF (Open IFS, EC-EARTH)

What is XIOS

LSCE

Web site : wiki page

- http://forge.ipsl.jussieu.fr/ioserver/wiki
- Ticket system management and sources browsing : TRAC

- Documentation : on wiki page and under SVN (doc/ directory,)
  - Reference guide : **xios_reference_guide.pdf**
  - User guide : **xios_user_guide.pdf**

- Support mailing list : subscribe yourself
  - XIOS users list (users support) : **xios-users@forge.ipsl.jussieu.fr**
  - XIOS developers list : **xios-dev@forge.ipsl.jussieu.fr**
  - XIOS team (non public) : **xios-team@forge.ipsl.jussieu.fr**

XIOS Team

- Yann Meurdesoif (CEA/LSCE – IPSL)
- Arnaud Caubel (CEA/LSCE – IPSL)
- Yushan Wang (LSCE)
- Julien Derouillat (CEA/LSCE – IPSL)
- Olga Abramkina (IDRIS)

Download and compile XIOS

Download XIOS

- svn co http://forge.ipsl.jussieu.fr/ioserver/svn/XIOS/trunk

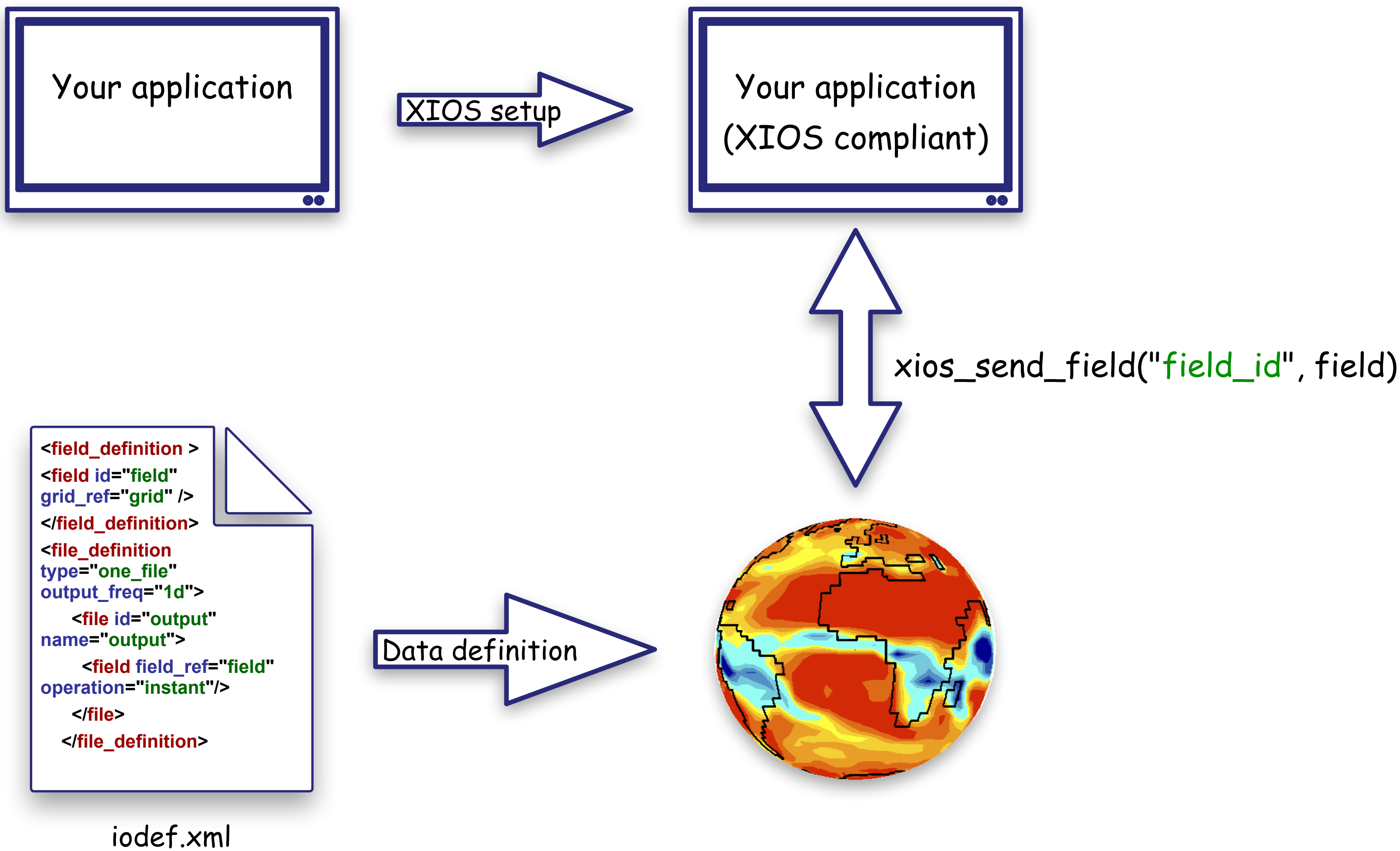
Compile XIOS

- ./make_xios

Hands-on 0

Option	Value	Default	Description
- - arch	arch_name		Mandatory. Define target architecture
- - avail			Show all predefined architectures
- - prod			Compilation in production mode (default)
- - debug			Compilation in debug mode
- - full			Generate dependencies and recompile from scratch
- - build_dir	build_directory		Name of the build directory
- - job	ntasks	1	To use parallel compilation with ntasks processus
- - netcdf_lib	netcdf_par netcdf_seq	netcdf_par	Choice of netcdf library
- - help			Show all available options and descriptions

XIOS Philosophy



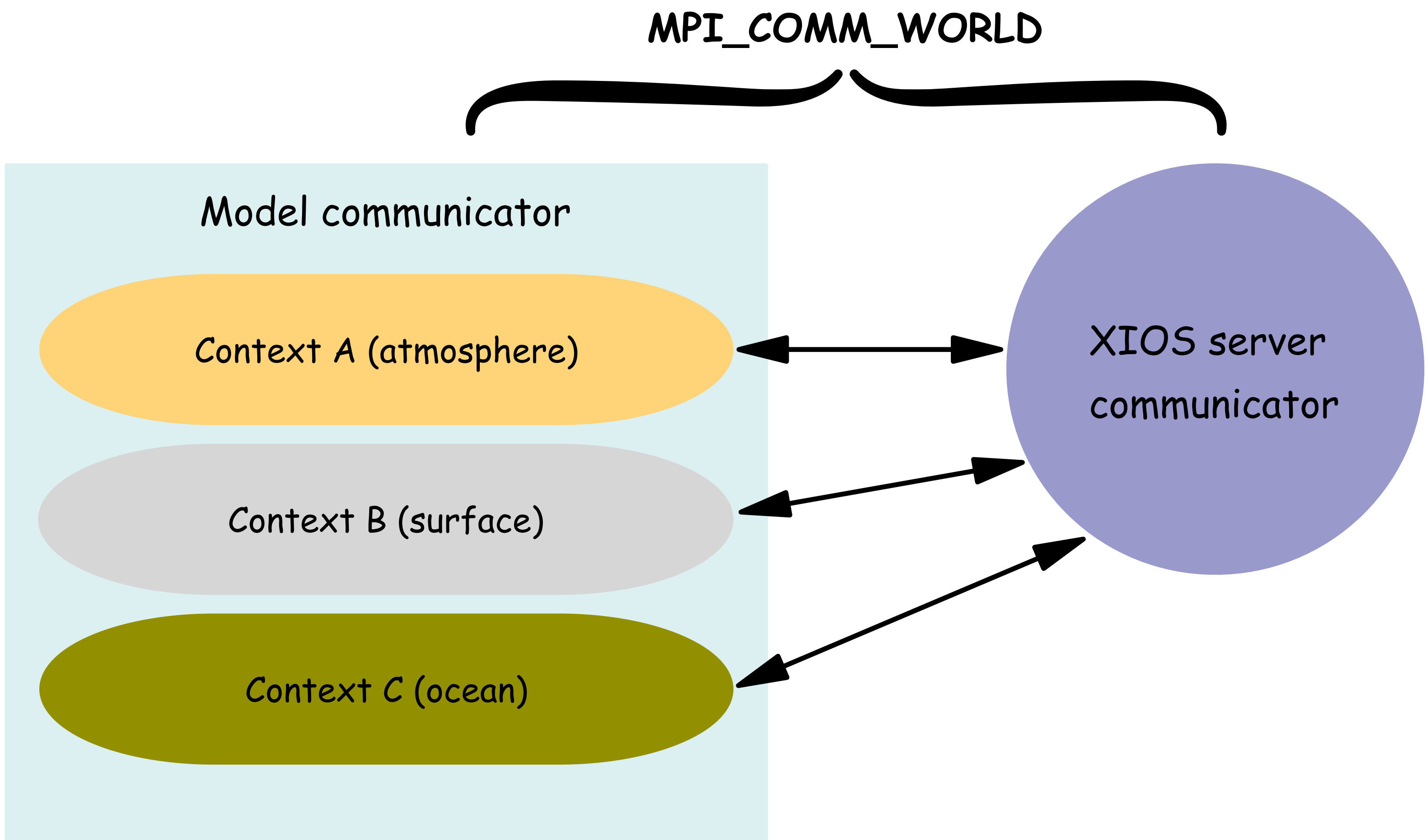
XIOS Fortran interface 1/3

CALL xios_initialize("code_id", return_comm=communicator)

- XIOS Initialization (mandatory)
- XML files are parsed at initialization
- "**code_id**" must be the same for all processes of the model (often refer as client)
- **communicator** : XIOS split the **MPI_COMM_WORLD** communicator between clients and servers and return the split one for client side

CALL xios_context_initialize("context_id", communicator)

- Context initialization (mandatory)
- "**context_id**" : id of the context to bind with context defined in XML file
- **communicator** : MPI communicator associated to the context (Must be the same or a sub communicator of which returned at XIOS initialization)
- Context initialization can be done at any time
- Different contexts can be initialized during same run
- All XIOS calls from model are collective for the associated context MPI communicator
- **set_current_context** to switch between contexts


MPI_COMM_WORLD
Model communicator
Context A (atmosphere)
Context B (surface)
Context C (ocean)
XIOS server
communicator

XIOS Fortran interface 2/3

LSCE

CALL xios_set_'element'_attr("element_id", attr=value)

- Set missing attribute
- Some attribute values are known only at run time
- All attribute can be set via the Fortran API
- New child element can be added
  - All XML tree can be created from Fortran interface
  - Ex : adding "**temp**" field element to "**field_definition**" group

```
CALL xios_get_handle("field_definition", field_group_handle)
CALL xios_add_child(field_group_handle, field_handle, id="temp")
```

CALL xios_define_calendar(type="Gregorian")
CALL xios_set_timestep(duration)

- **Mandatory** in fortran or in xml
- Set calendar type, time step length and other calendar specific attributes

CALL xios_close_context_definition()

- Closing context definition (**mandatory**)
- Context data base is analyzed and processed
- Any modification behind this point would not be taken into account and unexpected results may occur

XIOS Fortran interface 3/3

LSCE

CALL xios_update_calendar(ts)

- **ts** : time step number
- When entering a new time step, XIOS must be informed
- Time step 0 refers to part between context closure and first time step update
  - Only received field request can be done at time step 0
- Otherwise, time step must begin from 1
- Data can be exposed during a time step
  - **CALL xios_send_field("field_id",field)**
  - **CALL xios_recv_field("field_id",field)**
  - Sent data field would create a new flux tagged with timestamp related to the time step
  - Data can be received only if the outgoing flux have the same timestamp to the related time step

CALL xios_context_finalize()

- All opened context must be finalized after the end of time loop
- Finalize the current context

CALL xios_finalize()

- After finalizing all opened context, XIOS must be finalized, servers are informed, files are properly closed and performance report is generated

XIOS Hello World!

```fortran
SUBROUTINE hello_world(rank,size)
  USE xios
  IMPLICIT NONE
  INTEGER :: rank, size, timestep
  TYPE(xios_duration)      :: dtime
  DOUBLE PRECISION,ALLOCATABLE :: lon(:,:), lat(:,:), field (:,:)
  INTEGER :: ni, nj, ibegin, jbegin

  CALL xios_initialize("client", return_comm=comm)
  CALL xios_context_initialize("hello_world", comm)

  CALL xios_set_domain_attr("domain", ibegin=ibegin, ni=ni, jbegin=jbegin, nj=nj)
  CALL xios_set_domain_attr("domain ", lonvalue_2d=lon, latvalue_2d=lat)

  dtime%second=3600
  CALL xios_define_calendar(type="Gregorian")
  CALL xios_set_timestep(dtime)

  CALL xios_close_context_definition()

  DO timestep=1,96
    CALL xios_update_calendar(timestep)
    CALL xios_send_field("field", field)
  ENDDO

  CALL xios_context_finalize()
  CALL xios_finalize()
END SUBROUTINE hello_world
```

Initialize XIOS and one context

Define domain

Set time step to 1 hour

End of context definition

No more modification to the context

Enter the time loop

Free the context and quit XIOS

Hands-on 1

XIOS needs XML

XML : Extensible Markup Language

- Set of rules to define a document in a format
- Both human-readable and machine-readable

Tag : a markup construct that begins with "<" and ends with ">"

- Start-tag and end-tag : <......>   </......>
- empty-element tag : <...... />

Element : construct delimited by a start-tag and an end-tag, or consists only of an empty-element tag

- Element with start and end tag : <**domain** ... ... >   </**domain**>
- Empty-element : <**axis** ... ... />
- May have child elements

```
<file_group ... ...>
  <file ... ... />
  <file ... ... />
</file_group>
```

- May have content : text between start-tag and end-tag element : <**field**> A+B*2 </**field**>
  - Used in XIOS to define arithmetic's operations

XML

- **Attributes : a construct consisting of a name–value pair (name="value") that exists within a start-tag or an empty-element tag**
  - Ex : Element field has 3 attributes : **id**, **name** and **unit**

```
<field id="temp" name="temperature" unit="K" > </field>
<field id="temp" name="temperature" unit="K" />
```

- **Comments : begin with <!-- and end with -->**
  - **<field>** ***<!-- this is a comment, not a child nor a content -->*** **</field>**
  - "--" (double-hyphen) is not allowed inside comments. No nested comments

- **XML document must be well-formed**
  - XML document must contain only one root element
  - All start-tag element must have the matching end-tag element (case sensitive) and reciprocally
  - All element must be correctly nested

- **XML parser**
  - rapidxml
  - http://rapidxml.sourceforge.net/

General XIOS-XML Syntax

- **XML master file must be *iodef.xml***
  - Parsed first at XIOS initialization
  - Root element name is simulation
  - Root element can only contain **context** type elements

```
<simulation>
  <context id="ctx1">
    ... ...
  </context>
  <context id="ctx2">
    ... ...
  </context>
</simulation>
```

- **Main element families: represent object types stored in XIOS database**
  - **context** : isolate and confine models definition, no interference between them
  - **calendar** : mandatory, 1-to-1 association with context
  - **scalar, axis, domain**
  - **grid**
  - **field**
  - **file** : input or output
  - **variable** : define parameters for models and for XIOS parameterization

- **Each element family can be divided into 3 types (except for context)**
  - Simple elements : ex : field
  - Group elements : ex : field_group
    - Can contain children simple element
    - Can contain children nested group of the same type
  - Definition elements : ex : field_definition
    - Unique root element type
    - Act as a group element, can contains other groups or simple elements

General XIOS-XML Syntax

- **Each element may have several attributes**
  - i.e. : **<file id="out" name="output" output_freq="1d" />**
  - Attributes give information for the related element
  - Some attributes are mandatory: error is generated if attribute not defined
  - Some attributes are optional but have a default value
  - Some attributes are completely optional

- **Attributes values are ASCII string, depending on the attribute, can represent :**
  - A character string : **name="temperature"**
  - An integer or floating value : **output_level="3" add_offset="273.15"**
  - A Boolean : true/false : **enabled="true"**
    - Fortran notation .TRUE./.FALSE. is allowed but obsolete
  - A date or duration : **start_date="2000-01-01 12:00:00"**
    - See format later
  - A bound array **(inf,sup)[values]** : **value="(0,11) [1 2 3 4 5 6 7 8 9 10 11 12]"**

General XIOS-XML Syntax

```
<axis id="A" n_glo="10" name="axis"/>
<domain id="A"/> <!-- OK -->
<axis id="A" n_glo="5"/> <!-- not suggested -->
```

Special attribute id : identifier of the element

- Make reference to the element
- Unique for one given kind of element
  - Elements with same id ⇔ same element (append, overwrite)
  - Be very careful when reusing same ids, not advised (no fixed parsing order)
- Definition elements are equivalent to group elements with a fixed id
  - Ex: <field_definition ….> ⇔ <field_group id="field_definition" …>
- id is optional, but no reference to the element can be done later

XML file can be split in different parts.

- Very useful to preserve model independency, modularity
- id must be the same in both xml files
- Using attribute "src" in context, group or definition element
  - attribute value give the name of the file to be inserted in the database

```
--- iodef.xml ---
<context id="nemo" src="./nemo_def.xml" />

--- nemo_def.xml ---
<context id="nemo" >
  <field_definition … >
…
</context>
```

Inheritance in XML

LSCE

Why Inheritance ?

- Attributes can be inherited from another element of same family
- Hierarchical approach, very compact
- Avoiding useless redundancy

Inheritance by grouping : parent-child inheritance concept

- All children inherit attributes from their parent
- An attribute defined in a child is not inherited from his parent
- Special attribute "id" is **NEVER** inherited

```
<field_definition level="1" prec="4" operation="average" enabled=".TRUE.">
   <field_group id="grid_W" domain_ref="grid_W" axis_ref="depthw">
      <field id="woce" long_name="vertical velocity" unit="m/s" operation="instant" />
   </field_group>
</field_definition>
```

↓

```
<field id="woce" long_name="vertical velocity" unit="m/s" axis_ref="depthw"
         domain_ref="grid_W" level="1" prec="4" operation="instant" enabled="true" />
```

LSCE

Inheritance by referencing

- Only for **field**, **domain**, **axis**, and **scalar** elements
  - **field_ref**
  - **domain_ref**
  - **axis_ref**
  - **scalar_ref**

Don't mix up with **grid_ref** !

- Source element inherit all attributes of referenced element
  - Attributes already defined in source element are not inherited (or is overwritten)

```
<field id="toce" long_name="temperature" unit="degC" grid_ref="Grid_T" enabled="true" />
<field id="toce_K" field_ref="toce" long_name="temperature(K)" unit="degK" />

<field id="toce_K" long_name="temperature(K)" unit="degK" grid_ref="Grid_T" enabled="true"/>
```

- Reference inheritance is done **AFTER** group inheritance

Disable attribute inheritance by setting its value to "_reset_"

XIOS context

Why Context ?

- Context is similar to "namespace"
- Contexts are isolated from each other, no interference is possible
  - ids used inside one context can be reused in other context
- For parallelism, each context is associated with its own MPI communicator
  - No interference between MPI communicators
- Generally a context is associated to one model
  - Principle of modularity
- A model can declare more than one context

Context element :

- <context>...</context>
- Must be inside of the root XML element
- Must have an id
- Contains calendar and other element definition

```xml
<context id="nemo" >
  <calendar ... />
  <axis_definition>     ...  </axis_definition>
  <domain_definition>   ...  </domain_definition>
  <grid_definition>     ...  </grid_definition>
  <variable_definition> ...  </variable_definition>
  <field_definition>    ...  </field_definition>
  <file_definition>     ...  </file_definition>
</context>
```

XIOS calendar

Each context must define its own calendar

- One calendar by context
- Define a calendar type
  - Date and duration operation are defined with respect to the calendar's type
- Define starting date of the model
- Define time step of the model

Calendar type

- **Gregorian** : standard Gregorian calendar
- **D360** : fixed 360 days calendar
- **NoLeap** : fixed 365 days calendar
- **AllLeap** : fixed 366 days calendar
- **Julian** : Julian calendar (leap every 4 years)
- **user_defined** : months and days can be defined by user (planetology and paleoclimate)

Date and Duration

- A lot of XML attributes are of date or duration type
- Operation between date and duration are strongly dependent of the chosen calendar
  - Ex : date + 1 month = date + 30 day only for month 4,6,9,11

XIOS calendar

LSCE

Duration units

- Year : **y**
- Month : **mo**
- Day : **d**
- Hour : **h**
- Minute : **mi**
- Second : **s**
- Time step : **ts** (related to time step length)

Duration format

- Value of unit may be integer or floating (not recommended), mixed unit may be used in a duration definition
  - Ex. : "**1mo2d1.5h30s**"
  - Ex. : "**5ts**"

Date format

- **year-month-day␣hour:minute:second**
  - Ex. : "**2020-11-04 10:30:00**"
- Partial definition is allowed. Taking into account leftmost part
  - Ex. "**2020-11**" equivalent to "**2020-11-01 00:00:00**"
  - Ex. "**2020-11 12**" format error (OK in some case)

XIOS calendar

LSCE

Date format

- Date can be also define with a duration offset
  - Useful for defining a calendar based on standard units
  - Ex. : "**+5d**" equivalent to "**0000-1-6 00:00:00**"
  - Or mix : "**2012-5 +3600s**" equivalent to "**2012-5-1 01:00:00**"

Attributes for calendar

- **type** : define the calendar type (mandatory)
  - "**Gregorian**", "**D360**", "**NoLeap**" , "**AllLeap**", "**Julian**" or "**user_defined**"
- **time_origin** : (date) define the simulation starting date ("**0000-01-01 00:00:00**" by default)
- **start_date** : (date) define the starting date of the run ("**0000-01-01 00:00:00**" by default)
- **timestep** : (duration) define the time step of the model : mandatory

Setting up calendar

- From XML

```
<context id="nemo" />
  <calendar type="Gregorian" time_origin="2000-01-01" start_date="2020-10" timestep="1h"/>
  ...
</context >
```

XIOS calendar

LSCE

Defining an user defined calendar

- Planetology or paleo-climate can not use standard calendar

- Personalised calendar
  - Defining **day_length** in second (default **86400**)
  - Defining **month_lengths** : number of days for each month (in an array)

```
<!-- the simplified Martian calendar -->
<calendar  type="user_defined" day_length="88775"
        month_lengths="(1,24) [28 28 28 28 28 27 28 28 28 28 28 27 28 28 28 28 28 27 28 28 28 28 28 27]" />
```

  - Or if you don't want to specify month, you need to define **year_length** in second.

```
<!-- 300 days per year -->
<calendar  type="user_defined" day_length="86400" year_length="25920000"
        start_date="2020-11 12" />
```

  - In this way, the format for "date" will no longer contain "month". In Fortran interface, "month"=1
  - "**2020-11 12**" is now a valid date (11th day of year 2020, at 12 seconds)

- Possibility to define leap year
  - Attributes : **leap_year_month**, **leap_year_drift**, **leap_year_drift_offset**
  - See XIOS user guide

Fortran interface for calendar

Duration

- Fortran derived type : **TYPE(xios_duration)**
  - **(REAL) : year, month, day, hour, minute, second, timestep**

    xios_year, xios_month
    xios_day, xios_hour
    xios_minute
    xios_second
    xios_timestep

```
TYPE(xios_duration) :: duration
duration%second = 1800
duration = 1800 * xios_second
duration = 0.5 * xios_hour
```

Half an hour

Date

- Fortran derived type : **TYPE(xios_date)**
  - **(INTEGER) : year, month, day,**
    hour, minute, second

```
TYPE(xios_date) :: date(2014,12,15,10,15,0)
date%year = 2015
```

Date and duration operation

- **duration±duration, duration*real, -duration, ==, !=, >, <**
- **date-date, ==, !=, >=, >, <=, <**
- **date±duration**
- String conversion : **xios_duration_convert_[to/from]_string**
  xios_date_convert_[to/from]_string
- Useful functions : **xios_date_get_second_of_year xios_date_get_day_of_year**
  xios_date_get_fraction_of_year xios_date_get_fraction_of_day

Fortran interface for calendar

LSCE

Define a calendar from Fortran interface

```
CHARACTER(LEN=*) :: type
TYPE(xios_duration) :: timestep
TYPE(xios_date) :: start_date, time_origin
```

- Within single call
  - CALL xios_define_calendar(type, timestep, start_date, time_origin, ...)
  - type is mandatory.
- Or with individual call
  - CALL xios_define_calendar(type)
  - CALL xios_set_timestep(timestep)
  - CALL xios_set_time_origin(time_origin)
  - CALL xios_set_start_date(start_date)
- calendar **type** must be defined at first.

Hands-on 2-1

XIOS scalar

LSCE

- 7 element families in XML
  - ☑ context
  - ☑ calendar
  - ☐ scalar, axis, domain
  - ☐ grid
  - ☐ field
  - ☐ file
  - ☐ variable

- The scalar element <scalar ... />

- Attributes
  - (double) value
  - (string) name
  - (string) long_name
  - (string) scalar_ref

- More often used in data transformation
  - see later

XIOS axis

The axis element <axis ... />

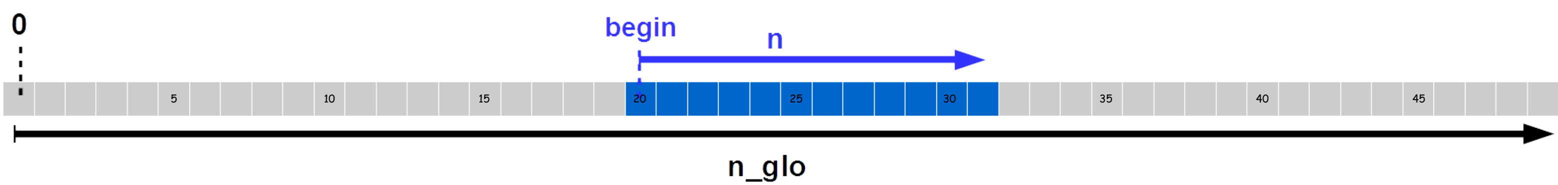
- Describe 1D axis, generally vertical axis
- **CALL xios_set_axis_attr("axis_id", ...)**

Defining the global size of the axis

- **(integer) n_glo** : global size

Defining the data parallelism distribution across MPI processes

- **(integer) n** : local axis size distribution
- **(integer) begin** : local axis distribution beginning with respect to the global axis
  - C-convention, starting from 0.
- If nothing specified, the axis is not distributed.
- Data distribution is different for each MPI process, not suitable for XML description
  - Attributes only known at run-time can be passed dynamically using the Fortran interface



Defining axis coordinate values and boundaries

- **(real 1D-array) value[n]**
- **(real 2D-array) bounds[2,n]**

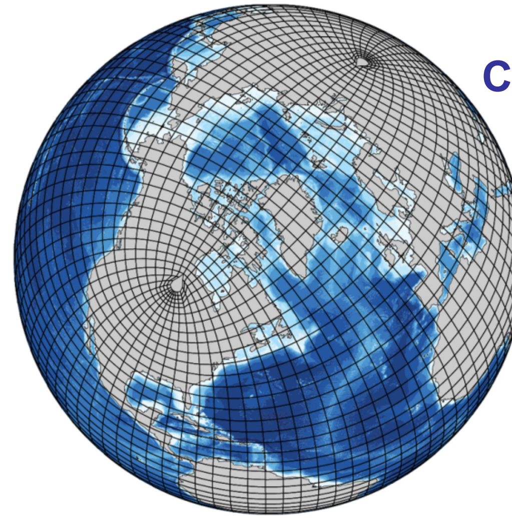
Hands-on 2-2

XIOS domain

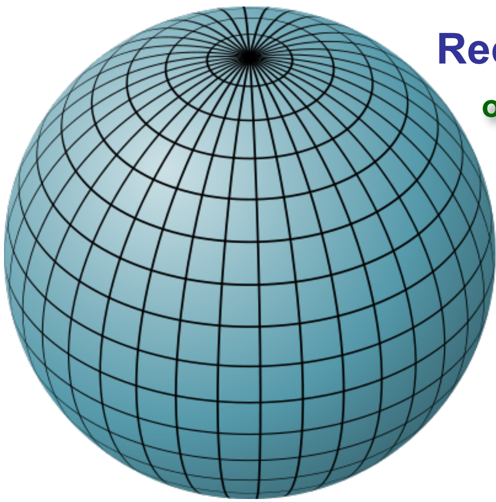
2D horizontal layer description : the domain element <domain />

- Describe generally 2D layers mapping the surface of the sphere
- Large variety of 2D domains can be described
- **(string)type** :

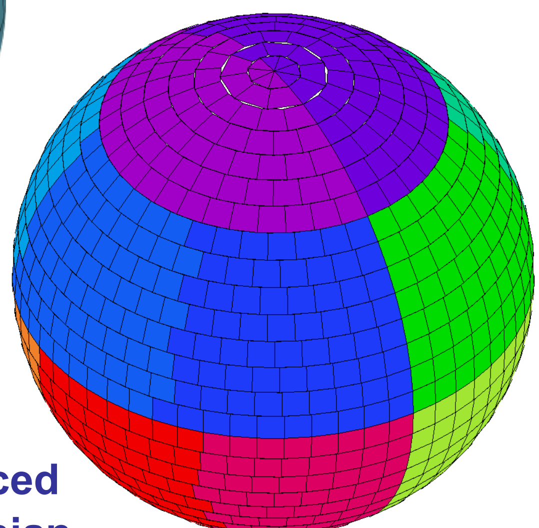
  "rectilinear", **"curvilinear"**, **"unstructured"**, **"gaussian"**



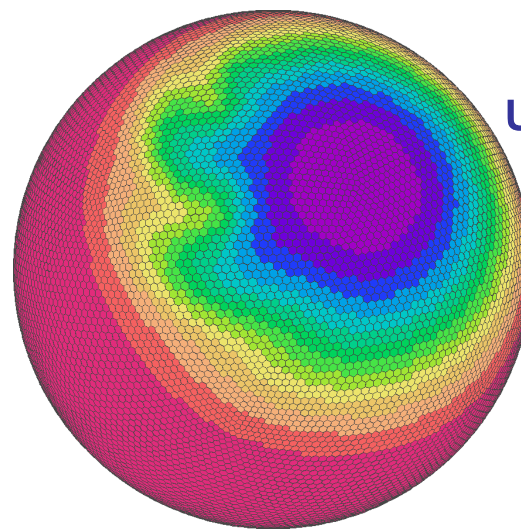
Curvilinear
nemo



Rectilinear
orchidee & lmdz



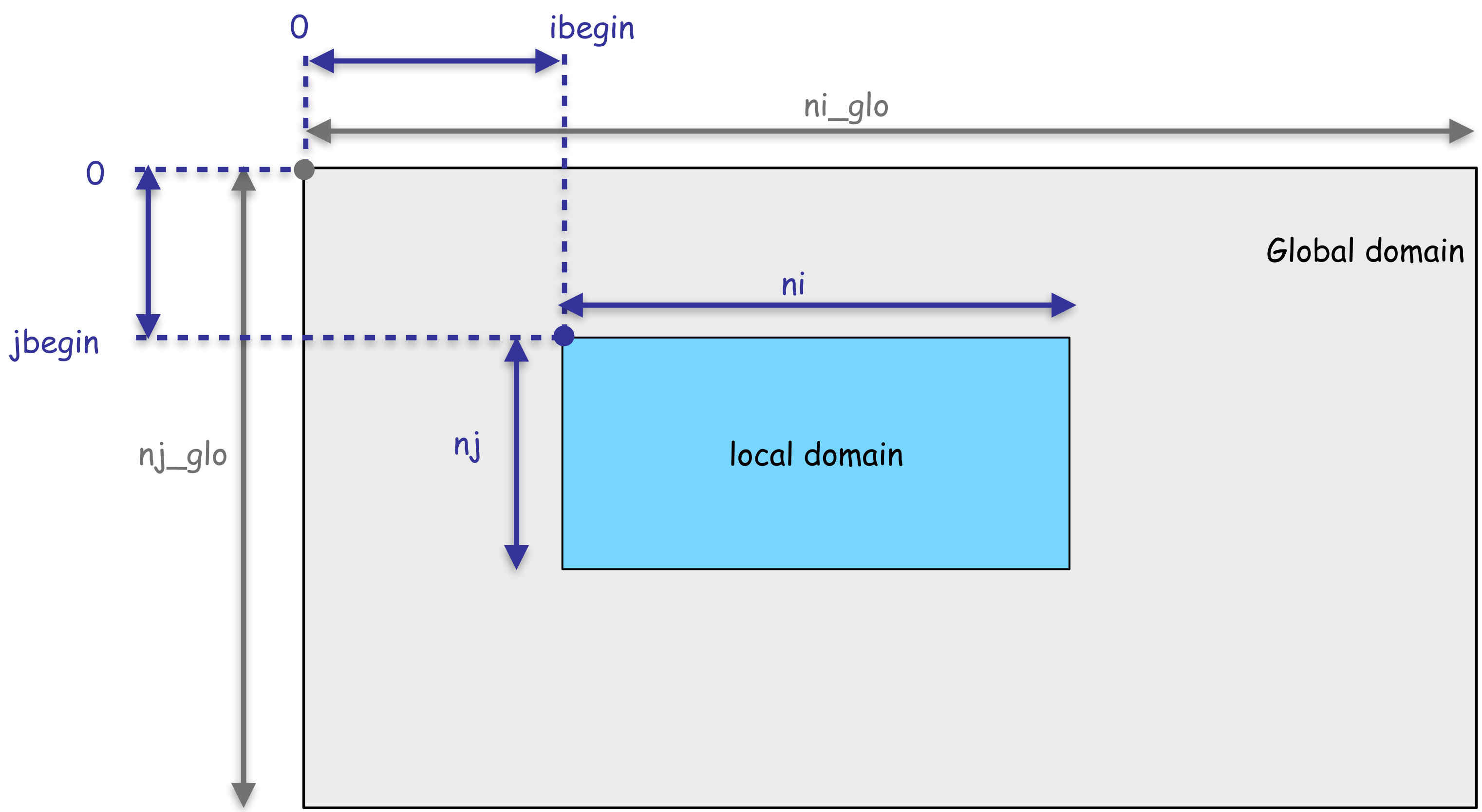
Reduced Gaussian



Unstructured
dynamico

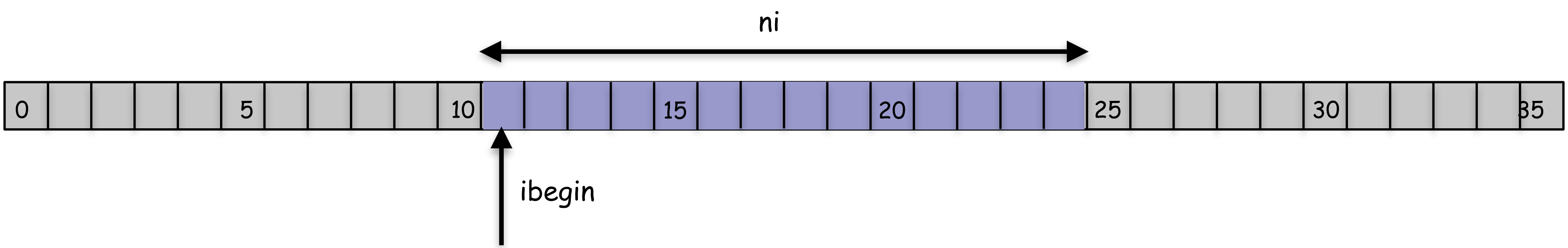
XIOS domain

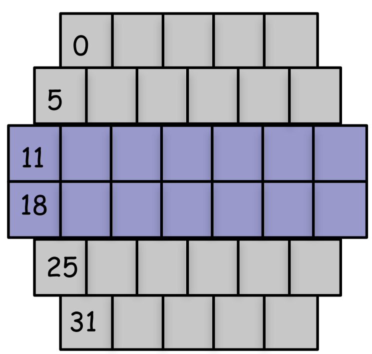
- **Rectilinear or curvilinear domains have a 2D description**
  - **(integer) ni_glo, nj_glo** : global domain size for each direction (longitude and latitude)
  - **(integer) ni, nj** : local domain size
  - **(integer) ibegin, jbegin** : starting location w.r.t the global domain (upper left corner)



XIOS domain

- **Unstructured or Gaussian domains have a 1D description**
  - **(integer) ni_glo** : global domain size
  - **(integer) ni** : local domain size
  - **(integer) ibegin** : starting location w.r.t the global domain





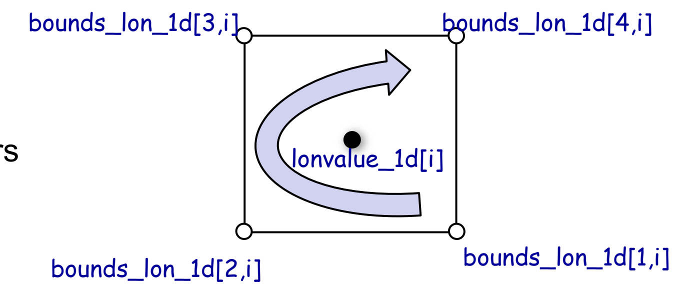
ni_glo = 36
ni = 14
ibegin = 11

XIOS domain

Defining coordinates

- For rectilinear domain
  - **lonvalue_1d[ni]** : longitude coordinates of cells
  - **latvalue_1d[nj]** : latitude coordinates of cells

  - **bounds_lon_1d[4,ni]** : longitudes boundaries of cell corners
  - **bounds_lat_1d[4,nj]** : latitudes boundaries of cell corners



- For curvilinear
  - **latvalue_2d[ni,nj]**
  - **lonvalue_2d[ni,nj]**

  - **bounds_lat_2d[4,ni,nj]**
  - **bounds_lon_2d[4,ni,nj]**

- For unstructured domain
  - **(integer) nvertex** : max number of corners/edges among cells
  - **(double) latvalue_1d[ni]**
  - **(double) lonvalue_1d[ni]**
  - **(double) bounds_lat_1d[nvertex,ni]**
  - **(double) bounds_lon_1d[nvertex,ni]**

Hands-on 2-3

XIOS grid

LSCE

7 element families in XML

- ☑ context
- ☑ calendar
- ☑ scalar, axis, domain
- ☐ grid
- ☐ field
- ☐ file
- ☐ variable

```xml
<grid_definition />

  <grid id="grid_3d">
    <domain domain_ref="domain"/>
    <axis axis_ref="axis_Z"/>
  </grid >

  <grid id="grid_4d">
    <domain id="new_domain" ... />
    <axis id="axis_P" ... />
    <axis id="axis_Q" ... />
  </grid >

</ grid_definition />
```

The grid element <grid ... />

- Can describe element of dimension : 0, 1, ..., 7
- Composed of **scalar**, **axis** and **domain**
- Empty grid is representing a scalar
- 0D : (**scalar**)
- 1D : (**axis**)
- 2D : (**domain**), or (**axis**, **axis**)
- ...
- Recommend using element reference but can also define element inside

Field geometry is provided by the underlying mesh description

Hands-on 2-4

XIOS field

- The field element <field ... />
- Represent incoming or outgoing data flux from models
- Data can be sent or received at each time step from model through the Fortran interface

Sending data	CALL xios_send_field("field_id", field)
Receiving data	CALL xios_recv_field("field_id", field)

- Fields geometry and parallel distribution is hosted by the underlying grid description
  - (string) grid_ref : id of the grid
  - For more flexibility fields can refer to a domain or/and an axis to create virtual grid
    - (string) domain_ref
    - (string) axis_ref

```
<grid id="grid_3d">
  <domain id="domain_2d" />
  <axis id="axis_1d" />
</grid>

<field id="temp" grid_ref="grid_3d" />
```

~

```
<axis id="axis_1d" />
<domain id="domain_2d" />

<field id="temp" domain_ref="domain_2d"
                 axis_ref="axis_1d" />
```

Not feasible if grid=(domain, axis, axis) for example

XIOS field

Field data from models must be conform to the grid description

- Fields can be declared of any dimensions in single or double precision
- But total **size** and **data order** must be the same as declared in the grid

```
<grid id="grid_3d">
  <domain id="domain_2d" type="rectilinear" ni_glo="100" ni="10" data_ni="12"
                                            nj_glo="50"  nj="5"  data_nj="7"/>
  <axis id="axis_1d" n_glo="20"/>
</grid>

<field id="temp" grid_ref="grid_3d"/>
```

- Global grid : 100x50x20
- Local grid : 10x5x20
- Data in model memory : **data_ni × data_nj × n_glo = 12×7×20 = 1680**
- Can be declared as :
  - **REAL(kind=4) :: temp(12,7,20)**
  - **REAL(kind=4) :: temp(1680)**
  - **REAL(kind=8) :: temp(1680)**
- but data order follows the column major order Fortran convention

Field can be output to files

- Will appear as a child element of file element
- A field can appear, in multiple files
  - using the reference attribute : **field_ref**

```
<field_definition>
  <field id="temp"     grid_ref="grid_3d"/>
  <field id="precip"   grid_ref="grid_3d"/>
  <field id="pressure" domain_ref="domain_2d"/>
</field_definition>

<file_definition>
  <file name="daily_output" freq_output="1d">
    <field field_ref="temp" />
    <field field_ref="pressure" />
  </file>

  <file name="monthly_output" freq_output="1mo">
    <field field_ref="temp" />
    <field field_ref="precip" />
  </file>
</file_definition>
```

XIOS field

Field attributes

- Field description :
  - **(string)** **name** : name of the field in the file. If not specified, "**id**" will be used in place
  - **(string)** **long_name** : set "**long_name**" netcdf attribute conforming to CF compliance
  - **(string)** **standard_name** : set "**standard_name**" netcdf attribute
  - **(string)** **unit** : set "**unit**" netcdf attribute
  - **(double)** **valid_min/valid_max** : set **valid_min** & **valid_max** nectdf attribute

- Enable/disable field output :
  - **(boolean)** **enabled** : if false, field will not be output (**default=true**)
  - **(integer)** **level** : set the output level of the field (**default=0**) with respect to the file attribute "**level_output** ".
    If **level>level_output** , the field will not be output.

- Precision and compression :
  - **(integer)** **prec** : define the output precision of the field : **8->double, 4->single, 2->2-byte integer**
  - **(double)** **add_offset, scale_factor** : output will be **(field+add_offset)/scale_factor**
  - **(integer)** **compression_level** **(0-9)** : set the gzip compression level provided by netcdf4/hdf5: due to HDF5 limitation, doesn't work for parallel writing. If not set data is not compressed.
  - **(boolean)** **indexed_output** : if set to true, only not masked value are output.

XIOS field

Field time integration

- At each time step , data field are exposed from model (**xios_send_field**)
- Data are extracted according to the grid definition
- Time integration can be performed on incoming flux
- The time integration period is fixed by file output frequency (**output_freq** attribute)
- **(string) operation** : time operation applied on data flux
  - **once** : data are used one time (first time)
  - **instant** : instant data values will be used
  - **maximum** : retains maximum data values over the integration period
  - **minimum** : retains minimum data values over the integration period
  - **average** : make a time average over the period
  - **cumulate** : cumulate date over the period
- Example : each day, output the time average and instant values of "**temp**" field

```
<file name="output" output_freq="1d">
  <field field_ref="temp" name="temp_average" operation="average"/>
  <field field_ref="temp" name="temp_instant" operation="instant"/>
</file>
```

LSCE

Time sampling management

- Some fields are not computed every time step
- **(duration) freq_op** : field will be extract from model at "**freq_op**" frequency
- **(duration) freq_offset** : time offset before extracting the field at "**freq_op**" frequency
- Strongly advised to set **freq_op** and **freq_offset** as a multiple of time step

- Example : for making a daily averaging, get "**temp**" value every 4 time steps. The first value extracted will be at 2nd time step.

```
<file name="output" output_freq="1d">
  <field field_ref="temp" operation="average" freq_op="4ts" freq_offset="1ts"/>
</file>
```

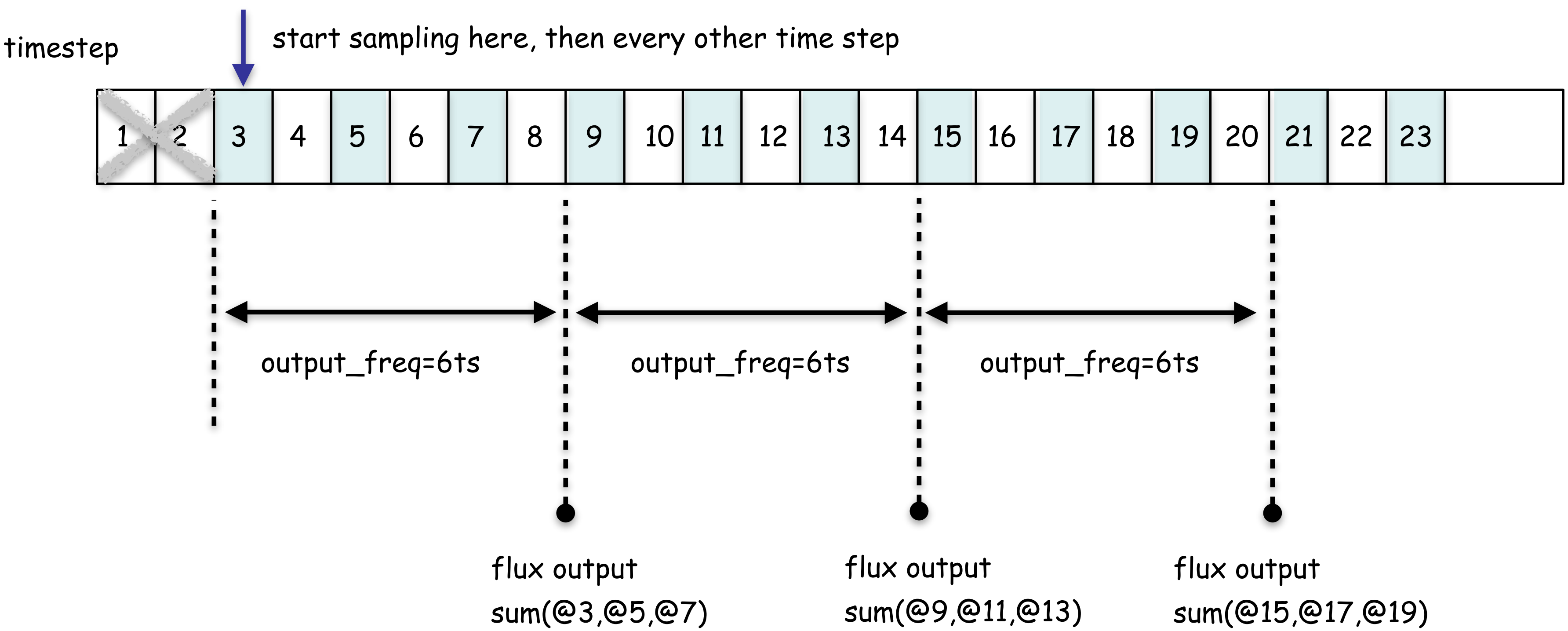
Undefined values and time operation

- Undefined values must not participate to time integration operation
  - Set **default_value** attribute as the undefined value. If not defined, missing value will be 0.
  - **(boolean) detect_missing_value** : for the current time step, all field value equal to **default_value** (undefined value) will not be taking into account to perform the time integration (**average, minimum, maximum, cumulate**)
- Very expensive since each value of the mesh must be tested

Hands-on 2-5

XIOS field

freq_offset = 2ts
freq_op = 2ts
output_freq = 6ts
operation = accumulate



LSCE

The file element <file ... />

- File element can contain **field** elements or **field_group** elements
- All listed field elements are **candidates** for output
- **(string) field_group_ref** : fields included in the referred field group will be included in file

```
<field_definition>
  <field_group id="fields_3d" grid_ref="grid_3d"/>
    <field id="temp"   >
    <field id="precip" >
  </field_group>
  <field id="pressure" domain_ref="domain_2d"/>
</field_definition>

<file_definition>
  <file name="daily_output" freq_output="1d">
    <field_group field_group_ref="fields_3d" operation="average"/>
    <field_group operation="instant"/>
      <field field_ref="temp" name="temp_inst" />
      <field field_ref="pressure" name="pressure_inst" />
    </field_group>
    <field field_ref="pressure" operation="average" />
  </file>
</file_definition>
```

Variables output as average :

- **temp**
- **precip**
- **pressure**

Variables output as instant

- **temp_inst**
- **pressure_inst**

LSCE

Enabling /disabling output

Hands-on 2-6

- Field can be enabled/disabled individually
  - **(bool)** **enabled** field attribute
- Enable/disable with level output
  - **(integer)** **output_level** file attribute : set level of output
  - **(integer)** **level** field attribute : if **level** > **output_level**, field is disabled
- Enable/disable all fields
  - **(bool)** **enabled** file attribute : if set to **false**, all fields are disabled
- Files with all fields disabled will not be output

File format

- For now file output format is only **NETCDF**
  - **Grib2** and **HDF5** output format will be considered in future
- Parallel write into a **single file** or sequential write to **multiple files** (1 file by xios server)
  - **(string)** **type** attribute : select output mode "**one_file**" / "**multiple_file**"
  - For "**multiple_file**" mode, files are suffixed with xios servers ranks
- Can choose between **netcdf4** et **netcdf4 classical** format
  - **(string)** **format** attribute : "**netcdf4**" for **netcdf4/hdf5** or "**netcdf4_classical"** for historical **netcdf3** format
  - In “**one_file**" mode, use **hdf5** parallel for **netcdf4** format and **pnetcdf** for classical format.
  - Sequential **netcdf** library can be used in **multiple_file** mode
- Data can be compressed : only available with **netcdf4** format (**hdf5**) in sequential write (**multiple_file**)
  - **(integer)** **compression_level** attribute : compression level (**0-9**), can be fixed individually with field attribute

XIOS variable

LSCE

The variable element <variable ... />

- Variable is used to define parameters
- Variable can be set or queried from model
  - Could replace Fortran **namelist** or IPSL **run.def** files
- Used internally by XIOS to define its own parameters

Attributes

- **(string) id**
- **(string) name** : name of the attribute (optional)
- **(string) type** : type of the variable (optional)
  - **"bool", "int16", "int", "int32", "int64", "float", "double", "string"**

Setting variable values from XML

- Values are defined in the content section

```
<file>
   <variable id="int_var"  type="int"> 10 </variable>
   <variable id="string_var" type="string"> 10 </variable>
</file>
```

variable_definition and variable_group

XIOS variable

LSCE

Set or query value from model

- Set variable : **ierr = xios_setvar('var_id',variable)**
- Get variable : **ierr = xios_getvar('var_id',variable)**
  - return **false** if **'var_id'** is not defined and second argument value is unchanged
  - Return **true** if **'var_id'** is defined and second argument contains the read value

```
<variable_definition>
   <variable id="int_var"  type="int"/> 10 </var>
   <variable id="string_var" type="string">a string variable</variable>
</variable_definition>



USE xios
…
INTEGER :: int_var
CHARACTER(LEN=256) :: string_var
LOGICAL :: ierr

  ierr=xios_getvar('int_var',intvar)
  ierr=xios_setvar('int_var',intvar+2)
  ierr=xios_getvar('int_var',intvar)           ! -> int_var=12
  ierr=xios_getvar('string_var',string_var)     ! -> string_var="a string variable"
```

How to setup hands-on exercises

That's all for today

- ☑ Background
- ☑ Install and compile XIOS
- ☑ Plug XIOS to your app
- ☑ XML syntax

7 element families

- ☑ context
- ☑ calendar
- ☑ scalar, axis, domain
- ☑ grid
- ☑ field
- ☑ file
- ☑ variable

Before doing the hands-on exercises : (training_notes.pdf)

- Please go to the root folder of the training **"XIOS_TRAINING"**.
- "**svn update**" to get the latest content of the training, including slides and exercises.
- "**source ./hands-on.env**" to initialize the correct computing environment.
- In each hands-on folder, you should firstly run the command "**./init-hands-on.sh**" to initiate the codes. You can re-run this command at any time you want to restart the exercise.
- To compile the program, use "**make**".
- To launch the executable, you can use "**./run_ubuntu**" which will launch with 4 MPI processes.
- Step by step solutions can be found in the "**answer**" folder.

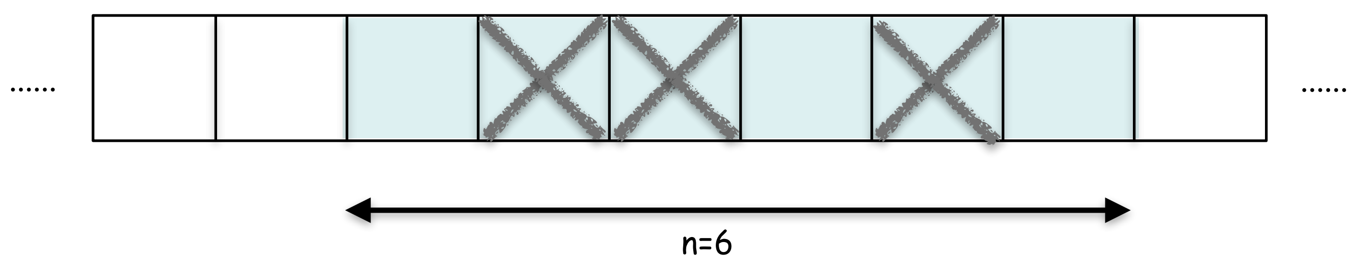
XIOS axis data distribution

Defining how data are stored in memory

- Data are stored in memory as Fortran array
- But data can be masked, or ghost cells are not valid data, or axis value can be compressed
- XIOS will extract only required value from memory
- Must describe valid data with attributes
- Whole data are valid by default

Masking Data (optional)

- **(boolean 1D-array) mask[n] (false/zero : data masked)**
- Masked data will not be extracted from memory and will appear as missing values in output files



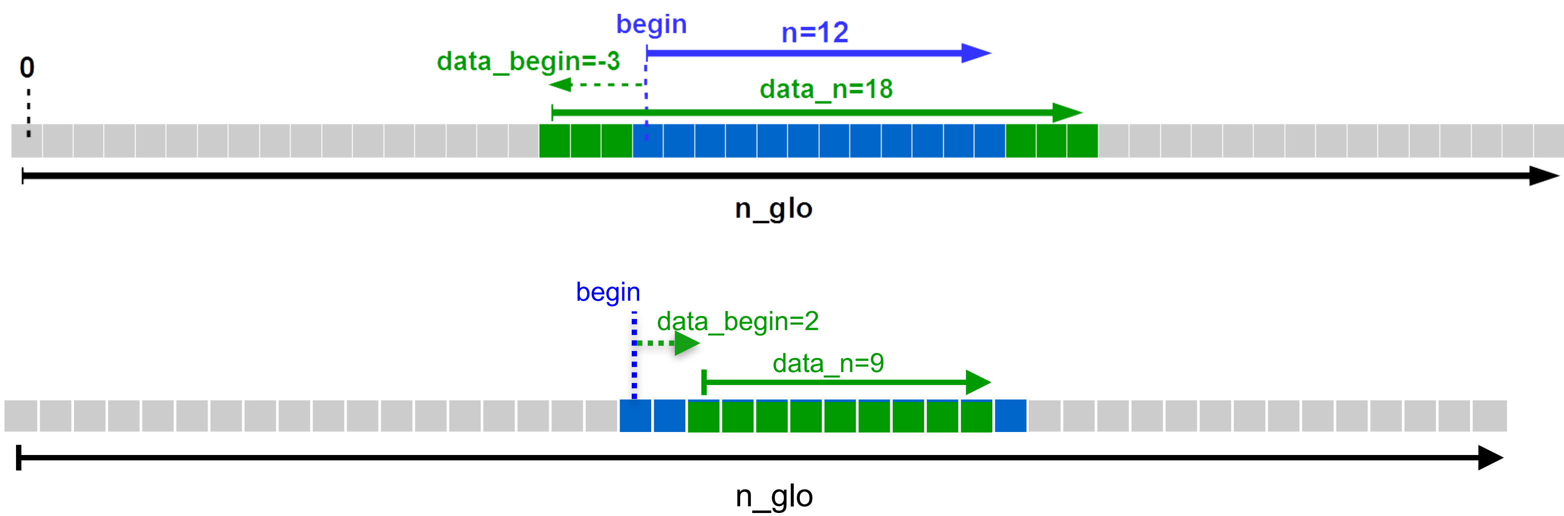
mask="(0,5)[true false false true false true]"

data = {a, b, c, d, e, f}

valid data = {a, d, f}

Defining ghost cells (optional)

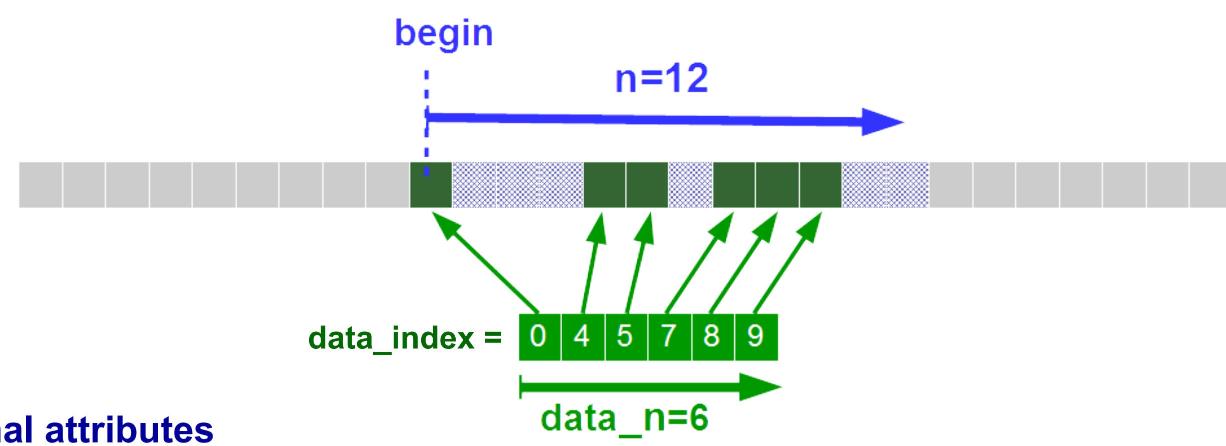
- **(integer) data_n** : size of the data in memory (default : **data_n=n**)
- **(integer) data_begin** : offset with respect to local axis distribution beginning
  - default : **data_begin=0**
  - Negative offset : data outside of the local distribution will not be extracted (ghost cell)
  - Positive offset : data in interval [**begin**, **data_begin**] and [**data_begin+data_n-1**, **begin+n-1**] are considered as masked.



XIOS axis data distribution

Defining compressed data (optional)

- Data can be compressed in memory (ex : land point), and can be decompressed for output
- Undefined data are considered as masked and will be output as missing value
- **(integer 1D-array) data_index**
  - Define the mapping between data in memory and the corresponding index in the local axis distribution
  - **data_index[i]=0** map the beginning of the local distribution
  - Negative index or greater than **n-1** will be outside of the distribution and will not be extracted



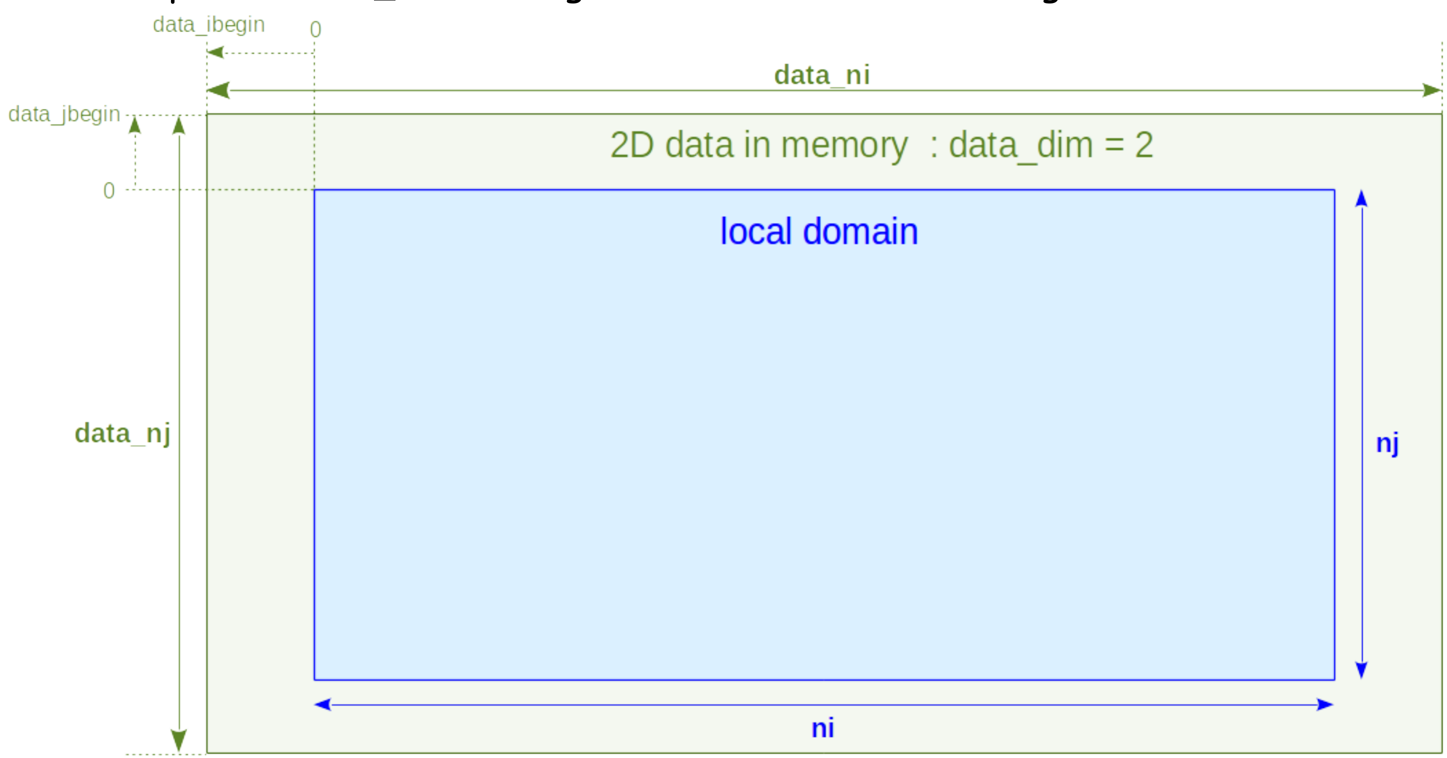
Other optional attributes

- **(string) name**
- **(string) long_name**
- **(string) unit**
- **(bool) positive** : set "**positive**" CF attribute in Netcdf output

XIOS domain data distribution

Data representation in memory : similar to 1D-axis but for 2 dimensions

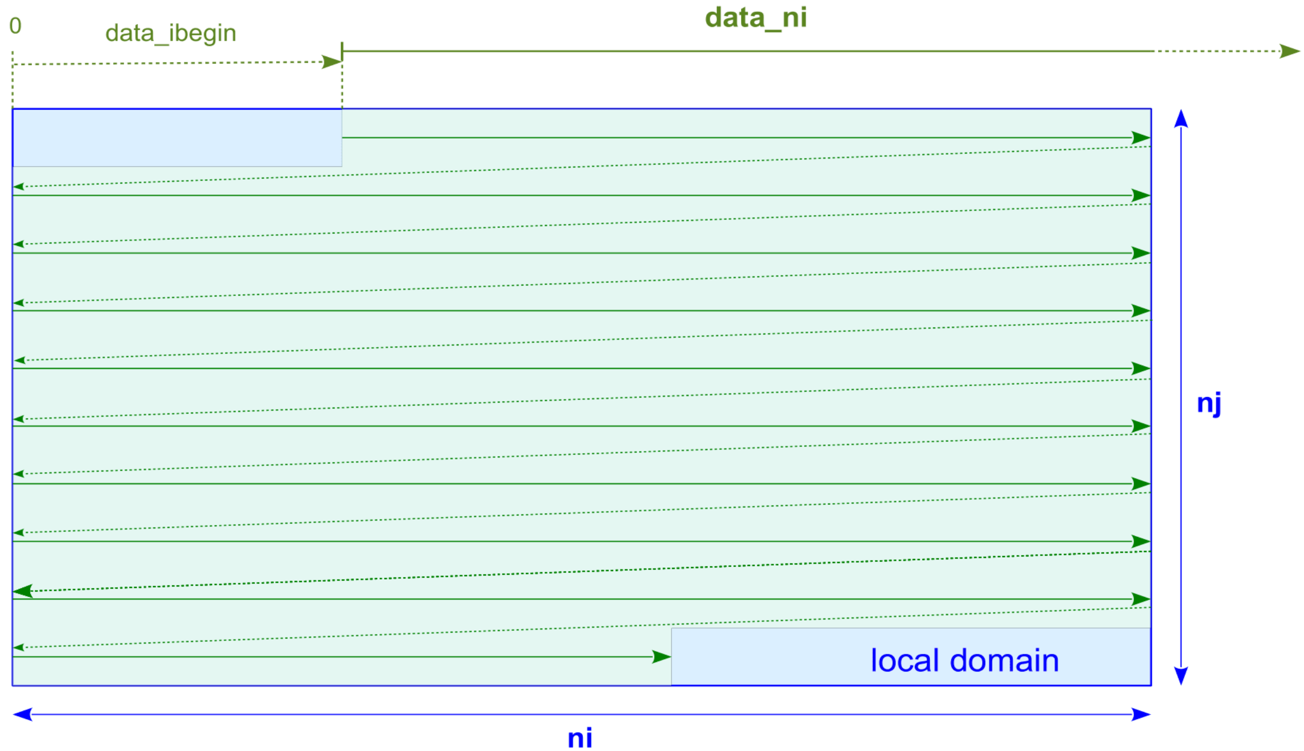
- Can be 1D-array (horizontal layer as a vector) or 2D-array
  - (integer) **data_dim** : **1(default)** or **2**
- **(integer) data_ni, data_nj** : size of the data array
- **(integer) data_ibegin, data_jbegin** : Offset for each dimension with respect to local domain distribution beginning : may be negative or positive (default : **0**)
- Example for **data_dim=2**, negative offsets to eliminate ghost cells



XIOS domain data distribution

- Example for **data_dim=1** : horizontal layer seen as a vector
- **(integer) data_ni** : size of the data array
- **(integer) data_ibegin**: Offset with respect to local domain distribution beginning
  - ➡ Positive offsets, local domain from different processes can overlap

1D data in memory : data_dim = 1



XIOS domain data distribution

LSCE

Unstructured domain has a 1D description

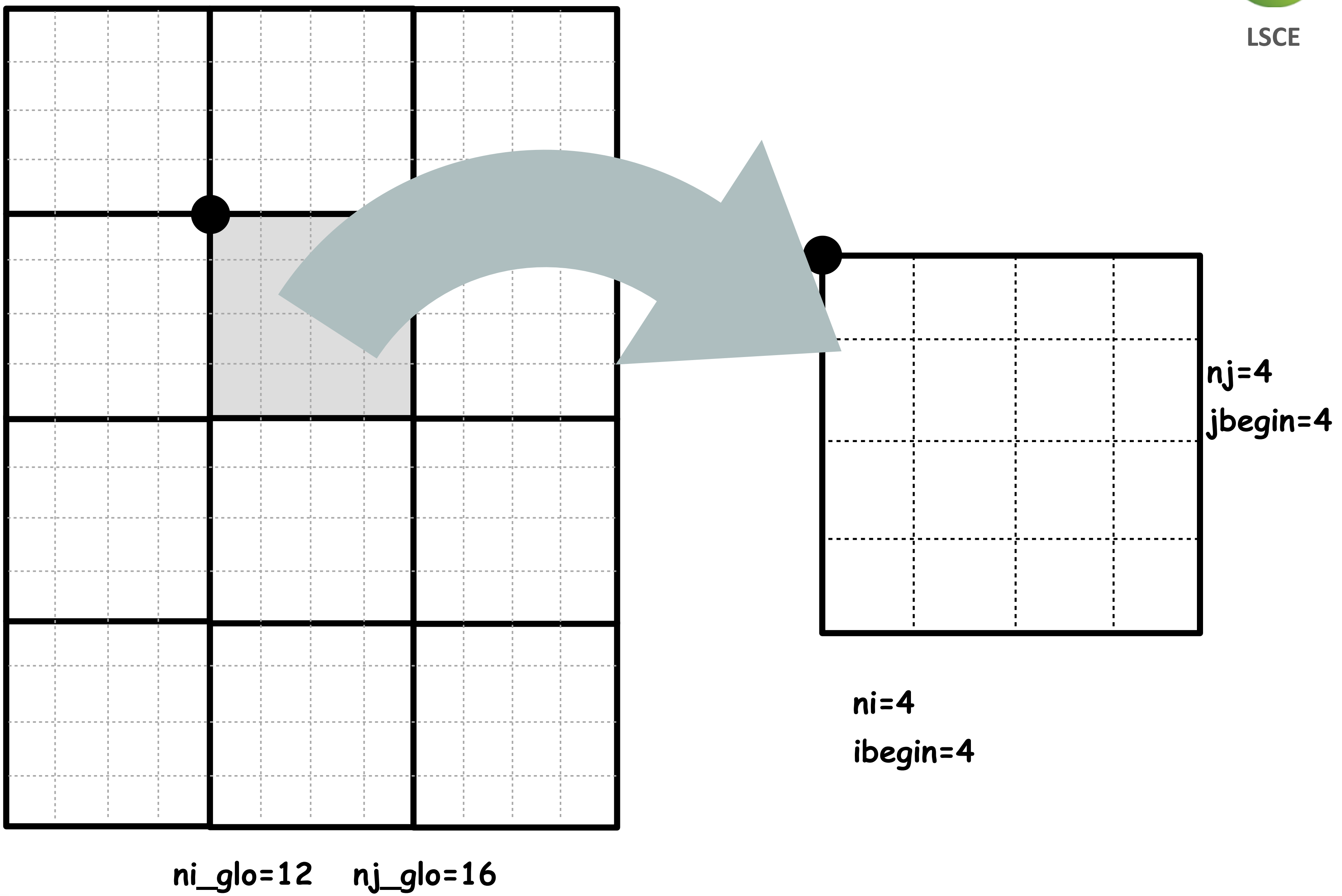
- Data in memory is always a vector
  - data_dim=1

Compressed data (on "data")

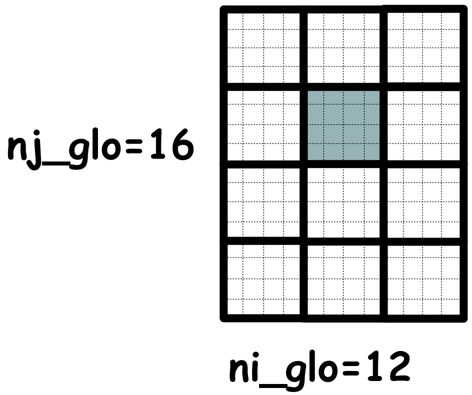
- For data_dim=1 (decompressed data is a 1D-array)
  - data_i_index[data_ni] : index for decompressed local domain represented by vector
  - exclusive with data_ibegin

- For data_dim=2 (decompressed data is a 2D-array)
  - data_nj must be equal to data_ni
  - data_i_index[data_ni], data_j_index[data_ni] : indexes for decompressed local domain represented as a 2D-array
  - exclusive with data_ibegin, data_jbegin

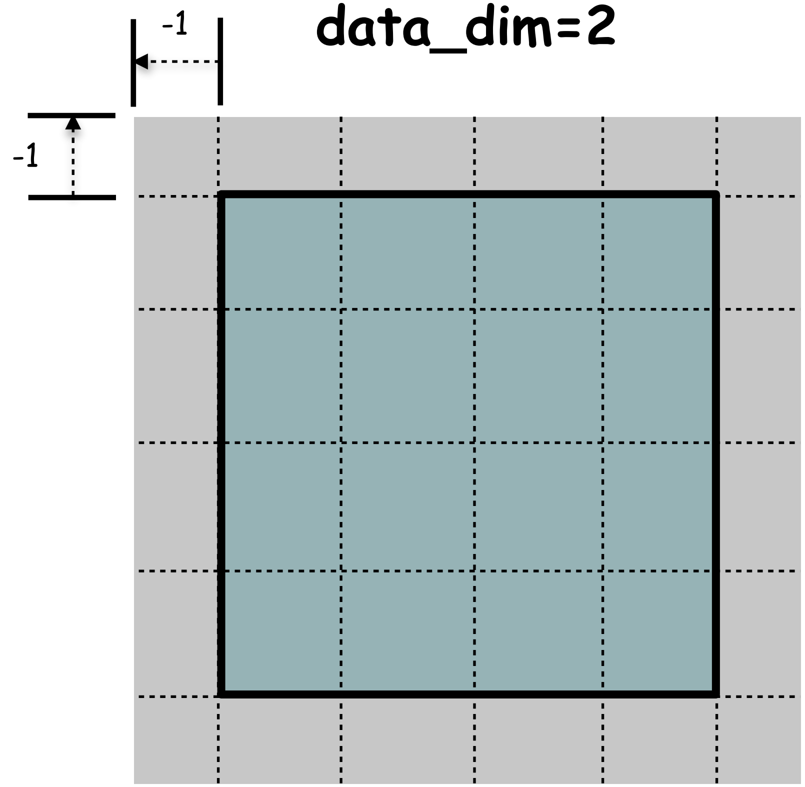
Clarification on the domain data distribution



Clarification on the data distribution on domain



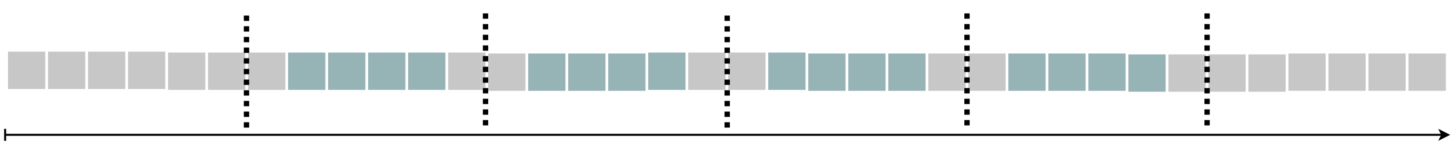
data_dim=2



ni = 4
nj = 4
ibegin = 4
jbegin = 4

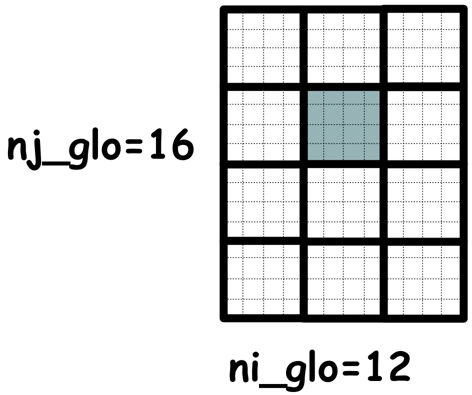
data_ibegin = -1
data_jbegin = -1
data_ni = 6
data_nj = 6

data from model :



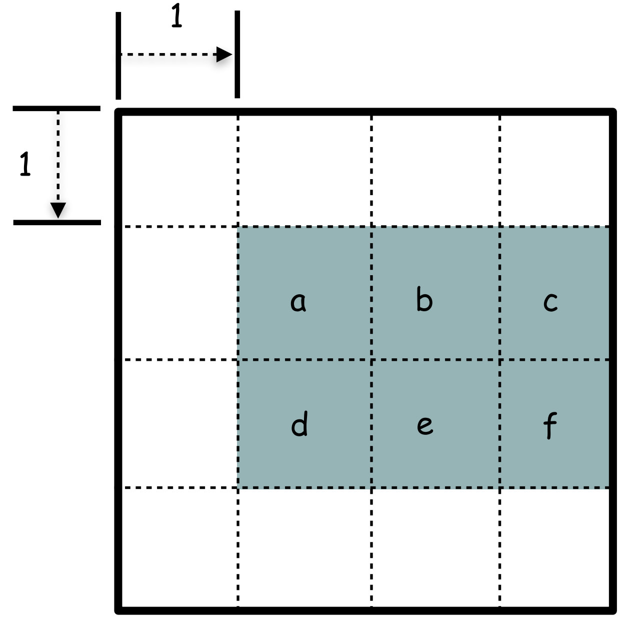
data size = 36

Clarification on the data distribution on domain



data_ibegin = 1
data_jbegin = 1
data_ni = 3
data_nj = 2

data_dim=2



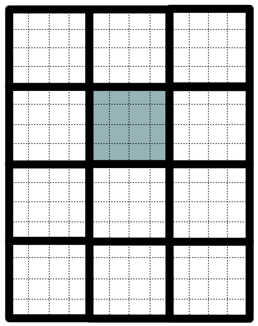
ni = 4
nj = 4
ibegin = 4
jbegin = 4

data from model :

a	b	c	d	e	f

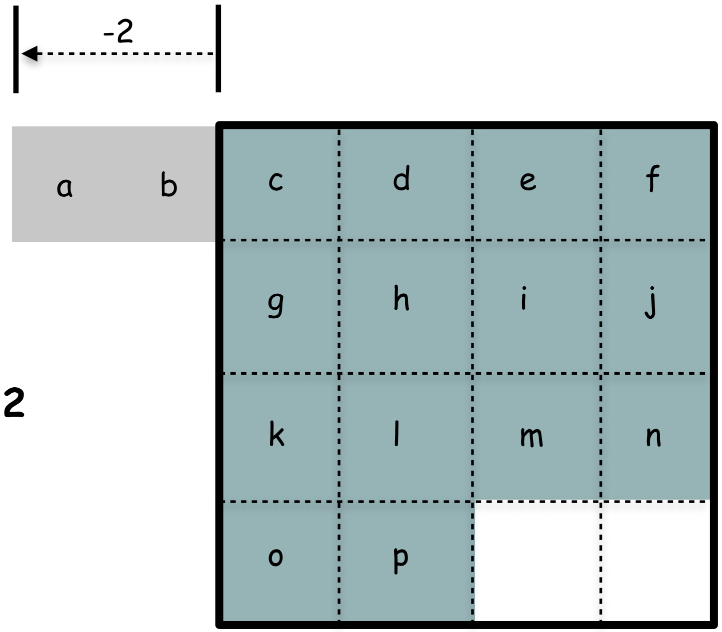
Clarification on the data distribution on domain

nj_glo=16



ni_glo=12

data_dim=1



data_ibegin = -2
data_ni = 16

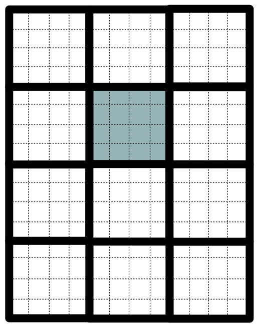
ni = 4
nj = 4
ibegin = 4
jbegin = 4

data from model :

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p

Clarification on the data distribution on domain

nj_glo=16

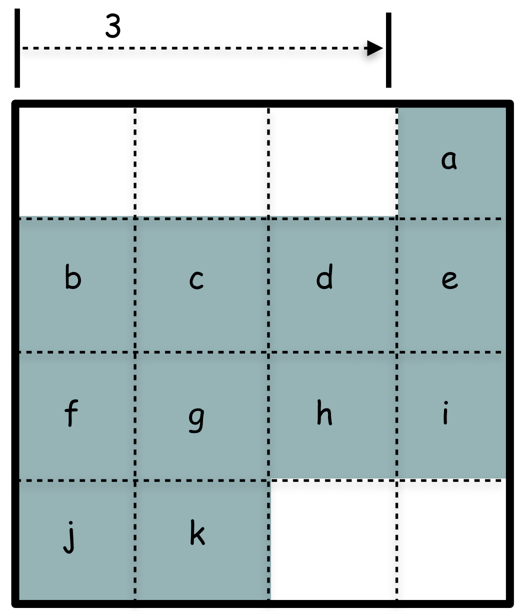


ni_glo=12

data_ibegin = 3

data_ni = 11

data_dim=1



ni = 4

nj = 4

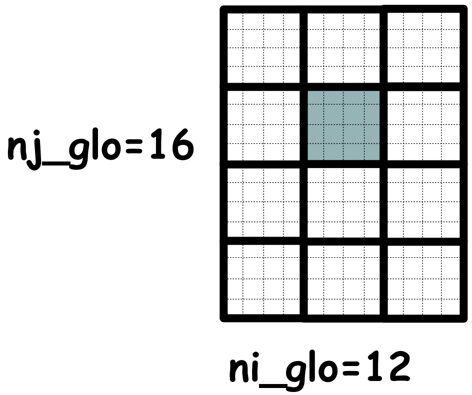
ibegin = 4

jbegin = 4

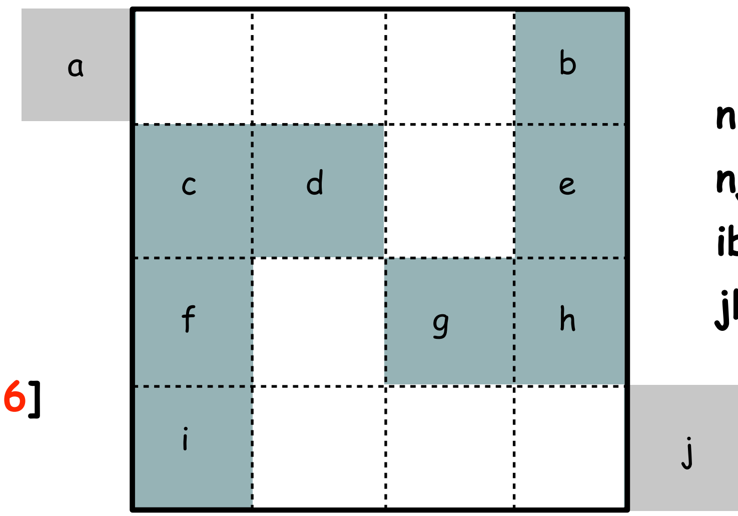
data from model :

a	b	c	d	e	f	g	h	i	j	k

Clarification on the data distribution on domain



data_dim=1



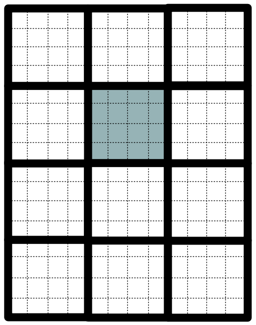
ni = 4
nj = 4
ibegin = 4
jbegin = 4

data_ni = 10
data_i_index =
[-1, 3, 4, 5, 7, 8, 10, 11, 12, 16]

data from model :

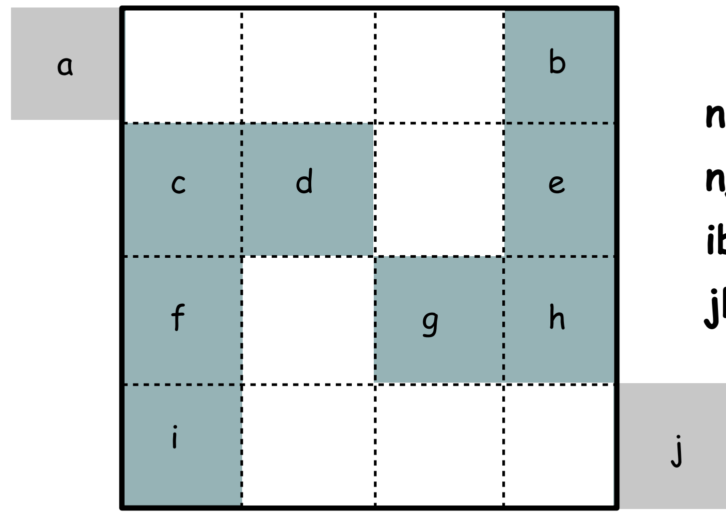
Clarification on the data distribution on domain

nj_glo=16



ni_glo=12

data_dim=2



ni = 4
nj = 4
ibegin = 4
jbegin = 4

data_ni = 10
data_nj = 10
data_i_index =
[-1, 3, 0, 1, 3, 0, 2, 3, 0, 4]
data_j_index =
[0, 0, 1, 1, 1, 2, 2, 2, 3, 3]

data from model :

XIOS data mask

Masking grid point individually

- Ex. **grid=(domain, axis)**
- masking one point in the 3rd axis means masking a full 2D layer in the 3d grid

- Grid point can be masked individually using the mask attribute

- Regarding of the dimensionality of mask arrays, **mask_1d** to **mask_7d** are allowed
  - Total mask size must be equal to the local domain size
  - Ex : **<grid id="grid_3d" mask_3d="(0,9)x(0,4)x(0,19)[0 1 1 0 ... 0 1]">**
  - Or : **<grid id="grid_3d" mask_1d="(0,9990)[0 1 1 0 ... 0 1]">**
  - Not practical with xml. Better set mask via Fortran API.
  - 0 or false => masked

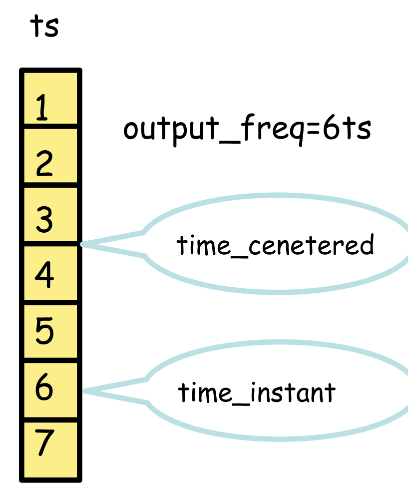
Hands-on 3

Output file structure

File structure

- XIOS respects CF convention as much as possible

- One time record (unlimited dimension) by file
  - **(duration)** **output_freq** : define the output frequency and the time axis
  - **time_counter** dimension and axis are written conforming to CF convention



- Fields of different grids can be in same file
  - Longitude, latitude and verticals axis are automatically written with the associate metadata following CF convention
  - Axis boundaries will be also written if available

- Some fields attributes (**standard_name**, **long_name**, **unit**,…) will be output as field metadata

Output file structure

- Example of **netcdf** file output with XIOS

```
netcdf output_atmosphere_2D_HR {
dimensions:
        axis_nbounds = 2 ;
        lon = 200 ;
        lat = 200 ;
        time_counter = UNLIMITED ; // (30 currently)
variables:
        float lat(lat) ;
                lat:axis = "Y" ;
                lat:standard_name = "latitude" ;
                lat:long_name = "Latitude" ;
                lat:units = "degrees_north" ;
                lat:nav_model = "domain_atm_HR" ;
        float lon(lon) ;
                lon:axis = "X" ;
                lon:standard_name = "longitude" ;
                lon:long_name = "Longitude" ;
                lon:units = "degrees_east" ;
                lon:nav_model = "domain_atm_HR" ;
        float tsol(time_counter, lat, lon) ;
                tsol:long_name = "Surface Temperature" ;
                tsol:online_operation = "average" ;
                tsol:interval_operation = "3600 s" ;
                tsol:interval_write = "1 d" ;
                tsol:cell_methods = "time: mean (interval: 3600 s)" ;
                tsol:coordinates = "time_centered" ;
        double time_centered(time_counter) ;
                time_centered:standard_name = "time" ;
                time_centered:long_name = "Time axis" ;
                time_centered:calendar = "gregorian" ;
                time_centered:units = "seconds since 1999-01-01 15:00:00" ;
                time_centered:time_origin = "1999-01-01 15:00:00" ;
                time_centered:bounds = "time_centered_bounds" ;
        double time_centered_bounds(time_counter, axis_nbounds) ;
        double time_counter(time_counter) ;
                time_counter:axis = "T" ;
                time_counter:standard_name = "time" ;
                time_counter:long_name = "Time axis" ;
                time_counter:calendar = "gregorian" ;
                time_counter:units = "seconds since 1999-01-01 15:00:00" ;
                time_counter:time_origin = "1999-01-01 15:00:00" ;
                time_counter:bounds = "time_counter_bounds" ;
        double time_counter_bounds(time_counter, axis_nbounds) ;

// global attributes:
                :name = "output_atmosphere_2D_HR" ;
                :description = "Created by xios" ;
                :title = "Created by xios" ;
                :Conventions = "CF-1.5" ;
                :production = "An IPSL model" ;
                :timeStamp = "2015-Dec-14 15:20:26 CET" ;
```

More on the output file

Adding specific metadata

- Using variable element **<variable/>**
- Variable as file child will be output as a global **netcdf** file attribute
- Variable as field child will be output as a **netcdf** variable attribute
- Example :

```
<file name="daily_output" freq_output="1d">
   <field field_ref="pressure" operation="average" >
     <variable name="int_attr" type="int"> 10 </variable>
     <variable name="double_attr" type="double"> 3.141592654 </variable>
   </field>
   <variable name="global_attribute" type="string"> A global file attribute </variable>
</file>
```

Flushing files

- File can be flushed periodically in order to force data in cache to be written
- **(duration) sync_freq** file attribute : flush file at **sync_freq** period

More on the output file

Appending data to an existing file

- When restart models, field data can be appended to a previous XIOS output file
- **(bool)** **append** : if set to **true** and if file is present, data will be appended
  - Otherwise a new file will be created
  - Default is creating a new file (**append="false"**)

Splitting files

Hands-on 4

- In order to avoid big file, file can be split periodically
- File suffixed with start date and end date period
- **(duration)** **split_freq** : split file at **split_freq** period

Generating time series (CMIP requirement)

- Fields included into a single file may be automatically spread into individual files
- One field by file, file name based on field name
  - **(string)** **ts_prefix** file attribute : prefix for time series files
  - **(bool)** **ts_enabled** field attribute : is set to true, field is candidate to be output as time series
  - **(duration)** **ts_split_freq** field attribute: individual field split frequency (default is file splitting frequency)
- **(string)** **timeseries** file attribute (**none / only / both / exclusive**) : activate time series output
  - **none** : standard output, no time series
  - **only** : only field with **ts_enabled="true"** will be output as time series and no other output
  - **both** : timeseries + full file
  - **exclusive** : field with **ts_enabled="true"** will be output as time series, the other field in a single file

Read data with XIOS

Reading data from file

- **(string) mode** attribute (**"read" / "write"**) : if set to read, file will be an input
- Each time record will be read at every **freq_output** frequency (a little ambiguous but ...)
- Value can be get from models at the corresponding time step using :

  CALL xios_recv_field("field_id", field)

- First time record will sent to model at time step 0 (before time loop).
- Except using **freq_offset** field attribute
  - Exemple : **freq_offset="1ts"** : first record will be read at first time step and not 0

```
--- xml ---

<file name="daily_output" freq_output="1ts" mode="read" >
  <field id="temp" operation="instant" freq_offset="1ts" grid_ref="grid_3d"/>
</file>

--- model ---

DO ts=1,n
 CALL xios_update_calendar(ts)
 CALL xios_recv_field("temp",temp)
ENDDO
```

- Field with no time record will be read only once

Hands-on 5

That's all for today

- Data distribution in axis
- Data distribution in domain
- Time series
- Read with XIOS

Before doing the hands-on exercises : (training_notes.pdf)

- Please go to the root folder of the training **"XIOS_TRAINING"**.
- "**svn update**" to get the latest content of the training, including slides and exercises.
- "**source ./hands-on.env**" to initialize the correct computing environment.
- In each hands-on folder, you should firstly run the command "**./init-hands-on.sh**" to initiate the codes. You can re-run this command at any time you want to restart the exercise.
- To compile the program, use "**make**".
- To launch the executable, you can use "**./run_ubuntu**" which will launch with 4 MPI processes.
- Step by step solutions can be found in the "**answer**" folder.

XIOS workflow functionalities

Why Workflow ?

- Fields are exposed from model at each time step
  - internally representing data flux assigned to a timestamp
- Each data flux can be connected to one or more filters
- Filters are connected to one or more input flux and generate a new flux on output
- All filters can be chained together to achieve complex operations
- All filters are parallel
- XML file describe a full graph of parallel tasks

Workflow entry point

- Input flux can be a field sent from model (**xios_send_field**)
- Input flux can be a field read from an input file (**mode="read"**)

Workflow end point

- Output flux can be sent to servers and written to file (**mode="write"**)
- Output flux can be read from model (**xios_recv_field**)
  - **(bool) read_access** field attribute : field read from models must set **read_access="true"**
  - Field read from file have automatically **read_access="true"**

XIOS workflow functionalities

LSCE

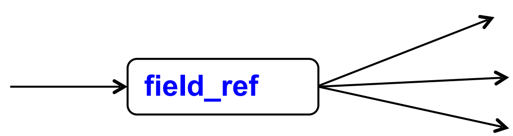
```
--- xml ---
<field id="precip" grid_ref="grid_3d"/>
<field id="precip_read" field_ref ="precip" read_access="true" />

<file name="daily_output" freq_output="1ts">
  <field id="temp" operation="instant" grid_ref="grid_3d"/>
</file>

--- model ---
DO ts=1,n
  CALL xios_update_timestep(ts)
  CALL xios_send_field("temp",temp)
  CALL xios_send_field("precip",precip)
  CALL xios_recv_field("precip_read",precip_read)  ! Now precip_read==precip
ENDDO
```

field_ref attribute : duplicate flux from the referenced field

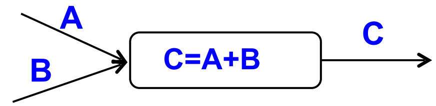
- For each reference to field, a new flux is created by duplicating source flux
- Also, make XML inheritance



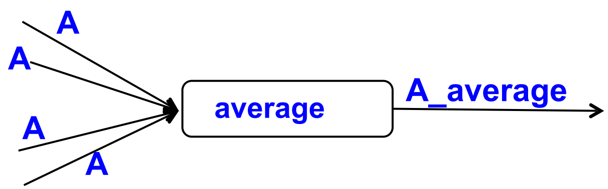
XIOS filter

Actually 3 kinds of filters

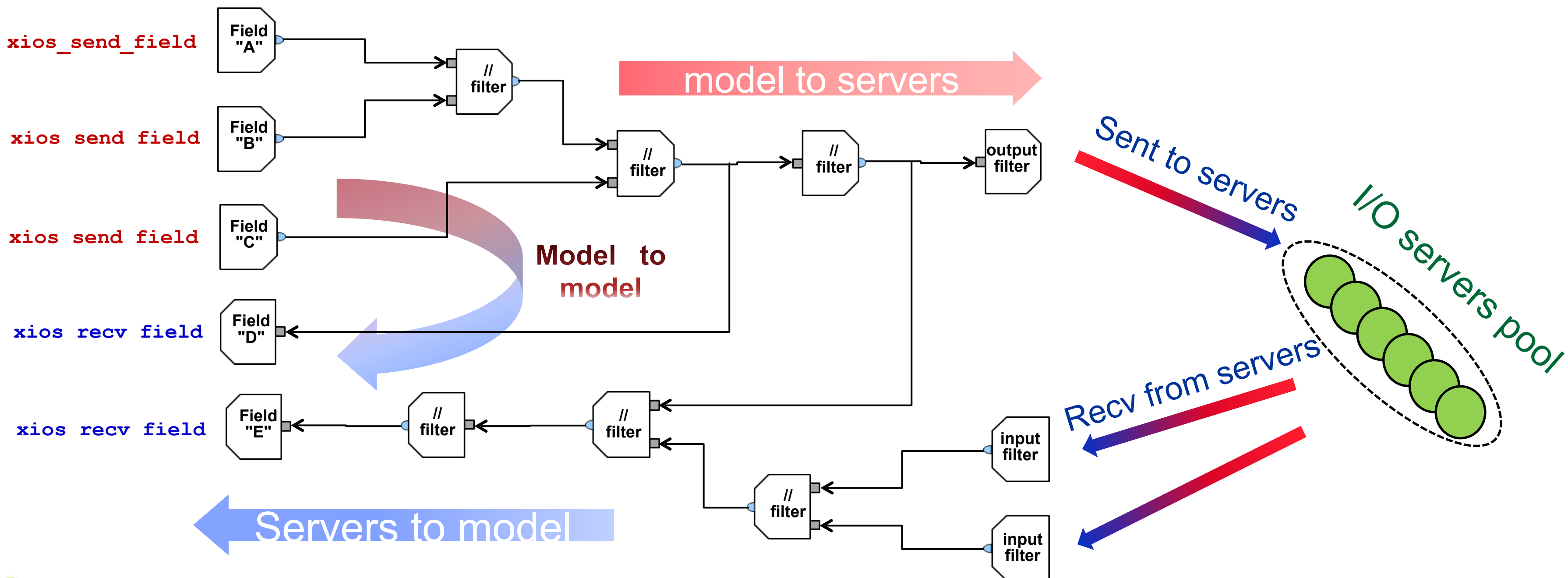
- Arithmetic filters : combine flux together



- Temporal filters : integrate flux over a period of time



- Spatial filters : transform the geometry of the incoming flux



XIOS arithmetic filter

Arithmetic filters

- Arithmetic filter can combine different flux of same timestamp with arithmetic operator or function
- All incoming flux must be on the same grid
  - Perform same operations for each grid point
- Arithmetic filters are defined in the content section of a field element
- Computed flux value will replace actual flux, even if coming from reference

```
<field id="temp" unit="°C" grid_ref="grid_3d" />
<field id="temp_K" unit="°K" field_ref="temp" > temp+273.15 </field>
```

- Specific "**this**" (auto-reference) keyword representing the incoming flux of the current field

```
<field id="temp" unit="°K" grid_ref="grid_3d" > this+273.15 </field>
```

- Arithmetic filters can be easily chained, computed flux can be reused

$$C = \frac{A + B}{A * B}$$

$$D = \frac{e^{-C*D}}{3}$$

```
<field id="A" />
<field id="B" />
<field id="C"  > (A + B) / (A*B)    </field>
<field id="D"  >  exp(-C*this) / 3  </field>
```

LSCE

Time integration filters

- **Time filters of are specified with the "operation" field attribute**
  - Possible value : "**once**", "**instant**", "**maximum**", "**minimum**", "**average**", "**accumulate**"
  - A new flux is generated at the end of the time integration period

- **Time filter is enabled only if :**
  - Field is included into a file
    - **output_freq** define the period over which integration is done
    - Generated flux is the sent to server to be recorded
  - Flux can be reused by an other field after time integration
    - The @ operator : means that time integration is performed over the flux
    - The time integration period is given by value of **freq_op** attribute of new flux

```
<field id="temp" operation="average" />
<field id="temp_ave" freq_op="1d"/> @temp </field>
```

- New flux "**temp_ave**" is created every day (**freq_op**="**1d**") by time averaging of "temp" flux

Chaining time filters

- Using the @ operator
- Example : compute and output the monthly average of the daily maximum and minimum of temperature and the monthly maximum and minimum of the daily temperature average

```
--- xml ---

<field id="temp"                          operation="average"/>
<field id="temp_min" field_ref="temp" operation="minimum" />
<field id="temp_max" field_ref="temp" operation="maximum" />

<file name="monthly_output" output_freq="1mo" />
  <field name="ave_daily_min" operation="average"   freq_op="1d"> @temp_min </field>
  <field name="ave_daily_max" operation="average"   freq_op="1d"> @temp_max </field>
  <field name="min_daily_ave" operation="minimum"   freq_op="1d"> @temp     </field>
  <field name="max_daily_ave" operation="maximum" freq_op="1d"> @temp     </field>
</file>
```

2nd (operation) — 1st (@ operand)

```
--- model ---

CALL xios_send_field("temp", temp)
```

Chaining and combine time filters and arithmetic's filters

- Compute the time variance of a temperature field $\sigma \approx \sqrt{\langle T^2 \rangle - \langle T \rangle^2}$

```
--- xml ---

<field id="temp" operation="average"/>
<field id="temp2" field_ref="temp" /> temp*temp </field>

<file name="monthly_output" output_freq="1mo" />
  <field name="sigma_T" operation="instant" freq_op="1mo"> sqrt(@temp2-@temp*@temp) </field>
</file>


--- model ---

CALL xios_send_field("temp",temp)
```

Hands-on 6

LSCE

Spatial filters

- Spatial filters may change the geometry, dimension and the parallel data distribution of a flux
- Algorithms must be parallel and scalable in order to perform the flux transformation on whole allocated parallel resources of a simulation
- More filters under development

Using spatial filters

- Spatial filters are enabled when the grid of a referenced field is different of the current grid field
  - No spatial filter enabled
  - (same grid ref)

```
<field id="temp" grid_ref="grid_regular"/>
<field id="new_temp" field_ref="temp" grid_ref="grid_regular" />
```

  - Trigger spatial filter
  - (different grid ref)

```
<field id="temp" grid_ref="grid_regular"/>
<field id="new_temp" field_ref="temp" grid_ref="grid_unstruct" />
```

- If grid are not matching exactly, try to find a way to transform source grid into target grid
  - If not possible an error is generated
  - Otherwise filter will be used

XIOS spatial filter

- To find which filter to activate, a matching is done between domain and axis composing the grid.
  - An exact matching between element do not activate filter
  - If not matching, see if it is possible to transform the source element domain or axis into target element with a transformation.
  - Otherwise an error is generated

```
<axis id="vert_axis" n_glo="100" />
<domain id="regular"  ni_glo="360" nj_glo="180" type="rectilinear" />
<domain id="unstruct" ni_glo="10000"          type="unstructured" />

<grid id="grid_regular">
  <domain domain_ref="regular>
  <axis axis_ref="vert_axis" >
</grid>

<grid id="grid_unstruct">
  <domain domain_ref="unstructured">
    <interpolate_domain/>
  <domain/>
  <axis axis_ref="vert_axis" >
</grid>

<field id="temp" grid_ref="grid_regular"/>
<field id="new_temp" field_ref="temp" grid_ref="grid_unstruct" />
```

XIOS spatial filter

- More than one filter can be implemented in same transformation

```
<axis id="vert_src" n_glo="100" />
<axis id="vert_dst" n_glo="50" />

<domain id="regular"  ni_glo="360" nj_glo="180" type="rectilinear" />
<domain id="unstruct" ni_glo="10000"          type="unstructured" />

<grid id="grid_regular">
  <domain domain_ref="regular/>
  <axis axis_ref="vert_src" />
</grid>

<grid id="grid_unstructured">
  <domain domain_ref="unstructured">
    <interpolate_domain/>
  <domain/>
  <axis axis_ref="vert_dst">
    <interpolate_axis/>
  </axis>
</grid>
```

- Domain interpolation will be perform first "**regular**" -> "**unstructured**"
- Axis interpolation will be perform in 2nd time "**vert_src**" -> "**vert_dst**"

XIOS spatial filter

Extract

- Extract sub-part of data : **extract_axis**, **extract_domain**

- Extract axis to scalar (**extract_axis**)
  - **(integer)** **position** : position of the element to be extract from axis

- Extract axis to axis (**extract_axis**)
  - **(integer)** **n** : number of elements to be extract from axis
  - **(integer)** **begin** : begin position of the element to be extract from axis
  - **(1D-array)** **index** : array including all indexes of elements to be extract from axis

- Extract domain to axis (**extract_domain**)
  - **(string)** **direction** : **"iDir"** or **"jDir"**
  - **(integer)** **position** : position of the slice to be extract from domain

- Extract domain to domain (**extract_domain**)
  - **(integer)** **ni** : number of elements to be extract from domain along the i-direction
  - **(integer)** **nj** : number of elements to be extract from domain along the j-direction
  - **(integer)** **ibegin** : i-position of starting element to be extract from domain
  - **(integer)** **jbegin** : j-position of starting element to be extract from domain

XIOS spatial filter

```
<domain id="regular" ni_glo="360" nj_glo="180" type="rectilinear" />
<axis id="axis" n_glo="100" />

<grid id="grid_src">
  <domain domain_ref="regular"/>
  <axis axis_ref="axis"/>
</grid>

<grid id="grid_extract">
  <domain domain_ref="regular">
    <extract_domain ni="50" nj="60" ibegin="20"  jbegin="100" />
  <domain/>
  <axis axis_ref="axis">
    <extract_axis begin="30" n="10"/>
  </axis>
</grid>

<field id="field" grid_ref="grid_src"/>
<field id="field_extracted" field_ref="field" grid_ref="grid_extract" />
```

- Extract data of size (50,60,10) starting at index (20,100,30)
- Only the extracted part will be output to files

Hands-on 7-1

Hands-on 7-2

XIOS spatial filter

LSCE

Reduce

- Reduce data : **reduce_scalar, reduce_axis, reduce_domain**

Hands-on 7-3

Hands-on 7-4

- Reduce scalar to scalar (**reduce_scalar**)
  - **(string) operation** : sum, average, max, min. (like MPI_Allreduce)
- Reduce axis to scalar (**reduce_axis**)
  - **(string) operation** : sum, average, max, min.
- Reduce axis to axis (**reduce_axis**)
  - **(string) operation** : sum, average, max, min. (like MPI_Allreduce)
- Reduce domain to scalar (**reduce_domain**)
  - **(string) operation** : sum, average, max, min.
  - **(bool) local** : whether the reduction should be performed locally on data owned by each process or on the global domain (default "**false**")
- Reduce domain to axis (**reduce_domain**)
  - **(string) operation** : sum, average, max, min.
  - **(string) direction** : **"iDir"** or **"jDir"**
  - **(bool) local** : whether the reduction should be performed locally on data owned by each process or on the global domain (default "**false**")

XIOS spatial filter

LSCE

Inverse

- **inverse_axis**

Duplicate

- **duplicate_scalar** : duplicate scalar to axis

Reorder

- **reorder_domain**
  - **(bool)** **invert_lat** : define whether the latitude should be inverted. (default "**false**")
  - **(double)** **shift_lon_fraction** : longitude offset. Represents a fraction of **ni_glo**. (default "**0**")
  - **(double)** **max_lon** : optional
  - **(double)** **min_lon** : optional
  - If both **min_lon** and **max_lon** are defined, domain will be reordered with latitude values ranging from **min_lon** to **max_lon** .

Hands-on 7-5

Generate domain

Generate_rectilinear_domain

- **(double) lon_start, lon_end, lat_start, lat_end**
- **(double) bounds_lon_start, bounds_lon_end, bounds_lat_start, bounds_lat_end**
- Range in [0°, 360°] for longitude, [-90°, 90°] for latitude
- Useful to perform automatic interpolation on regular grid
- Generate automatically parallel distribution, longitude and latitude values
- **ni_glo** and **nj_glo** must be defined in the domain element

LSCE

Interpolate (only polynomial)

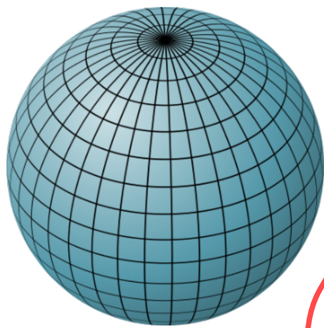
interpolate_domain

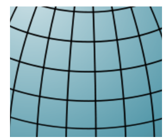
- Perform interpolation between any kind of domain
- Compute weight on the fly and in parallel at XIOS closing definition step
- Interpolation is done on parallel on the incoming distributed flux
- Current algorithm is only conservative remapping of 1st or 2nd order

- **(integer) order** : set the order (1 or 2) of the conservative interpolation (default "2")
- **(bool) renormalize** : used in case where targeted cells intersect masked source cells. If set to "true", flux is renormalized prorate of the non masked intersected area. (default "false")
- **(bool) quantity** : set to "true" to preserve extensive property of the field (default "false")
- **(bool) detect_missing_value** : if set to "true" , input data of the field to be interpolated are analyzed to detect missing values. (default "false")
- **(bool) use_aera** : if set to "true", area for source and target domain (if any) will be used to renormalize compute weight by the ratio given area / computed area. Default value is false. Used with domain **radius** attribute
- **(string) mode** : "read", "compute", "read_or_compute". This attribute determines the way to obtain interpolation weight information. Default "compute"
- **(bool) write_weight** : set to "true" to write the computed weight to file.
- **(string) weight_filename** : define the file name where the weights will be written or read. If not specified, when trying to read or write, a name will be automatically generated (contextid_srcdomain_destdomain).
- **(string) read_write_convention** : index will begin from 0 if set to "c", from 1 if set to "fortran"

Hands-on 7-6

XIOS spatial filter

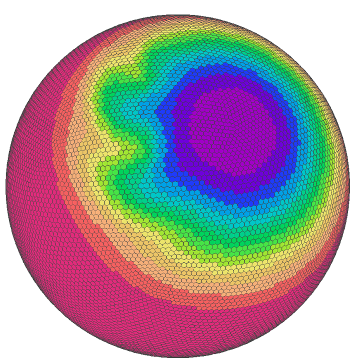


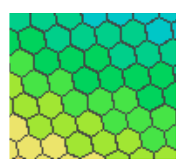


```
<grid id="grid_src" >
  <domain id="domain_src" type="rectilinear"/>
  <axis    axis_ref="an_axis"   />
</grid >
```

```
<field id="field_src" grid_ref="grid_src" />
```

```
<field id="field_dest"  field_ref="field_src"
                        grid_ref="grid_dest"  />
```



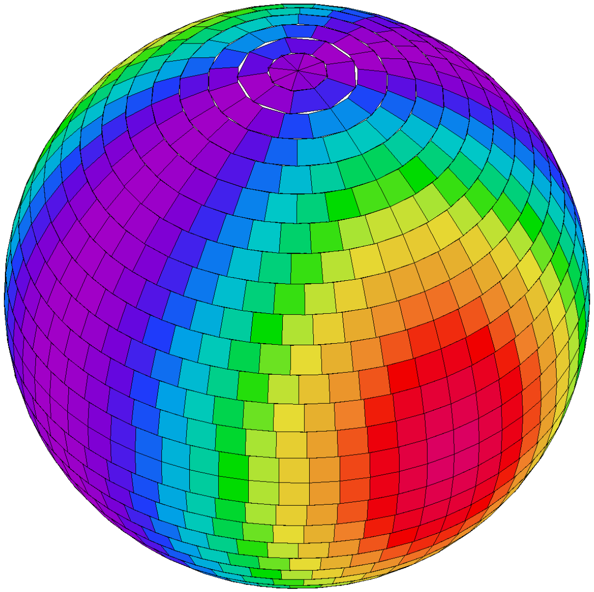


```
<grid id="grid_dest" >
  <domain id="domain_dest" type="unstructured">
    <interpolate_domain order="2"/>
  </domain>
  <axis    axis_ref="an_axis"   />
</grid >
```

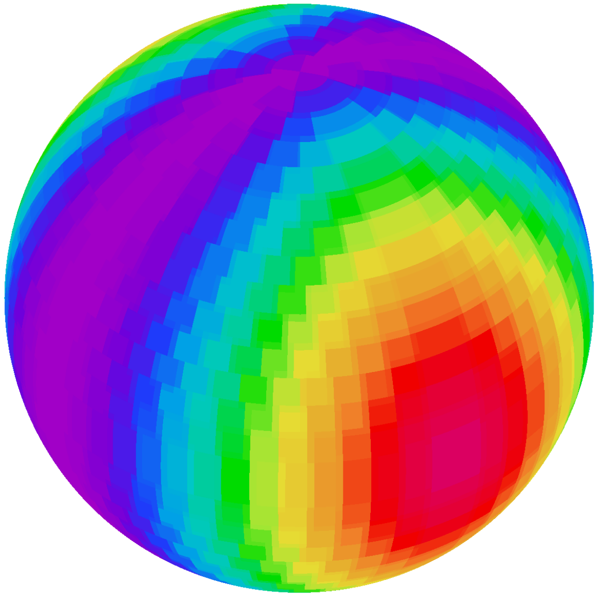
XIOS spatial filter

interpolate_domain

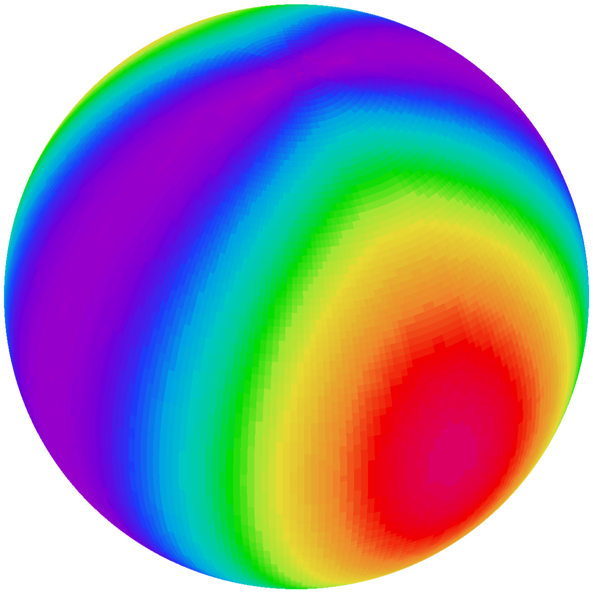
- Parallel weight computation on "the fly"
- Parallel remapping, management of masked cells
- Handle geodesic unstructured mesh (great circle) and rectilinear lon-lat or gaussian mesh (great and small circle)
- Ex : Remapping Gaussian reduced 60x30 -> regular lon-lat 2°



Source mesh



Remapping order 1



Remapping order 2

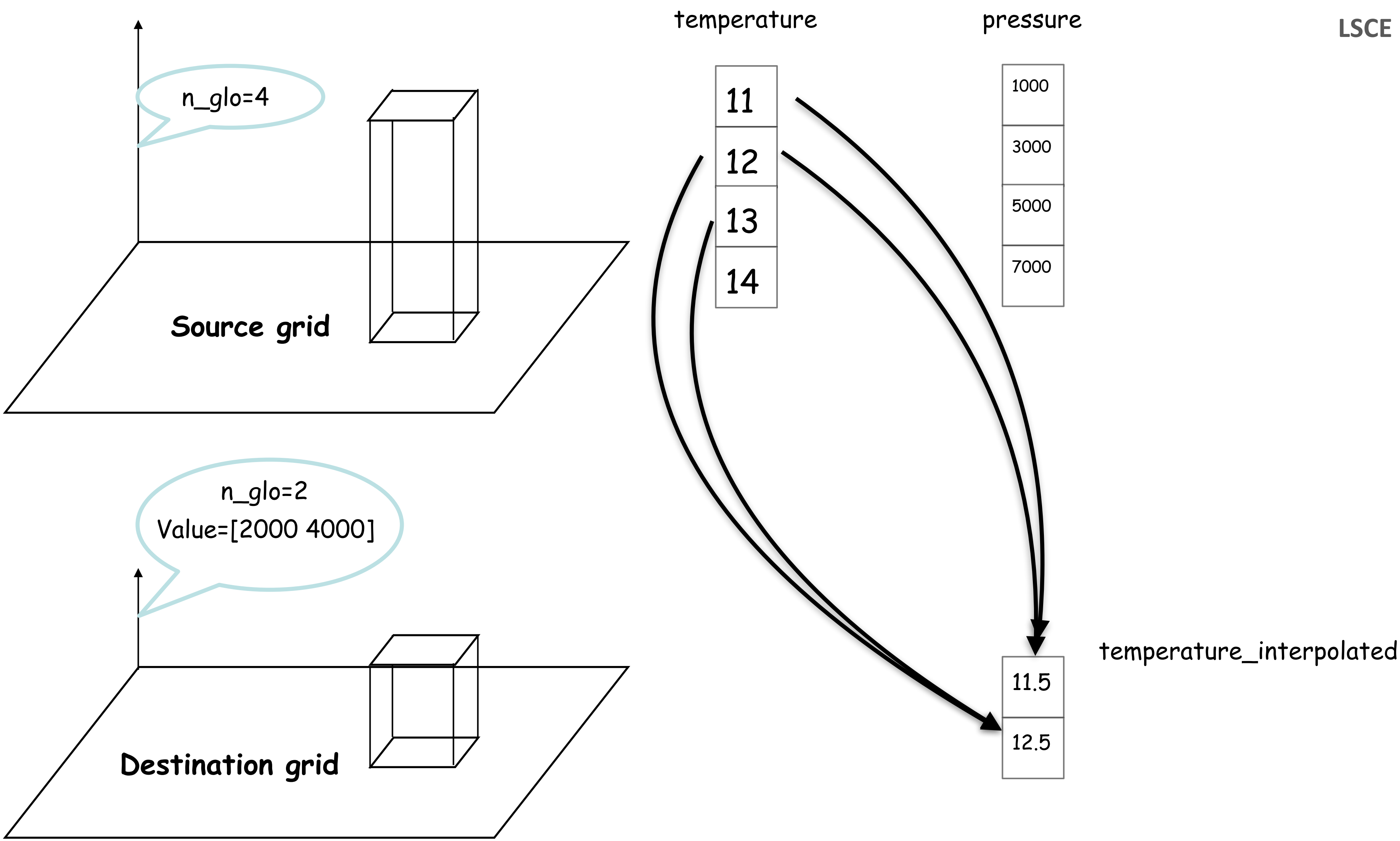
Interpolate (only polynomial)

interpolate_axis

- **(integer) order** : optional. set the order of the polynomial interpolation (default "**1**")
- **(string) type** : "**polynomial**" only. Optional
- **(string) coordinate** : defines the coordinate (**value**) associated with an axis on which interpolation will be performed
- Apply only on 3D field

Hands-on 7-7

XIOS spatial filter



XIOS spatial filter

Chaining spatial transformation

- Chaining can be easily achieved by referencing intermediate field
  - Ex : interpolate unstructured grid to regular and then make a zoom

```
<field id="temp_unstr"                                        grid_ref="grid_unstruct" />
<field id="temp_reg"           field_ref="temp_unstr" grid_ref="grid_regular" />
<field id="temp_reg_extract" field_ref="temp_reg"     grid_ref="grid_regular_extract" />
```

- To avoid intermediate field definition, use **grid_path** attribute
  - **(string) grid_path** attribute : define the list of intermediate grid (**grid_path="grid1,grid2"**)

```
<field id="temp_unstr"        grid_ref="grid_unstruct" />

<field id="temp_reg_extract"    field_ref="temp_unstr"     grid_path="grid_regular"
                                grid_ref="grid_regular_extract" />
```

- Other possibilities is to chain transformation in domain or axis definition

```
<field id="temp_unstr"                              domain_ref="unstructured" />
<field id="temp_reg_extract" field_ref="temp_unstr" domain_ref="regular_extract" />

<domain id="unstructured"   n_glo="10000" type="untructured" />

<domain id="regular_extract" ni_glo="360" nj_glo="180"  type="rectilinear" >
  <generate_rectilinear_domain />
  <interpolate_domain />
  <extract_domain ibegin="20" ni="50" jbegin="100" nj="60" />
</domain>
```

Hands-on 7-8

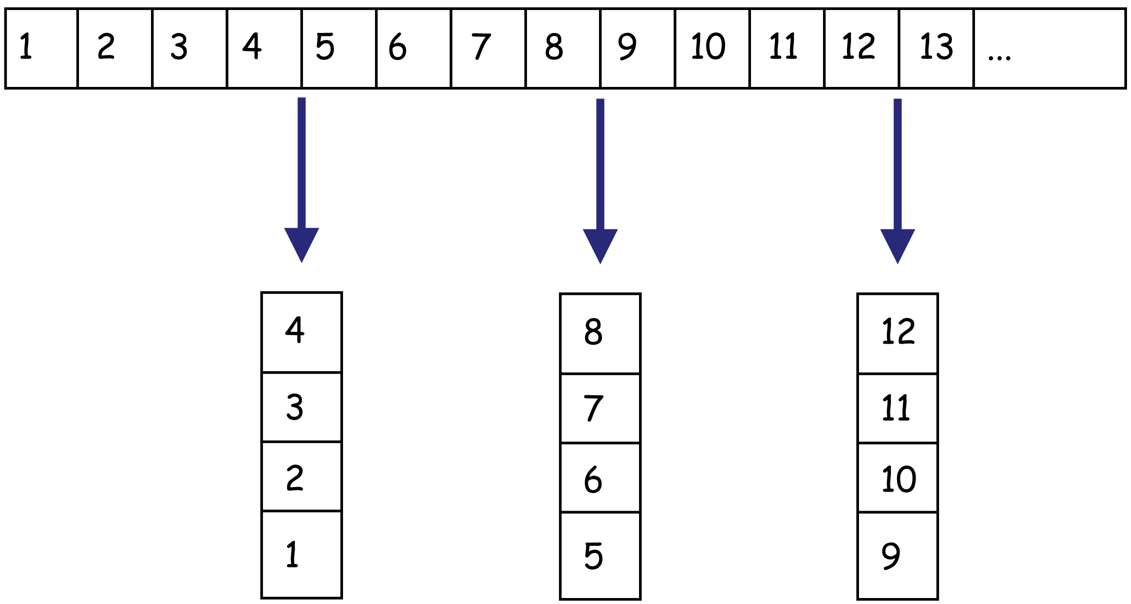
XIOS temporal splitting filter

LSCE

temporal_splitting

- This filter generates a data flux which has one extra dimension comparing to the input flux
  - Ex : A 2D field over 4 time steps is transformed into a 3D field with the last dimension of size 4
  - Like doing a time integration, no arithmetic operation is applied, all data is recorded

At each time step, data size = grid size



After temporal splitting, data size = grid size x 4

Hands-on 8

LSCE

temporal_splitting

- To use this filter, you need to at first reshape the input grid : add one scalar element to the grid to increase the grid's dimension

```
<grid id="grid_src">
  <domain domain_ref="domain"/>
</grid>
```

⇨

```
<grid id="grid_dst_1">
  <domain domain_ref="domain"/>
  <scalar id="scalar"/>
</grid>
```

- Source field data can be passed on the new grid using arithmetic operation

```
<field id="field_src" grid_ref="grid_src" />

 <field id="field_dst_1" grid_ref="grid_dst_1" > field_src </field>
```

- You can then use the temporal splitting filter as other spatial transform filters

```
<grid id="grid_dst_1" >
  <domain domain_ref="domain" />
  <scalar id="scalar" />
</grid>
```

⇨

```
<grid id="grid_dst">
  <domain domain_ref="domain" />
  <axis id="axis_ts" n_glo="4" >
    <temporal_splitting />
  </axis>
</grid>
```

Hands-on 8

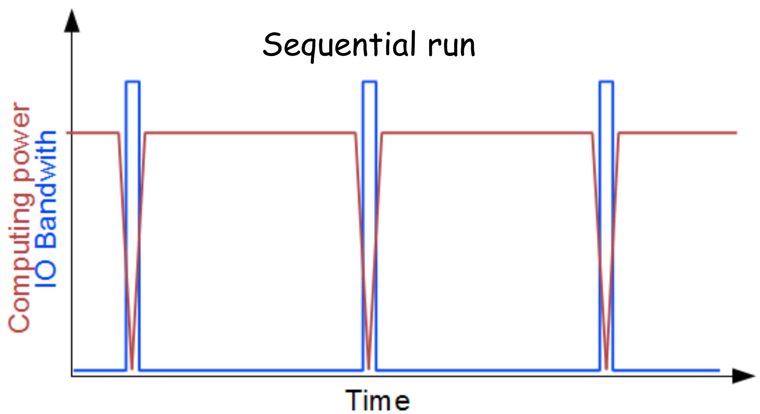
XIOS workflow graph

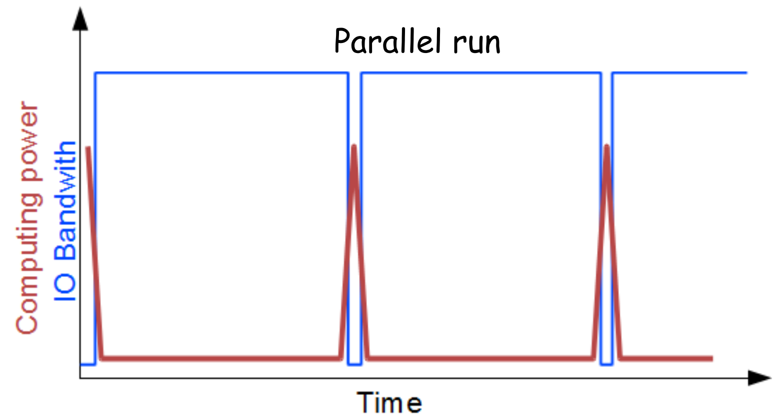
LSCE

A good tool for visualize workflow

- Field attribute
  - **(bool) build_workflow_graph** : set to "true" to enable workflow
- Can be inherited by reference
- https://forge.ipsl.jussieu.fr/ioserver/chrome/site/XIOS_TEST_SUITE/graph.html
- Interactive
- One graph file per context.
  - graph_data_*.json
- Can be useful for debugging

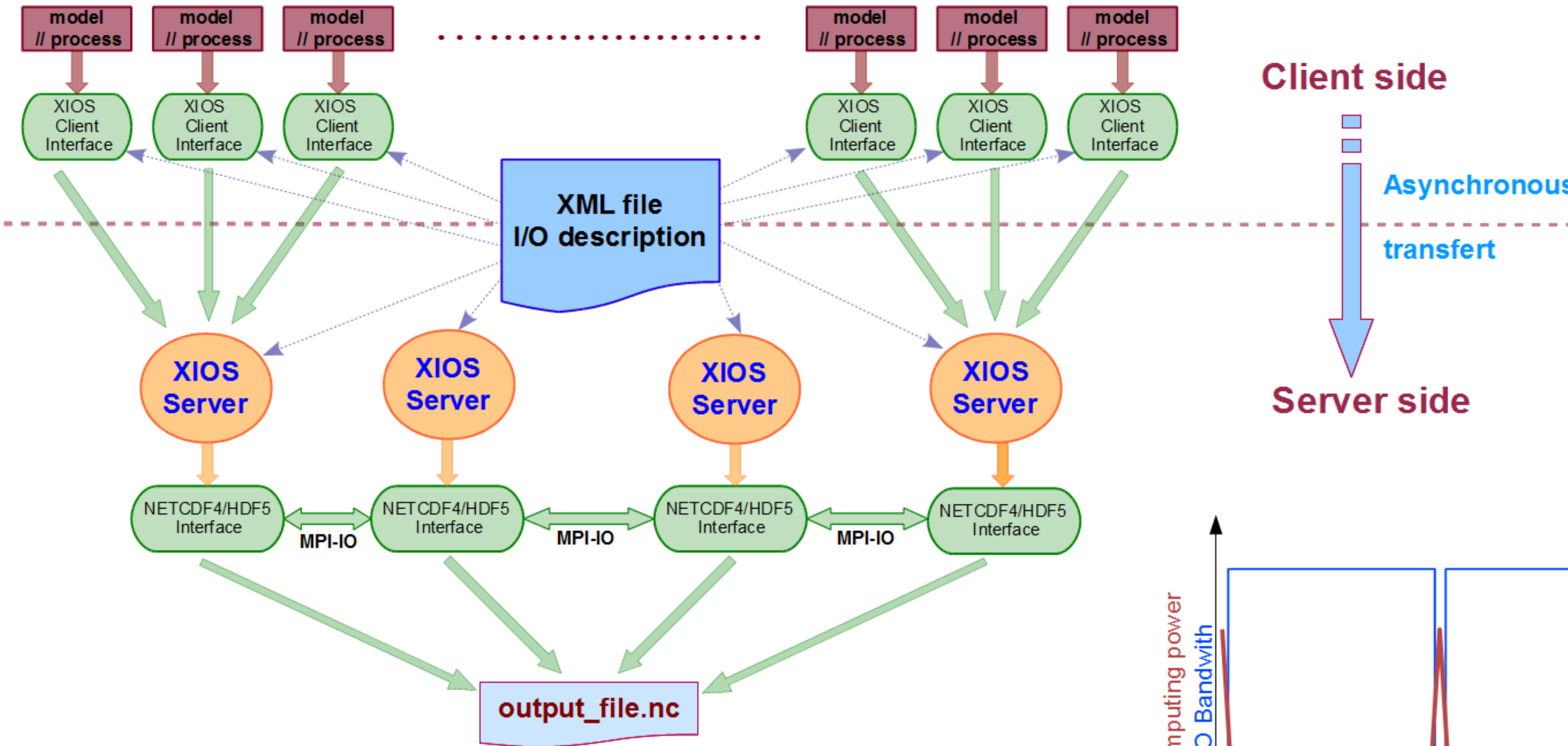
Hands-on 9

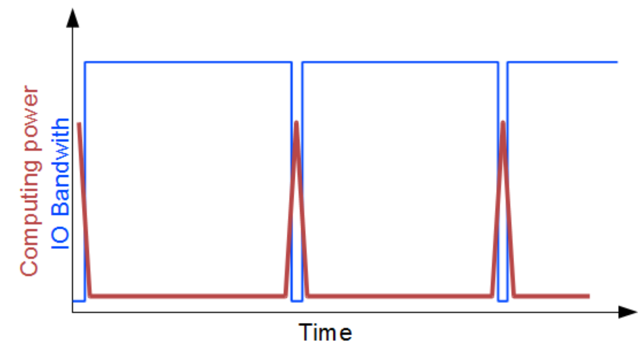


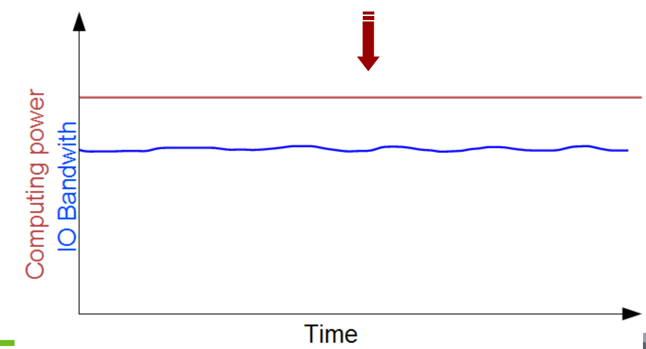


- IO become a big bottleneck in parallel computing up to O(10000) cores
- One file by process ?
  - Good way to achieve moderate scalability
  - Depending on the file system, performance may break down when attempting to write simultaneously thousand of files
  - Files need to be rebuilt into a single file in order to be analysed.
  - Rebuilt may take a longer time than the simulations
- Using parallel IO ?
  - Best way to achieve scalable IO without rebuild file
  - But difficult to aggregate a lot of I/O bandwidth with a big number of writing processes
  - Parallel IO is very less scalable than models due to hardware restriction (pricy and not took into account for performance evaluation)

X(ml) IO S(erver)







XIOS servers

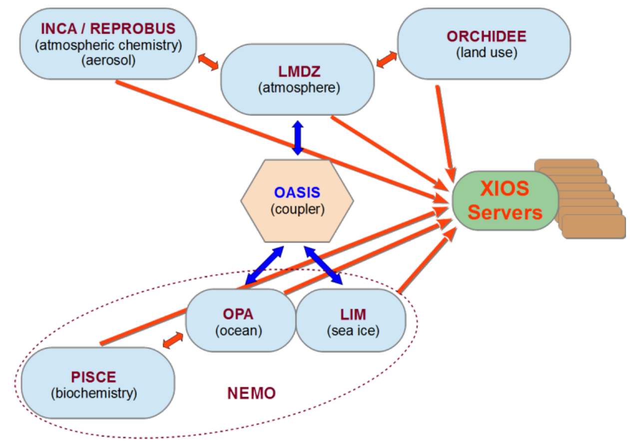
Pool of process dedicated to parallel I/O

- **XIOS : a software Burst Buffer ?**
  - Data are written all along the simulation
  - Smoothing I/O peaks
  - Constant I/O flow to file system
  - Overlap I/O by computation

XIOS communication protocol

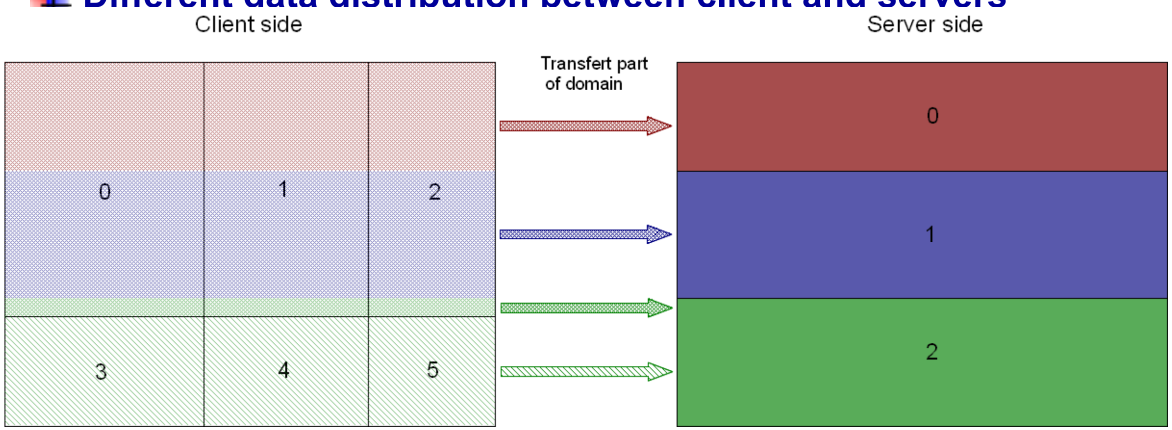
Complex and fully asynchronous protocol

- One way to send data from clients to servers
- One way to receive data from servers to clients



Same pools of I/O servers used in coupled model

Different data distribution between client and servers



Data are sent asynchronously at writing time

- Use only MPI point to point asynchronous communication : MPI_Issend, MPI_Irecv, MPI_Test, MPI_Probe…
- No synchronisation between clients and server, and between servers
- No latency cost, communications are overlapped by computation
- Writing is also overlapped by computation

Data are received asynchronously with prefetching (by advance) on client side

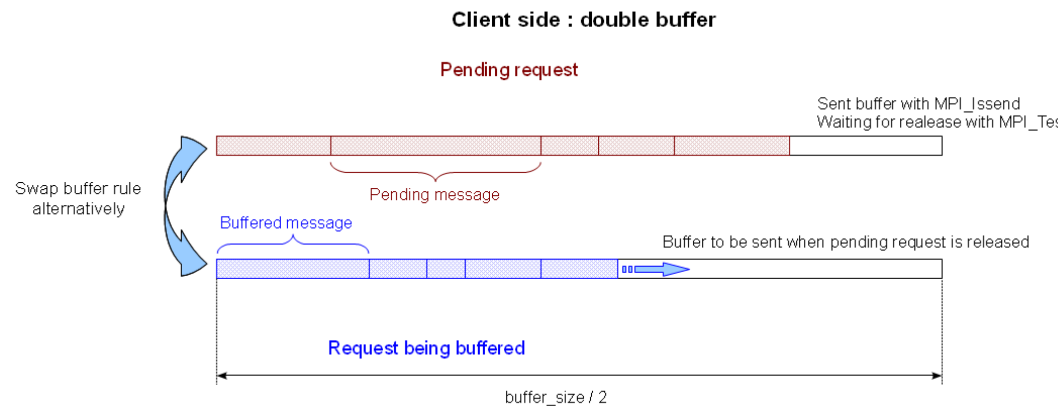
XIOS buffer

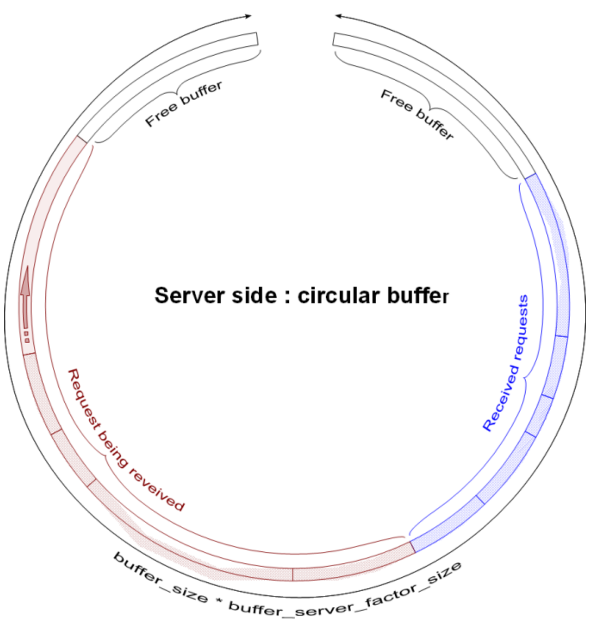
Large usage of buffers

- Smoothing I/O peaks

Client Side : double buffers

- Outgoing message in transfer
- Bufferization of the incoming flow





Server Side : circular buffer

- Received requests are processed
- In same time than receiving request from client

Overlapping data transfer and I/O by computing

Server mode vs. Attached mode

Server mode

- MPMD mode
  - mpirun -np 1024 model.exe : -np 16 xios_server.exe

- Placing XIOS servers in parallel partition
  - Strongly hardware dependent
  - But generally better to spread servers on different computing nodes

Attached mode

- To make development easier XIOS provide an "attach" mode
  - Don't need to launch xios servers executable
  - mpirun -np 12 model.exe
  - XIOS act only as a library

- Each client is itself a server for other clients
  - Pool of servers is equal to the number of clients

- Synchronous
  - Client must wait for the data to be written before continue

- Each client make parallel write
  - performance issue

XIOS 2-level server mode

LSCE

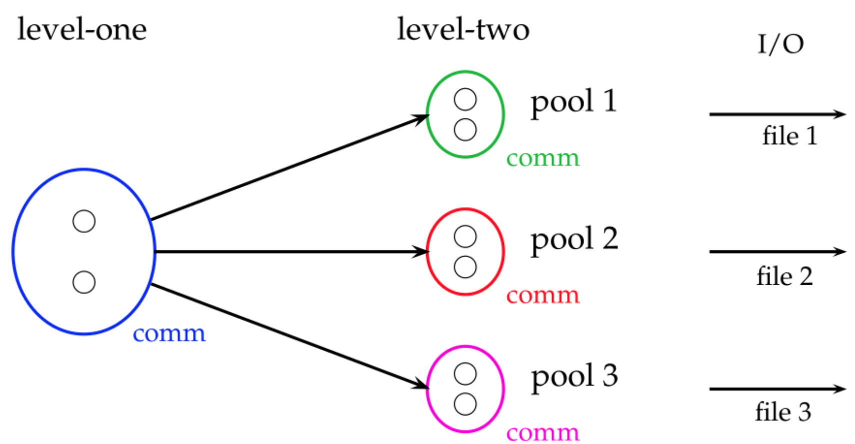
Why 2-level server?

- When number of XIOS servers increases, parallel I/O becomes inefficient due to I/O bandwidth
- Want XIOS servers to work with different output file

Intermediaries (level one) and writers (level two)

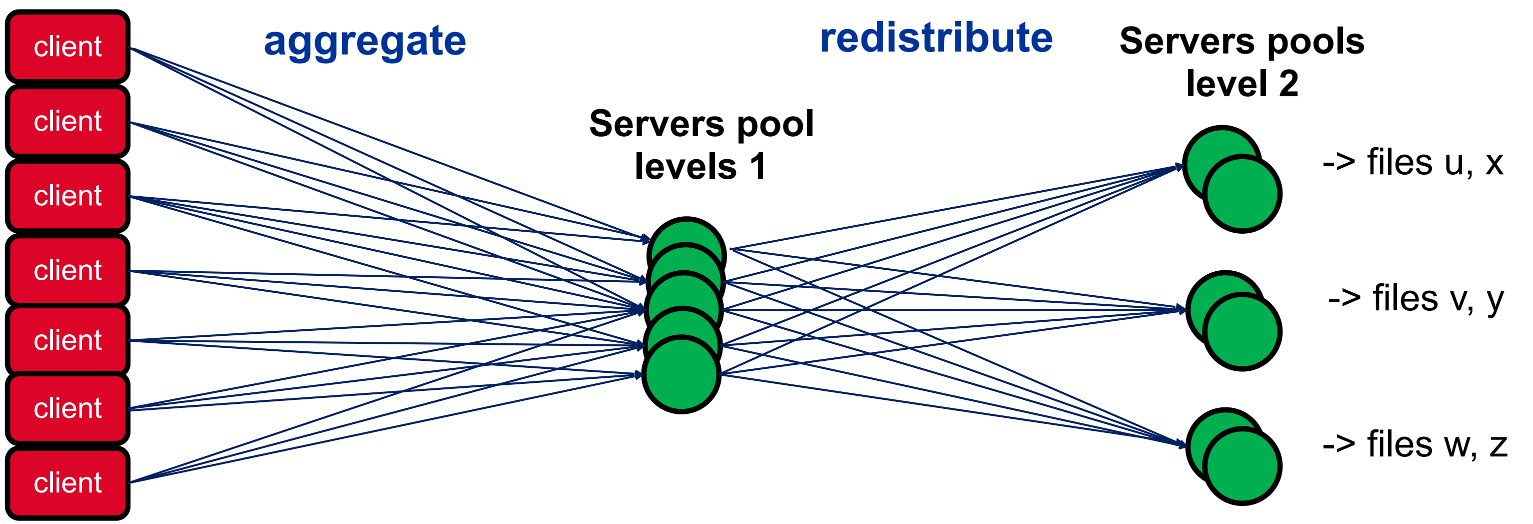
- Level-one servers will receive data from clients, redistribute, and send data to subsets of level-two servers (called "pools")
- Level-two servers will do the I/O
- Each file is written by only one pool
- No compression
- But if 1 process is assigned per pool (default option), I/O is then sequential and HDF5 compression can be used

Hands-on 10



XIOS 2-level server mode

- **Parameters: (context id="xios")**
  - **(bool) using_server2** : default **false**
  - **(integer) ratio_server2** : default 50
  - **(integer) number_pools_server2** :
  - sets the number of server-two pools
  - (default is number of second level servers)



XIOS performance report

Performance report

- Report is generated at XIOS finalization

Client side : xios_client_00.out
-> report : Performance report : total time spent for XIOS : 32.3497 s
-> report : Performance report : time spent for waiting free buffer : 1.1336 s
-> report : Performance report : Ratio : 3.50421 %
-> report : Performance report : This ratio must be close to zero. Otherwise it may be useful to increase buffer size or numbers of server

Server side : xios_server_00.out
-> report : Performance report : Time spent for XIOS : 51.0071
-> report : Performance report : Time spent in processing events : 21.5263
-> report : Performance report : Ratio : 42.2026%

Client side : Time spent for waiting free buffer is small compare to total time

- Every thing is OK, no impact of I/O on computing time

Client side : Time spent for waiting free buffer is significant

- Server side : if ratio (time for process event / total time) is close to 100%
  - I/O throughput is not enough fast to maintains asynchronism
  - Add more servers
- Servers side : if ratio is much less than 100% (60-80%)
  - Servers are not overloaded but cannot absorb and smooth I/O peaks
  - Buffer are to small and need to be increased

Memory consumption

- XIOS consumes memory internally
- XIOS uses large transfer buffer
- Part of memory is consumed by NETCDF4/HDF5
- But generally, memory consumption is scalable (client & server)

- Information about memory usage
- Buffer size is automatically computed
  - Can be different for each communication channel (client-server couple)
  - Dependent of the parallel data distribution
- 2 buffers for each client-server couple
  - 1 for sending data from client to server (I/O write)
  - 1 for receiving data from server to client (I/O read)

Client side : **xios_client_00.out**

-> report : Memory report : Context <atmosphere> : client side : total memory used for buffer 2932872 bytes
-> report : Memory report : Context <atmosphere> : server side : total memory used for buffer 209733 bytes
-> report : Memory report : Minimum buffer size required : 209730 bytes
-> report : Memory report : increasing it by a factor will increase performance, depending of the volume of data wrote in file at each time step of the file

Server side : xios_server_00.out
-> report : Memory report : Context <atmosphere_server> : client side : total memory used for buffer 209733 bytes
-> report : Memory report : Context <atmosphere_server> : server side : total memory used for buffer 1710664 bytes

Managing buffer size

- Buffer sizes are automatically computed
- User can choose between 2 behaviors (parameter **optimal_buffer_size**) :
- Buffer sizes optimized for memory
  - Size adjusted to the biggest transfer
  - Minimal memory consumption for buffer
  - But losing most part of asynchronous transfer
- Buffer sizes optimized for performance
  - Sizes are adjusted to bufferize all data between two output period
  - Fully asynchronous
- User can adjust size by itself using a multiplying factor
  - **(double) buffer_size_factor**

XIOS parametrization

- **(string) optimal_buffer_size** : specify buffer sizing behavior (**default : "performance"**)
  - **"performance" or "memory"**
- **(double) buffer_size_factor** : multiplying the computed buffer size by this factor
  - Use with caution
- **(integer) min_buffer_size** : fix the minimum size of buffers
  - Use only in case of bad computed size
  - Can help to workaround an unexpected problem
- **(boolean) using_server**: specify "server mode" or "attached mode"
  - XIOS try to determine itself the chosen mode by analyzing MPI communicator
  - Useful only for coupled model configuration
- **(integer) info_level**: level of xios information output (**0-100**), **0** nothing, **100** full, (**default=0**)
- **(boolean) print_file** : if true, xios standard output and error are redirected in files indexed by process rank, (**default=false**)
- **(boolean) xios_stack** : if true, you will get a full error traceback (**default=true**)

Hands-on 11

XIOS parametrization

XIOS context is used for parametrization

- Specific XIOS context in XML file
- Used only for reading variable value
- Actually, all parameters are optional, just override default value

```
<context id="xios">
  <variable_definition>

     <variable id="optimal_buffer_size" type="string">performance</variable>
     <variable id="buffer_size_factor" type="double">1.0</variable>
     <variable id="min_buffer_size" type="int">100000</variable>
     <variable id="using_server" type="bool">false</variable>
     <variable id="using_oasis" type="bool">false</variable>
     <variable id="info_level" type="int">50</variable>
     <variable id="print_file" type="bool">true</variable>

  </variable_definition>
</context>
```

XIOS performance

LSCE

- **Configuration : model IPSLCM6-LR**
  - Atmosphere : 144x143x79 (2 °, 79 vertical levels)
  - Ocean : ORCA1, L75 (1° , 75 vertical levels)
  - Performances : 16 SYPD on 930 cores on Curie (Bull, intel Sandy-Bridge)

- **CMIP6 light I/O throughput (piControl, large part of the CMIP6 runs)**
  - Config : 1 years (1850) piControl : 4 XIOS servers
  - No I/O : **4980 s**
  - Only IO Standard : **5460 s** (+10%)
  - Only CMIP6 I/O : **5460 s** (+10%, 0% compared to standard I/O)
  - CMIP6 + standard : **5820 s** (+16%, +6% compared to only standard I/O)

- CMIP6 medium I/O throughput : 1 year historical 1850, CMIP6 I/O + standard
  - 927 files / variables, 158 Gb (compressed)
  - 12 XIOS servers
  - CMIP6 + standard : **6454 s** (+18 % compared to only standard I/O)

XIOS performance

LSCE

CMIP 6 High I/O throughput : one year Full CMIP6 I/O output + standard I/O

- 1173 files/variables, 1.5 Tb (compressed)
- Non negligible impact on computing time : +44 %
- Impact come from workflow cost, not I/O
- But for a low number of runs (<5%), so it remains acceptable

config	time	% Vs standard I/O
4 XIOS -2 NODES	16440 s	+201 %
8 XIOS - 4 NODES	13020 s	+138 %
16 XIOS - 2 NODES	9300 s	+70 %
16 XIOS - 4 NODES	9600 s	+75 %
16 XIOS - 8 NODES	9360 s	+71 %
24 XIOS - 2 NODES	8460 s	+54 %
24 XIOS - 8 NODES	8040 s	+47 %
24 XIOS - 12 NODES	**7860 s**	**+44 %**
32 XIOS - 2 NODES	8460 s	+55 %

XIOS TUTORIAL