Design Rationale of the JcupLT Coupling Library: Lessons Learned from Jcup Development and Applications

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Abstract

Coupling libraries are essential infrastructure for multi-component simulations in weather, climate, and earth system modeling. Jcup is a coupling library developed since 2007 and applied to a wide range of coupled simulations, including atmosphere–ocean coupling, land surface modeling, seismic–structural coupling, and AI-integrated simulations. Through nearly two decades of development and application, both the strengths and limitations of Jcup's design have become clear. This paper documents the design rationale of JcupLT, a successor coupling library that inherits the proven design principles of Jcup while addressing the performance and usability issues identified through practical applications. The name JcupLT stands for both *Lightning* and *Lightweight*, reflecting its design goals of high speed and low overhead. We describe the development history and applications of Jcup, identify its strengths and limitations, and explain how each design decision in JcupLT was motivated by practical experience.

1 Introduction

Coupled simulations play a fundamental role in weather and climate science. The atmosphere, ocean, land surface, and other components of the earth system interact through exchanges of momentum, heat, moisture, and other physical quantities. Simulating these interactions requires coupling component models that differ in grid structure, time step, and domain decomposition. Dedicated software, known as a coupler or coupling library, is used to manage the timing, interpolation, and inter-process data exchange required for such coupling.

Several coupling software packages have been developed for earth system modeling, including OASIS3-MCT (Craig et al., 2017; Valcke, 2013), ESMF (Hill et al., 2004), YAC (Hanke et al., 2016), C-Coupler2 (Liu et al., 2018), and Scup (Yoshimura and Yukimoto, 2008). Each of these packages provides different trade-offs among generality, performance, and ease of use.

Jcup (Arakawa et al., 2011, 2020) is a coupling library developed since 2007, primarily targeting weather and climate models. Unlike many other couplers that support specific grid systems and built-in interpolation methods, Jcup was designed to be independent of grid structure by using remapping tables as input information and allowing users to implement arbitrary interpolation code. This design philosophy enabled Jcup to couple models with diverse grid systems without requiring modifications to the library itself.

Over the course of its development and application, Jcup has been used in atmosphere–ocean coupling, land surface modeling, seismic–structural coupling, heterogeneous system coupling with AI, and ensemble coupling of multiple model instances. These diverse applications validated many of Jcup's design decisions but also revealed performance and usability limitations that motivated the development of a successor library.

JcupLT is a new coupling library that inherits the proven design principles of Jcup while addressing its identified weaknesses. The name "LT" carries a double meaning: *Lightning* and *Lightweight*, signifying the goals of high speed and low overhead.

The purpose of this paper is to document the design rationale of JcupLT—specifically, *why* each design decision was made, grounded in the practical experience accumulated through Jcup's development and applications. This paper is not intended to present novel algorithms or claim methodological advances over other coupling software. Rather, it serves as a record of design decisions and their motivations, which we hope will be useful to developers and users of coupling software in the earth system modeling community.

The remainder of this paper is organized as follows. Section 2 describes the development history and applications of Jcup. Section 3 identifies the design principles of Jcup that proved effective in practice. Section 4 describes the limitations that became apparent through applications. Section 5 explains the design of JcupLT, detailing how each improvement addresses a specific limitation. Section 6 provides a summary comparison of Jcup and JcupLT. Section 7 presents performance evaluation results. Section 8 concludes the paper.

2 Development History and Applications of Jcup

2.1 Development history

The development of Jcup began in 2007 as part of the Innovative Program of Climate Change Projection for the 21st Century (KAKUSHIN Program). Figure 1 shows the timeline of Jcup's development and applications.

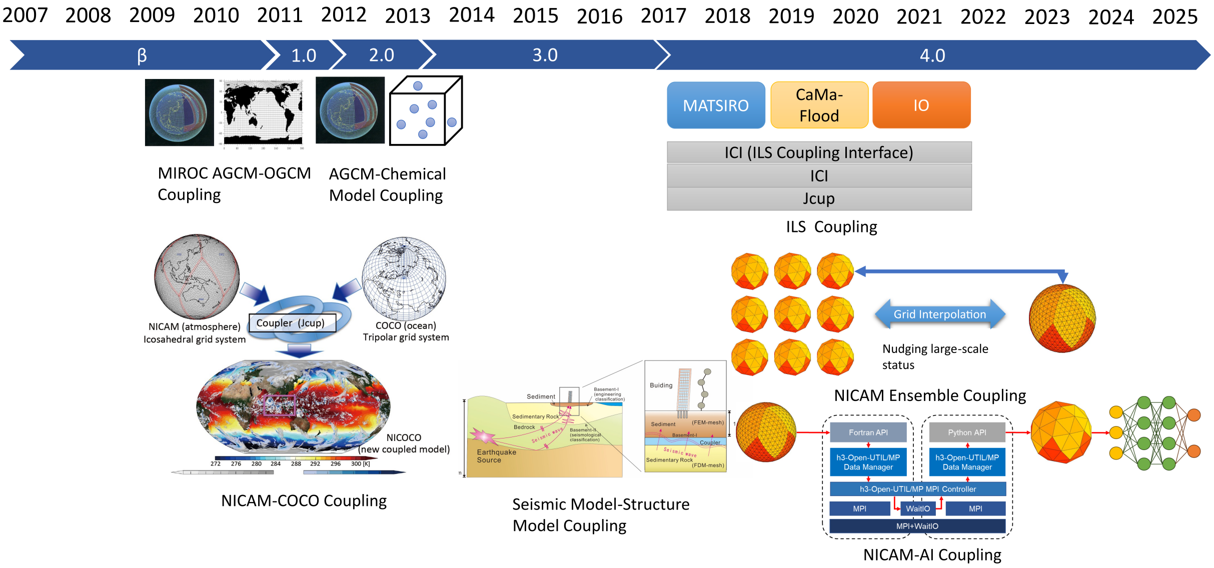

Figure 1: Timeline of Jcup development and applications.

Version 1.0 was released in 2011, and the initial design focusing on data exchange algorithms was described by Arakawa et al. (2011). Updates from Version 1.0 to Version 3.0 were made in relatively rapid succession. After Version 3.0, the pace of development slowed, and Version 4.0 has been in stable use since 2017, with only minor improvements. The design philosophy and applications of Version 3.0 were documented by Arakawa et al. (2020).

2.2 Applications

Jcup has been applied to a wide range of coupled simulations, which can be grouped into the following categories.

Atmosphere–ocean and atmosphere–chemistry coupling in MIROC. The first application of Jcup was a test coupling of the atmospheric model and ocean model components in the climate model MIROC, as well as an atmosphere–chemistry model coupling. These test cases served as initial validation of Jcup's basic functionality.

NICAM–COCO coupling (NICOCO). Jcup was used to couple the Non-hydrostatic Icosahedral Atmospheric Model (NICAM; Satoh et al. 2014, 2019) with the ocean model COCO (Miyakawa et al., 2017). The resulting coupled model, named NICOCO, has been actively used up to the present day. This application demonstrated Jcup's ability to couple models with fundamentally different grid systems: NICAM uses an icosahedral grid, while COCO uses a tripolar grid.

CoupledIO. An IO component, CoupledIO, was developed and coupled with NICAM through Jcup. This application extended the use of coupling beyond model-to-model data exchange to include model-to-IO data exchange.

Seismic–structural coupling. A test coupling between a seismic wave propagation model and a structural vibration model was carried out (Matsumoto et al., 2015). This application demonstrated Jcup's applicability beyond weather and climate modeling, coupling models with cubic grids and unstructured grids.

h3-Open-UTIL/MP and heterogeneous coupling. Since 2019, the coupler h3-Open-UTIL/MP has been developed as part of the h3-Open-BDEC project (h3 Open-BDEC Project, 2019), led by the Information Technology Center at the University of Tokyo. Jcup serves as the underlying library for this coupler. Within this framework, Jcup's functionality has been extended to realize coupling configurations that were not possible with conventional couplers, such as coupling between NICAM and AI across heterogeneous systems (Arakawa et al., 2022) and ensemble coupling of multiple NICAM instances (Arakawa et al., 2025).

Integrated Land Simulator (ILS). Since 2017, the Integrated Land Simulator (ILS) has been under active development (Nitta et al., 2020). ILS couples the land surface model MATSIRO, the river model CaMa-Flood, and the IO component ILSIO through Jcup, and is designed so that additional models can be coupled according to user requirements. This application, together with the coupling of the MIROC atmospheric model (MIROC AGCM) with ILS, was a major driver for identifying the performance limitations of Jcup that motivated the development of JcupLT.

3 Effective Design Principles of Jcup

Through the applications described above, several design principles of Jcup proved to be effective and were inherited by JcupLT.

3.1 Grid-independent coupling via remapping tables

Jcup uses grid point indices and remapping tables as input information for coupling. The remapping table specifies the correspondence between sending-side and receiving-side grid point indices, together with interpolation coefficients. Because Jcup does not assume any specific grid structure, it can couple models with arbitrary grid systems, provided that each grid point has a unique index.

This design proved essential in practice. For example, in the NICOCO coupled model, Jcup successfully coupled NICAM's icosahedral grid with COCO's tripolar grid. In the seismic–structural coupling test, models using cubic grids and unstructured grids were coupled without any modification to the library. This grid-independent design is a foundational principle that JcupLT inherits unchanged.

3.2 User-implementable interpolation code

Jcup allows users to implement their own interpolation code. Because the library does not embed any specific interpolation algorithm, users can implement area-weighted averaging, linear interpolation, nearest-neighbor approximation, or any other method appropriate for their application.

This flexibility proved valuable in practice, as different coupled simulations required different interpolation methods depending on the physical quantities being exchanged and the grid systems involved. JcupLT retains this user-defined interpolation mechanism.

3.3 Modular architecture isolating MPI operations

Jcup's internal architecture is organized as a hierarchy of modules. In particular, all MPI routine calls are encapsulated within a dedicated MPI module, and other modules invoke MPI functionality only indirectly through this module.

This design decision was originally motivated by the immaturity of MPI implementations at the time of Jcup's initial development. By isolating MPI calls in a single module, the library could be adapted to changes in MPI specifications with minimal code modification.

This modular structure proved valuable in an unanticipated way: when the heterogeneous communication library h3-Open-SYS/WaitIO (Sumimoto et al., 2022, 2025) was used for coupling across different computer architectures (e.g., NICAM–AI coupling), only the MPI module needed to be modified, and the rest of the library remained unchanged.

3.4 Aggregated data transfer

Jcup provides a mechanism for aggregating multiple data variables into a single communication operation by assigning the same exchange tag to the variables in the API call `jcup_set_data`. This aggregation can reduce the number of MPI communication calls and the associated overhead. Performance benefits of this feature were demonstrated in test cases using the ToySMP benchmark (Nakajima et al., 2024).

4 Limitations Identified through Applications

As Jcup's range of applications expanded, several limitations became apparent. These limitations fall into four categories: internal processing complexity, MPI communication implementation, interpolation placement, and remapping table API design.

4.1 Internal processing complexity

Jcup was designed to support coupling configurations in which multiple component models coexist within a single executable binary, and in which those components may have different grid systems. This level of generality was intended not only to broaden the range of applicable use cases, but also to differentiate Jcup from other couplers and to demonstrate novelty.

However, throughout the entire history of Jcup's development and application, no use case has ever required such intra-binary multi-component coupling. In practice, components have always been compiled into separate executables. The support for intra-binary coupling added substantial complexity to the internal processing logic without providing practical benefit.

While the exact performance impact of this complexity has not been quantified through benchmarking, the resulting code complexity significantly impaired the maintainability of the software.

4.2 MPI communication implementation

During the early development of Jcup, MPI implementations were not fully mature, and non-blocking communication (`MPI_Isend` and `MPI_Irecv`) could cause deadlocks depending on the data size. To avoid these issues, Jcup adopted a communication pattern that combined `MPI_Isend` and `MPI_Irecv` in a way that was effectively synchronous. This conservative approach ensured reliability but introduced communication overhead in certain coupling configurations, as computation and communication could not overlap.

4.3 Receive-side-only interpolation

In Jcup, interpolation calculations are always performed on the receiving component. This design was initially considered natural, as the receiving component is the one that needs the remapped data.

However, this constraint caused performance issues when the receiving component was the computationally dominant one. Specifically, in the coupling of the MIROC atmospheric model (MIROC AGCM) with ILS, the interpolation calculation performed on the atmospheric model side added overhead to the already computationally intensive atmospheric component, degrading overall performance.

4.4 Separation of remapping table and interpolation coefficients

In Jcup's API for setting the remapping table (`jcup_set_mapping_table`), the grid point index correspondence is passed as an argument, but the interpolation coefficients are handled separately. This separation was a deliberate design choice based on Jcup's philosophy of strictly distinguishing operations that change data values from those that do not.

While this philosophy is conceptually clean, it resulted in a cumbersome workflow for users. Conceptually, grid point correspondences and interpolation coefficients are inseparable parts of the same remapping operation and should be treated as a single unit. The artificial separation required users to manage these related quantities independently, complicating the implementation of interpolation code.

Furthermore, the user-defined interpolation subroutine interface in Jcup did not explicitly provide the grid point index arrays or coefficient arrays as arguments. Users had to obtain and manage this information themselves, as shown in the following interface:

Listing 1: Jcup's user-defined interpolation interface.

```
interface interpolate_data
  subroutine interpolate_data(recv_model, send_model, &
    mapping_tag, sn1, sn2, send_data, &
    rn1, rn2, recv_data, num_of_data, &
    tn, exchange_tag)
    character(len=*), intent(IN) :: recv_model, send_model
    integer, intent(IN) :: mapping_tag
    integer, intent(IN) :: sn1, sn2
    real(kind=8), intent(IN) :: send_data(sn1, sn2)
    integer, intent(IN) :: rn1, rn2
    real(kind=8), intent(INOUT) :: recv_data(rn1, rn2)
    integer, intent(IN) :: num_of_data
    integer, intent(IN) :: tn
    integer, intent(IN) :: exchange_tag(tn)
  end subroutine interpolate_data
end interface
```

5 Design of JcupLT

JcupLT was designed to address each of the limitations described in Section 4, while inheriting the effective design principles described in Section 3. This section describes each design improvement and its motivation.

5.1 Simplification of coupling patterns

As noted in Section 4.1, no practical application of Jcup has ever required coupling between components within a single executable. JcupLT therefore restricts its scope to coupling between separate executables only.

This simplification significantly reduced the complexity of the internal processing logic, resulting in a cleaner code structure and improved maintainability. The simplified design also makes it easier for new developers to understand and extend the library.

5.2 Adoption of asynchronous communication

Modern MPI implementations have matured substantially since Jcup's early development, and non-blocking communication can now be used reliably. JcupLT takes full advantage of this by issuing `MPI_Isend` immediately when `jlt_put_data` is called. Data reception (`MPI_Irecv`), completion of pending operations, and interpolation calculations are performed internally within `jlt_set_time`.

This design enables overlap between computation and communication. Performance measurements confirming this improvement are presented in Section 7.

5.3 Support for send-side interpolation

JcupLT allows the interpolation calculation to be performed on either the sending or the receiving component, controlled by the `is_recv_intpl` flag in the `jlt_set_mapping_table` API.

This feature directly addresses the performance issue identified in Section 4.3. In the coupling of MIROC AGCM with ILS, switching to send-side interpolation eliminated the interpolation overhead on the computationally dominant atmospheric component, improving overall performance. Performance measurements confirming this improvement are presented in Section 7.

Note that with send-side interpolation, results may differ at the level of floating-point rounding when the number of MPI processes changes. With receive-side interpolation, whether binary reproducibility is maintained depends on the interpolation mode (`"FAST"`, `"SAFE"`, or `"PARALLEL"`).

5.4 Unified remapping table and interpolation interface

In JcupLT, the remapping table API `jlt_set_mapping_table` accepts the sending grid indices, receiving grid indices, and interpolation coefficients together as arguments. This eliminates the artificial separation that existed in Jcup (Section 4.4) and treats the remapping operation as a single, coherent unit.

Furthermore, the user-defined interpolation subroutine interface has been redesigned to explicitly provide the grid point index arrays and coefficient arrays as arguments:

Listing 2: JcupLT's user-defined interpolation interface.

```fortran
abstract interface
  subroutine interpolation_user_ifc(send_data, recv_data, &
    send_index, recv_index, coef, &
    num_of_layer, num_of_conv, intpl_tag)
    real(kind=8), intent(IN) :: send_data(:,:)
    real(kind=8), intent(INOUT) :: recv_data(:,:)
    integer, intent(IN) :: send_index(:)
    integer, intent(IN) :: recv_index(:)
    real(kind=8), intent(IN) :: coef(:)
    integer, intent(IN) :: num_of_layer
    integer, intent(IN) :: num_of_conv
    integer, intent(IN) :: intpl_tag
  end subroutine
end interface
```

Comparing Listing 1 with Listing 2, the JcupLT interface directly provides `send_index`, `recv_index`, and `coef` as arguments, whereas the Jcup interface requires users to obtain and manage this information through separate mechanisms. This change makes the implementation of interpolation code substantially simpler and less error-prone.

5.5 Built-in default interpolation routines

In Jcup, interpolation calculations were entirely the responsibility of the user. However, in practice, the vast majority of interpolation calculations took the form:

$$R_p = \sum_n C_n \cdot S_n \tag{1}$$

where R_p is the value at receiving grid point p, S_n are the values at the corresponding sending grid points, and C_n are the interpolation coefficients.

JcupLT provides this standard interpolation as a built-in default routine. Users can select from several built-in modes: `"FAST"` for maximum performance, `"SAFE"` for reproducibility independent of the number of MPI processes, and `"PARALLEL"` for OpenMP-parallelized interpolation. A user-defined interpolation subroutine can be registered via `jlt_set_user_interpolation` only when non-standard interpolation is required.

This design reduces the effort required for common coupling tasks while retaining full flexibility for specialized applications.

5.6 Remaining limitations

The aggregated data transfer feature of Jcup (Section 3.4) is not implemented in JcupLT. Because JcupLT uses non-blocking communication, aggregating multiple data variables into a single send operation would require a more complex buffering mechanism that is incompatible with the current asynchronous design. Implementing aggregated transfer for the asynchronous communication framework is a topic for future development.

6 Summary Comparison of Jcup and JcupLT

Table 1 summarizes the key design differences between Jcup and JcupLT.

7 Performance Evaluation

This section presents performance measurements comparing Jcup and JcupLT.

7.1 Measurement environment

Two supercomputer systems were used for the performance measurements presented in this section.

The asynchronous communication measurements were performed on the Miyabi-C partition of the Miyabi supercomputer, operated by the Joint Center for Advanced High Performance Computing (JCAHPC) at the University of Tokyo and the University of Tsukuba (Information Technology Center, The University of Tokyo, 2024). Table 2 summarizes the specifications of Miyabi-C.

The send-side interpolation measurements were performed on the Earth Simulator 4 (ES4), operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). ES4 is a multi-architecture supercomputer that became operational in March 2021. The vector engine partition, consisting of NEC SX-Aurora TSUBASA B401-8 nodes, was used for these measurements. Table 3 summarizes the specifications of the ES4 vector engine partition.

Table 1: Comparison of Jcup and JcupLT design features.

Feature	**Jcup**	**JcupLT**
Coupling scope	Intra-binary and inter-binary	Inter-binary only
Communication	Effectively synchronous	Non-blocking (asynchronous)
Interpolation side	Receive-side only	Send-side or receive-side (selectable)
Remapping table API	Grid indices and coefficients handled separately	Grid indices and coefficients passed together
Interpolation interface	User must manage indices and coefficients	Indices and coefficients provided as arguments
Default interpolation	None (user-implemented only)	Built-in (FAST / SAFE / PARALLEL)
Aggregated transfer	Supported	Not yet implemented
Grid-independent design	Inherited (remapping table approach)	
User-defined interpolation	Inherited (with improved interface)	
Modular MPI isolation	Inherited	

Table 2: Specifications of the Miyabi-C partition.

Item	**Specification**
Number of nodes	190
CPU	2× Intel Xeon Max 9480 (56 cores each, per node)
Peak performance	6.8 TFLOPS per node (1.29 PFLOPS total)
Interconnect	InfiniBand NDR200

Table 3: Specifications of the ES4 vector engine partition.

Item	**Specification**
Number of nodes	684
Vector engine	8× NEC SX-Aurora TSUBASA (per node)
Peak performance	19.5 PFLOPS (total)
Interconnect	InfiniBand HDR200 (200 Gb/s)

7.2 Effect of asynchronous communication

To verify the effectiveness of the asynchronous communication adopted in JcupLT, communication times were measured using a test model on two nodes of Miyabi-C.

Figure 2 shows the total execution time and the time integration loop time when the number of exchange data variables was fixed at 10 and the number of processes was varied. Figure 3 shows the corresponding times when the number of processes was fixed at $8+8$ and the number of data variables was varied. In both cases, JcupLT was more than twice as fast as Jcup.

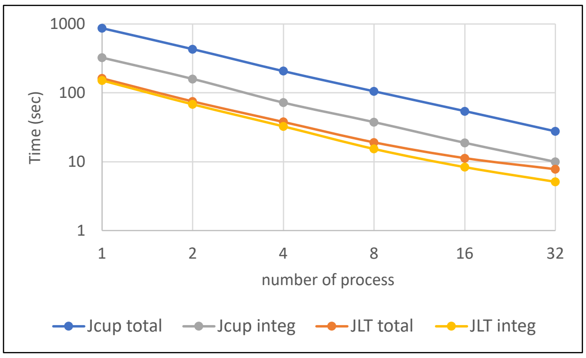

Figure 2: Execution time as a function of the number of processes (10 exchange data variables, 2 nodes on Miyabi-C).

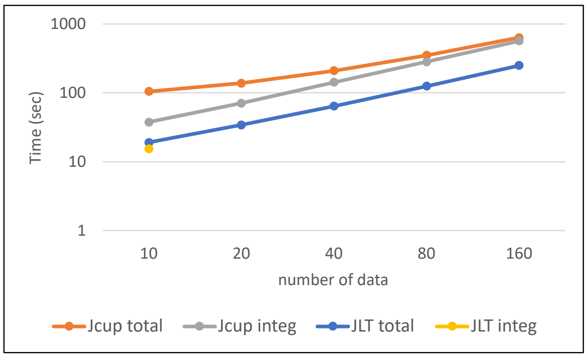

Figure 3: Execution time as a function of the number of exchange data variables ($8+8$ processes, 2 nodes on Miyabi-C).

7.3 Effect of send-side interpolation

To evaluate the effect of send-side interpolation, the coupling of MIROC AGCM with ILS was measured on the vector engine partition of ES4. The configuration used 64 processes for MIROC AGCM and $8+4+1$ processes for ILS (8 for the land surface model MATSIRO, 4 for the river model CaMa-Flood, and 1 for the IO component ILSIO).

Note that these measurements were performed using JcupMC (MIROC Custom), an intermediate version of Jcup that preceded JcupLT. JcupMC implements the same send-side interpolation mechanism that was later incorporated into JcupLT.

Figure 4 and Figure 5 show the execution time breakdown of the time integration loop for each of the 64 MIROC AGCM processes. In the original configuration (Figure 4), the interpolation and data exchange were performed on the atmospheric model side (receive-side interpolation), and the data exchange overhead (shown in blue) accounted for approximately 20% of the total execution time. In the modified configuration (Figure 5), the interpolation was moved to the ILS side (MATSIRO, send-side interpolation), and the data exchange overhead was reduced to a negligible level.

8 Summary

This paper has documented the design rationale of the JcupLT coupling library, tracing the path from the development and applications of its predecessor Jcup to the specific design decisions embodied in JcupLT.

Through nearly two decades of development and application, Jcup demonstrated the effectiveness of several key design principles: grid-independent coupling via remapping tables, user-implementable interpolation code, modular architecture isolating MPI operations, and aggregated data transfer. These principles have been inherited by JcupLT.

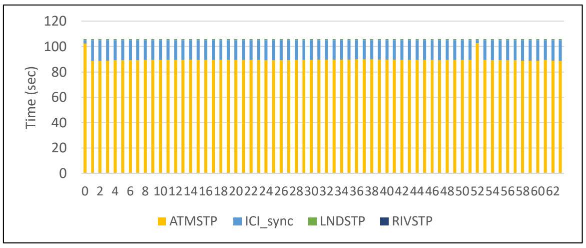

Figure 4: Execution time breakdown per MIROC AGCM process with receive-side interpolation (original Jcup). Yellow: atmospheric computation (ATMSTP); blue: data exchange (ICI_sync); green: land surface computation (LNDSTP); purple: river computation (RIVSTP).

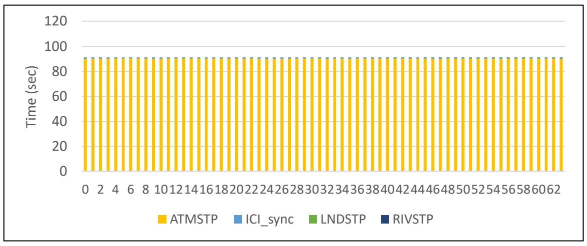

Figure 5: Execution time breakdown per MIROC AGCM process with send-side interpolation (JcupMC). The data exchange overhead is reduced to a negligible level.

At the same time, practical applications revealed four main limitations: unnecessary internal complexity from supporting unused intra-binary coupling patterns, effectively synchronous MPI communication, receive-side-only interpolation causing performance bottlenecks, and a cumbersome API that separated conceptually related remapping information.

JcupLT addresses each of these limitations: coupling patterns are simplified to inter-binary only, non-blocking asynchronous communication is adopted, send-side interpolation is supported, the remapping API is unified, and built-in default interpolation routines are provided.

One limitation remains: the aggregated data transfer feature has not been implemented in JcupLT due to its incompatibility with the current asynchronous communication design. This is a topic for future development.

The primary goal of JcupLT is to provide a practical, efficient, and easy-to-use coupling environment for researchers conducting coupled simulations. We hope that this documentation of design rationale will be useful not only to JcupLT users and developers, but also to the broader community developing and maintaining coupling software for earth system modeling.

Data Availability

The JcupLT source code is available at `https://github.com/Jcuplib/jlt`.

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