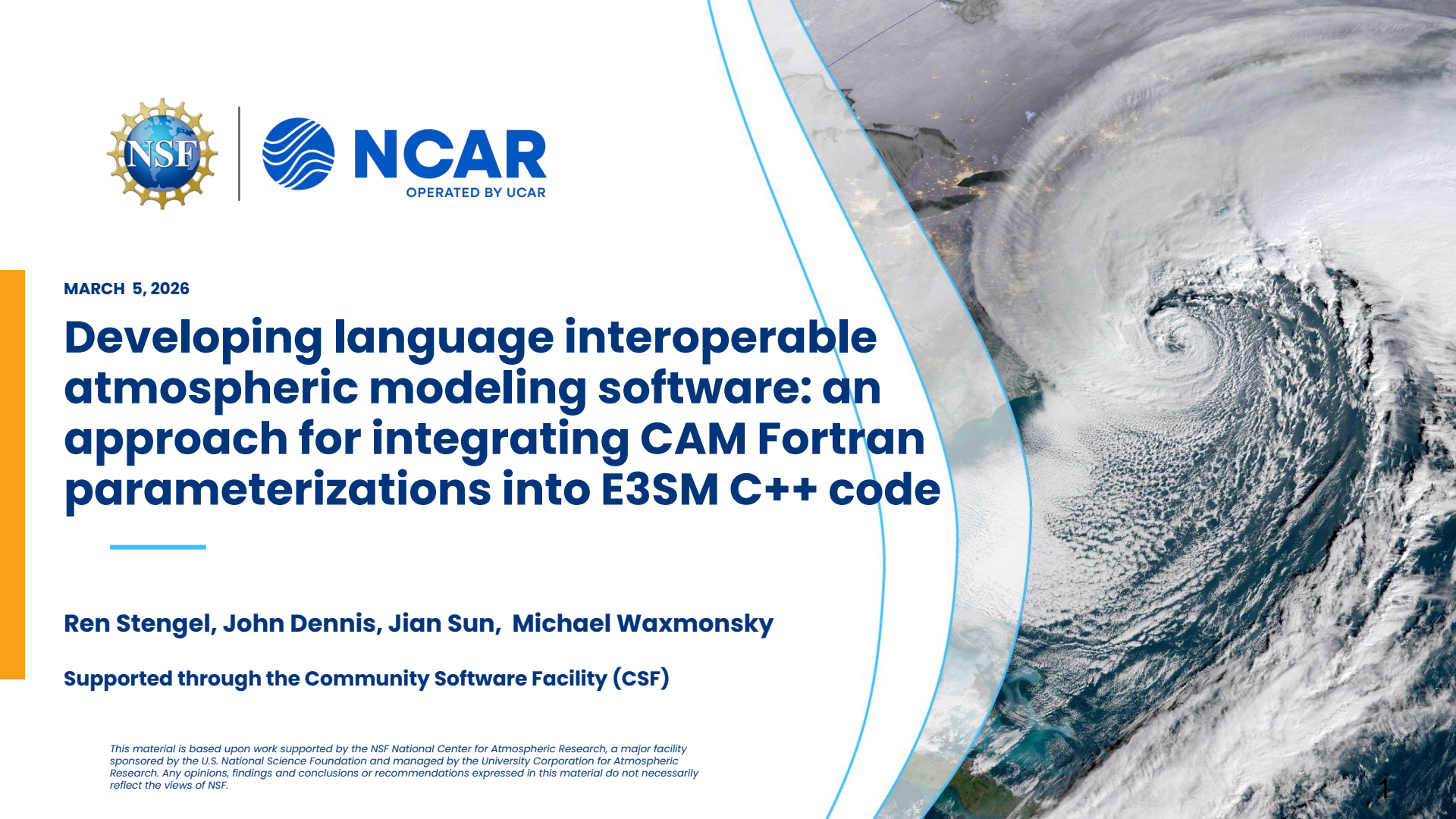

MARCH 5, 2026

Developing language interoperable atmospheric modeling software: an approach for integrating CAM Fortran parameterizations into E3SM C++ code

Ren Stengel, John Dennis, Jian Sun, Michael Waxmonsky

Supported through the Community Software Facility (CSF)

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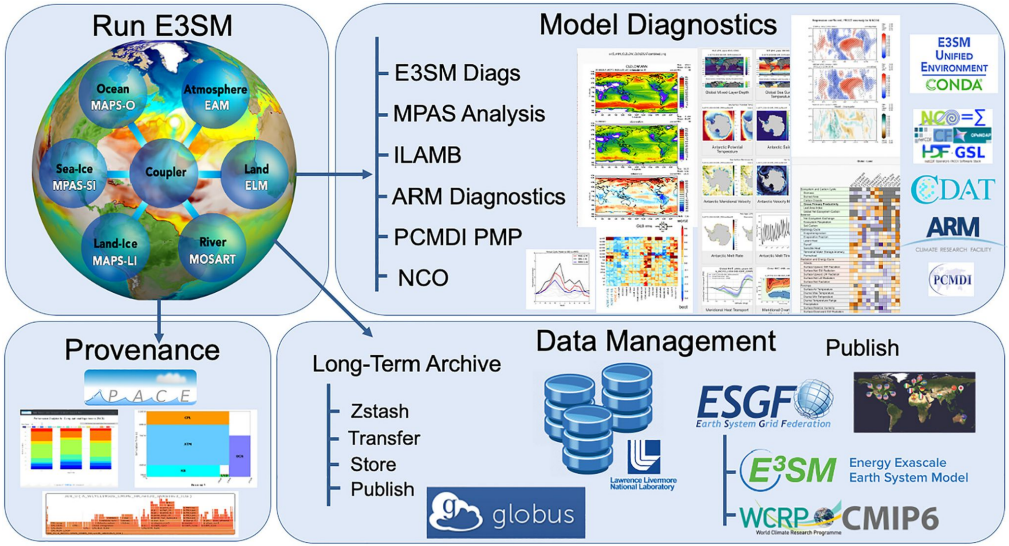
Motivation

- Multiple ongoing/past projects that involve code modernization
  - CCPP: Interoperable physics written in Fortran
  - Earthworks: GPU-enablement through OpenACC directives
  - StormSPEED: Integration of performance-portable Kokkos/C++ dynamical core
  - Experimentation with JAX
- Code modernization efforts have different goals
  - Complexity containment
  - Physics package portability
  - GPU-enablement
- Observations:
  - Primary industry support is: Python and C++
  - Significantly less support for Fortran and even less for Fortran on GPUs
  - Graduate students/Postdocs (i.e. **future scientific leaders**) are using Python
- How would multi-language support impact community contribution?
  - StormSPEED: C++ dynamical core in Fortran application (CAM)
  - This project: Fortran physics in Kokkos/C++ application (EAMxx)

Energy Exascale Earth System Model (E3SM)

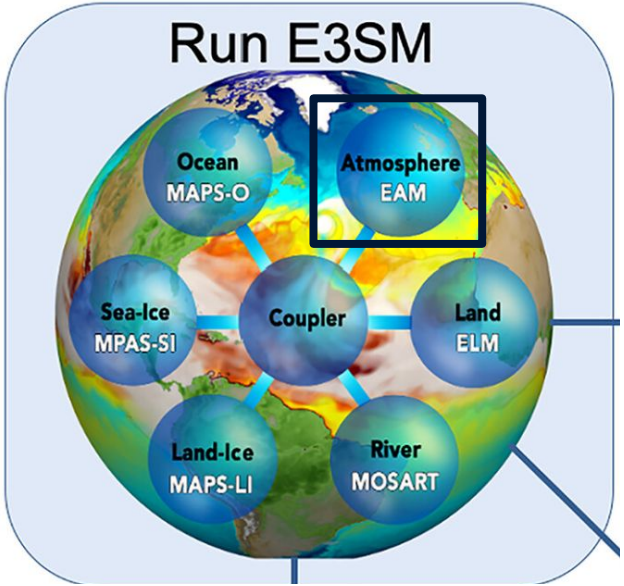
- E3SM is DOE's earth system modeling framework
- The goal is to provide a framework capable of exascale simulations



https://doi.org/10.1029/2019MS001821

EAMxx – atmospheric modeling component

- **Supports language interoperability for parameterizations and physics**
- Hardware portability and performance on GPUs with Kokkos



We will focus on the atmospheric component: EAMxx

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E3SM simulation description interface

- Uses the standard **`./xmlchange`** functionality:
  - Select COMPSET and grid
  - Set up compilers, machine environment, and batch job parameters
  - Simulated run time, time stepping, etc

```
./xmlchange RUN_TYPE="startup"
if [[ $COMPSET == *"F20TR"* ]]; then
   ./xmlchange RUN_STARTDATE='1850-01-01'
elif [[ $COMPSET == "FMTHIST" || $COMPSET == "FLTHIST" ]]; then
   ./xmlchange RUN_STARTDATE='2001-01-01'
else
   ./xmlchange RUN_STARTDATE='0001-01-01'
fi
./xmlchange RESUBMIT='0'
./xmlchange CONTINUE_RUN='FALSE'
./xmlchange STOP_N='2',STOP_OPTION='ndays'
./xmlchange JOB_WALLCLOCK_TIME='00:15:00'
./xmlchange JOB_QUEUE=$QUEUE_NAME
./xmlchange BUDGETS=TRUE

if [[ $DYCORE == "theta-l_kokkos" ]]; then
cat << EOF >> user_nl_elm
   check_finidat_year_consistency = .false.
   check_dynpft_consistency = .false.
   create_crop_landunit = .false.
EOF
fi
```

E3SM simulation description interface

- Uses the standard **`./xmlchange`** functionality:
  - Select COMPSET and grid
  - Set up compilers, machine environment, and batch job parameters
  - Simulated run time, time stepping, etc
- Uses **`./atmchange`** to change atmospheric process settings at runtime
- CCPP (used by CAM-SIMA) uses XML files to determine atmospheric process settings which then generates code to compile

```
./xmlchange RUN_TYPE="startup"
if [[ $COMPSET == *"F20TR"* ]]; then
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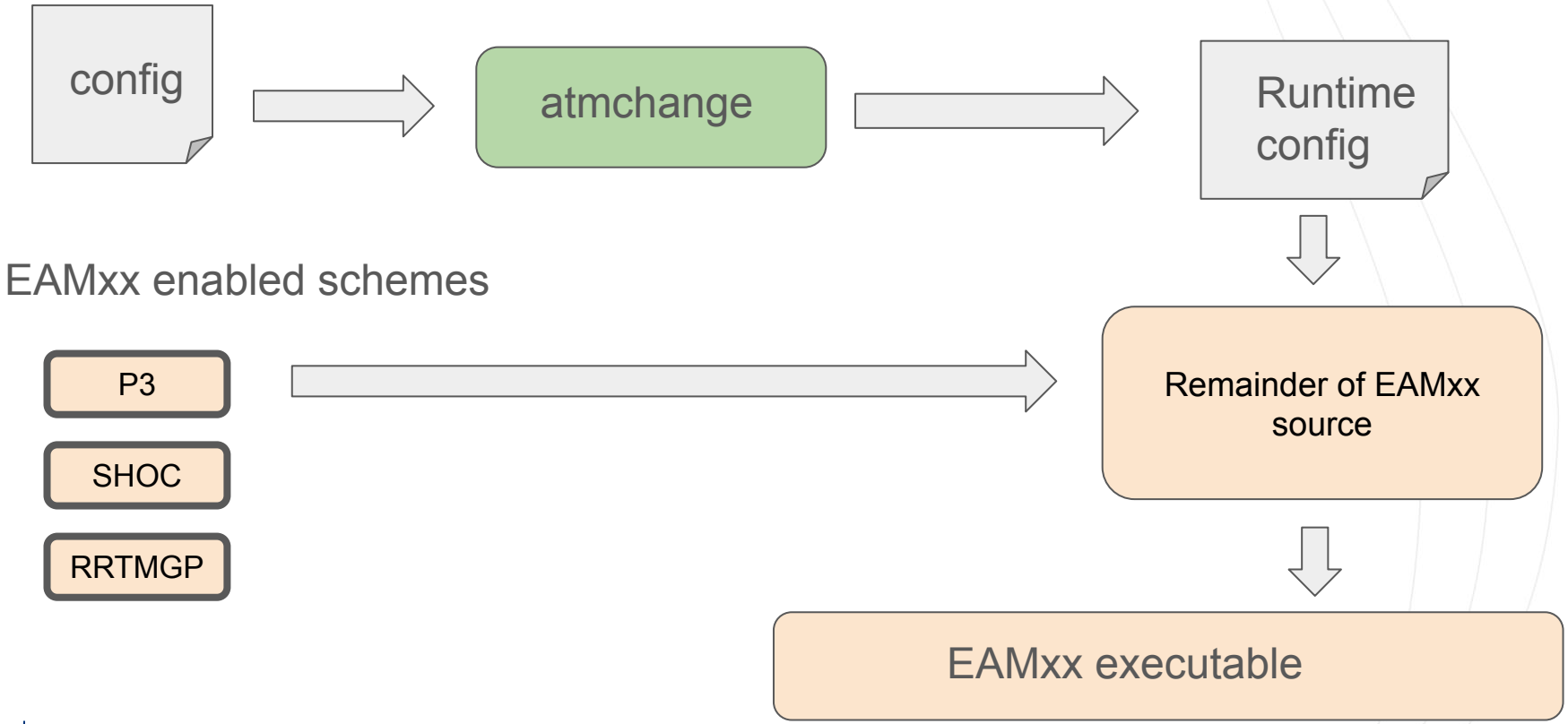
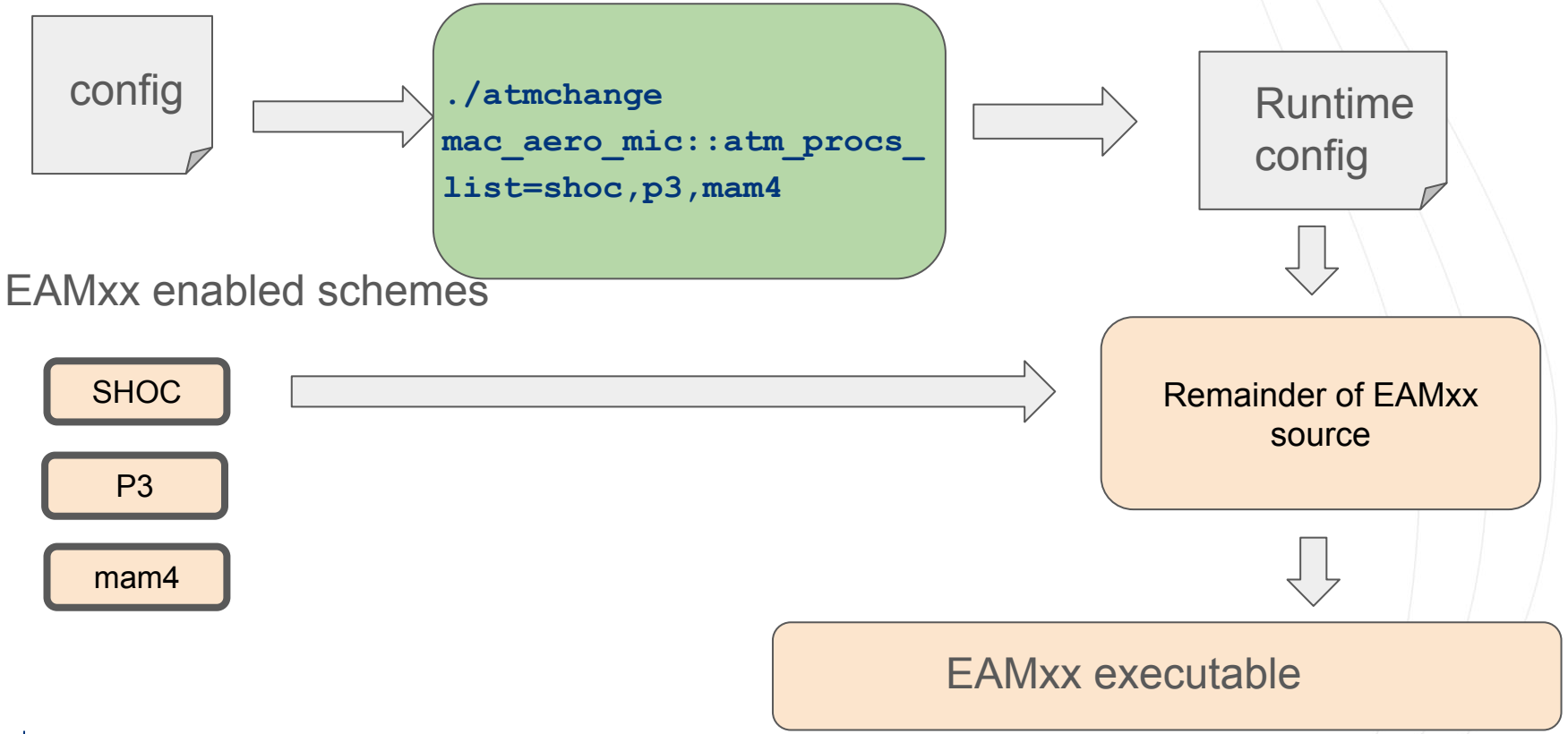
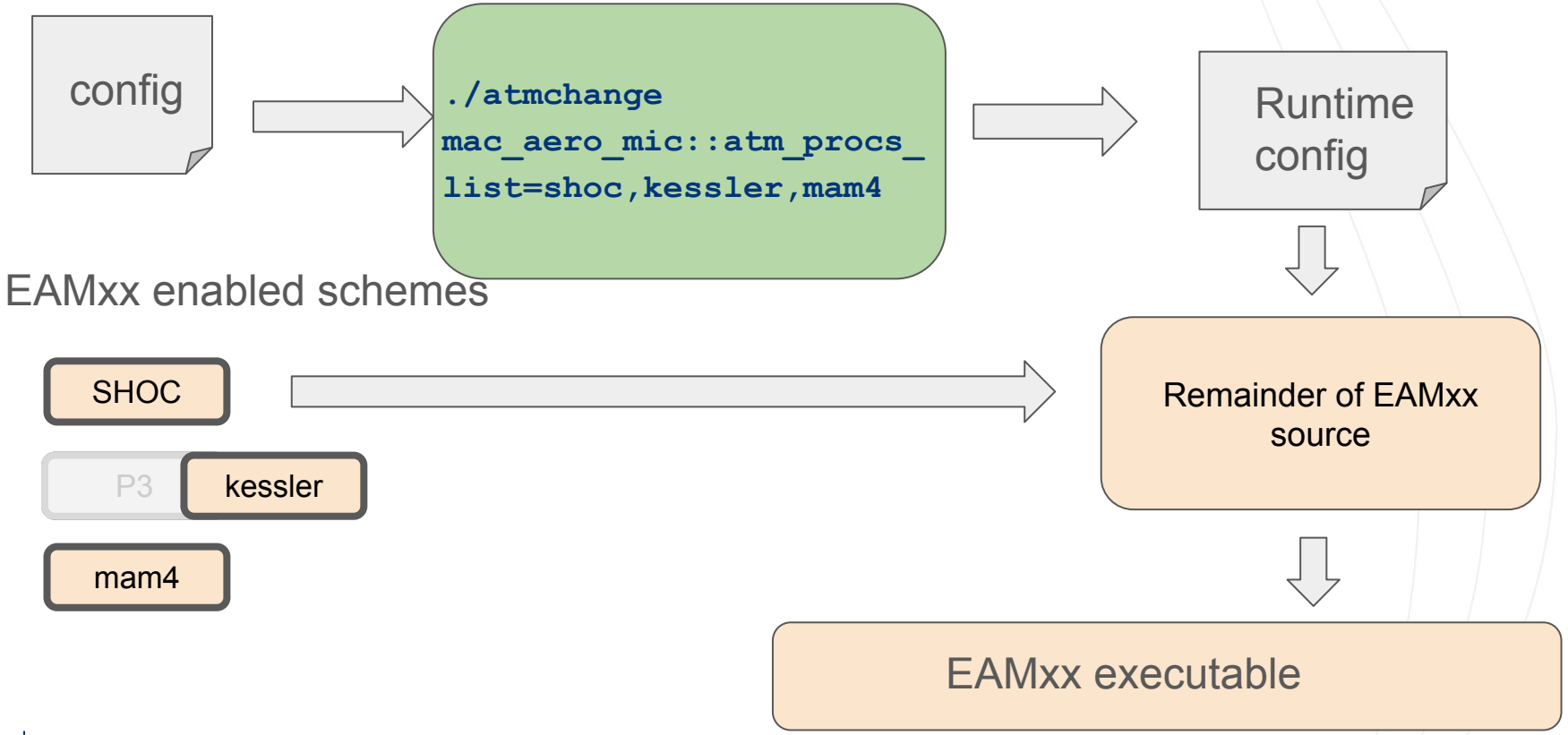
EAMxx change atmospheric processes



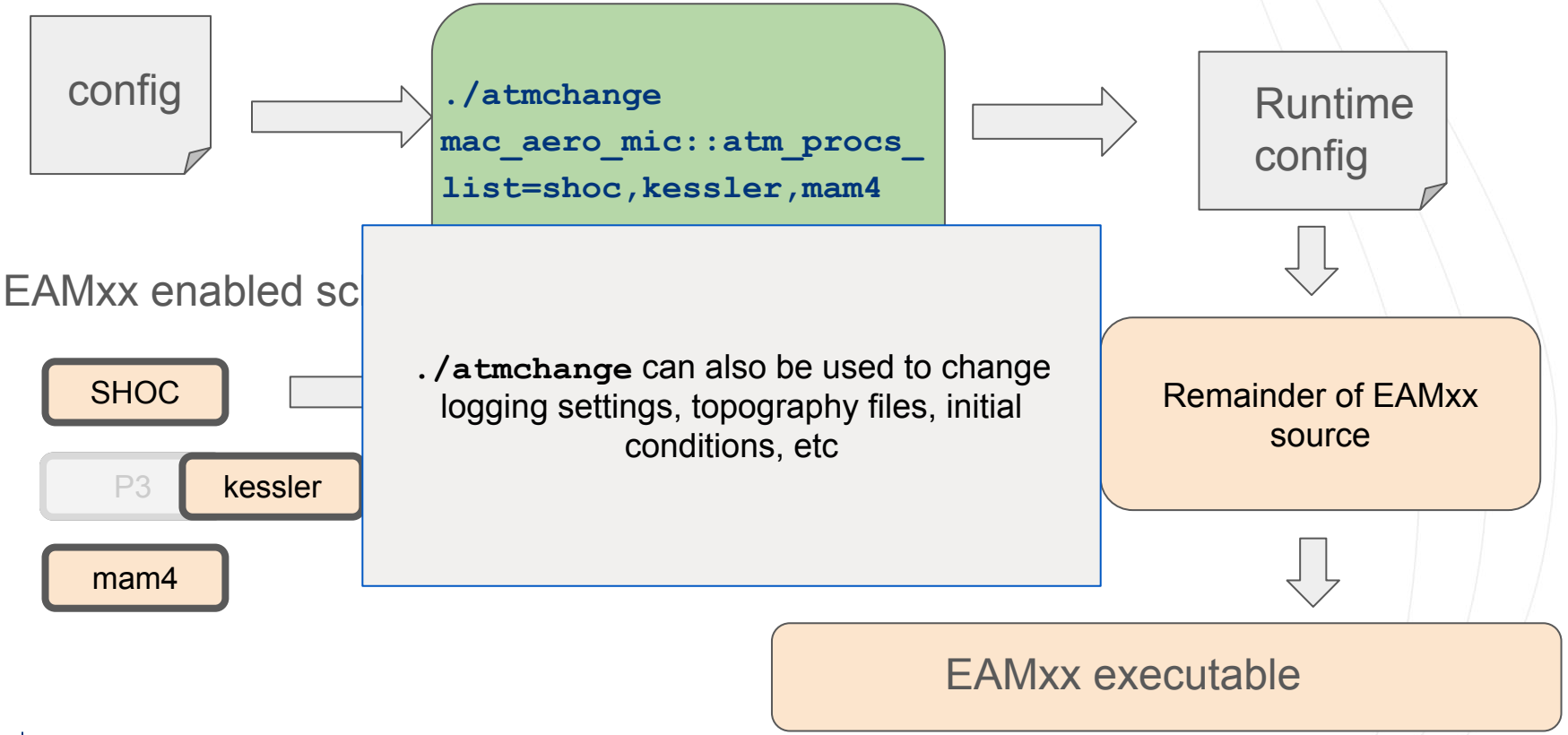
EAMxx change atmospheric processes



EAMxx change atmospheric processes



EAMxx change atmospheric processes



EAMxx automation & sanity checks

- EAMxx handles grid management & time stepping
- Pre- and post-condition checks for all fields
  - Built-in or user defined checks
  - Embeds domain specific knowledge and improves debuggability
- Automatic data handling
  - File IO
  - Data field management between processes

```
Property check 'precip_liq_surf_mass lower bound check: 0' result: Pass
Property check 'precip_ice_surf_mass lower bound check: 0' result: Pass
Property check 'eff_radius_qc within interval [0, 100]' result: Pass
Property check 'eff_radius_qi within interval [0, 5000]' result: Pass
Property check 'eff_radius_qr within interval [0, 5000]' result: Pass
Property check 'NaN check for field T_mid' result: Pass
Property check 'NaN check for field qv' result: Pass
Property check 'NaN check for field qc' result: Pass
```

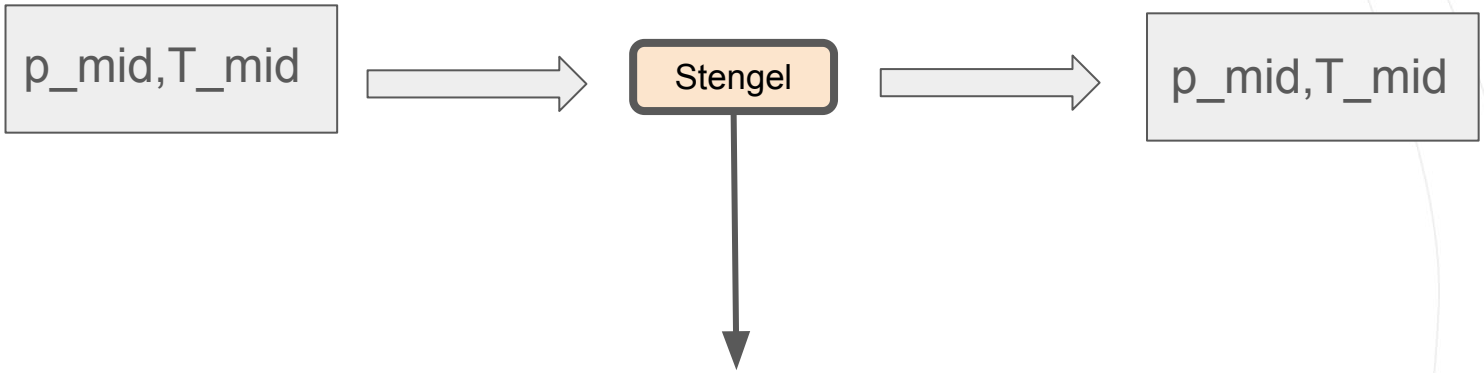
EAMxx parameterization interface overview

- EAMxx parameterizations require the following interface functions:

constructor()	set_grids()	initialize_impl()	run_impl()	finalize_impl()
Usually empty	Define fields and grid layout	Create field checks Initialize things	Run physics!	Usually empty

EAMxx parameterization interface example

- Use an identity transform parameterization as an example

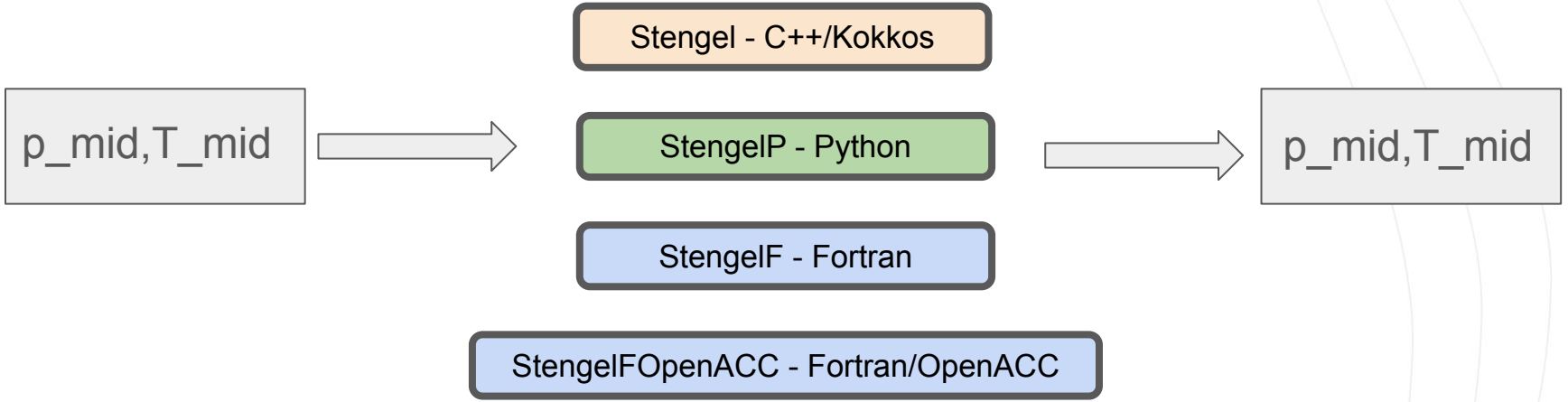


Pressure and temperature at the midpoints (p_mid, T_mid)

p_mid = 2 * p_mid; T_mid = 2 * T_mid
p_mid = 0.5 * p_mid; T_mid = 0.5 * T_mid

EAMxx parameterization interface example

- Use an identity transform parameterization as an example
- Parameterizations can be written with bridges to code in other languages



Pressure and temperature at the midpoints (p_mid, T_mid)

p_mid = 2 * p_mid; T_mid = 2 * T_mid
p_mid = 0.5 * p_mid; T_mid = 0.5 * T_mid

EAMxx parameter interface - C++/Kokkos

set_grids()

m_grid = gm->get_grid("physics");

add_field<Updated>("T_mid", ….);
add_field<Updated>("p_mid", ….);

initialize_impl()

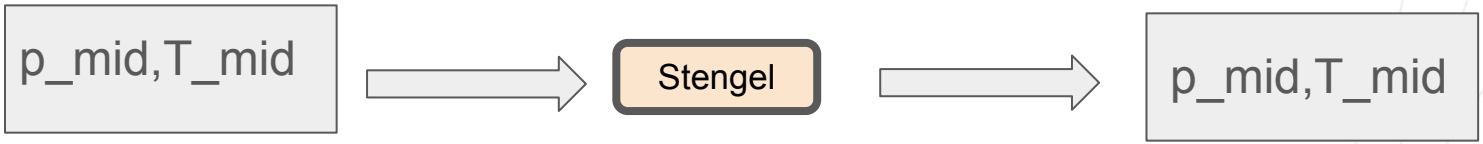
Nothing to do here.

run_impl()

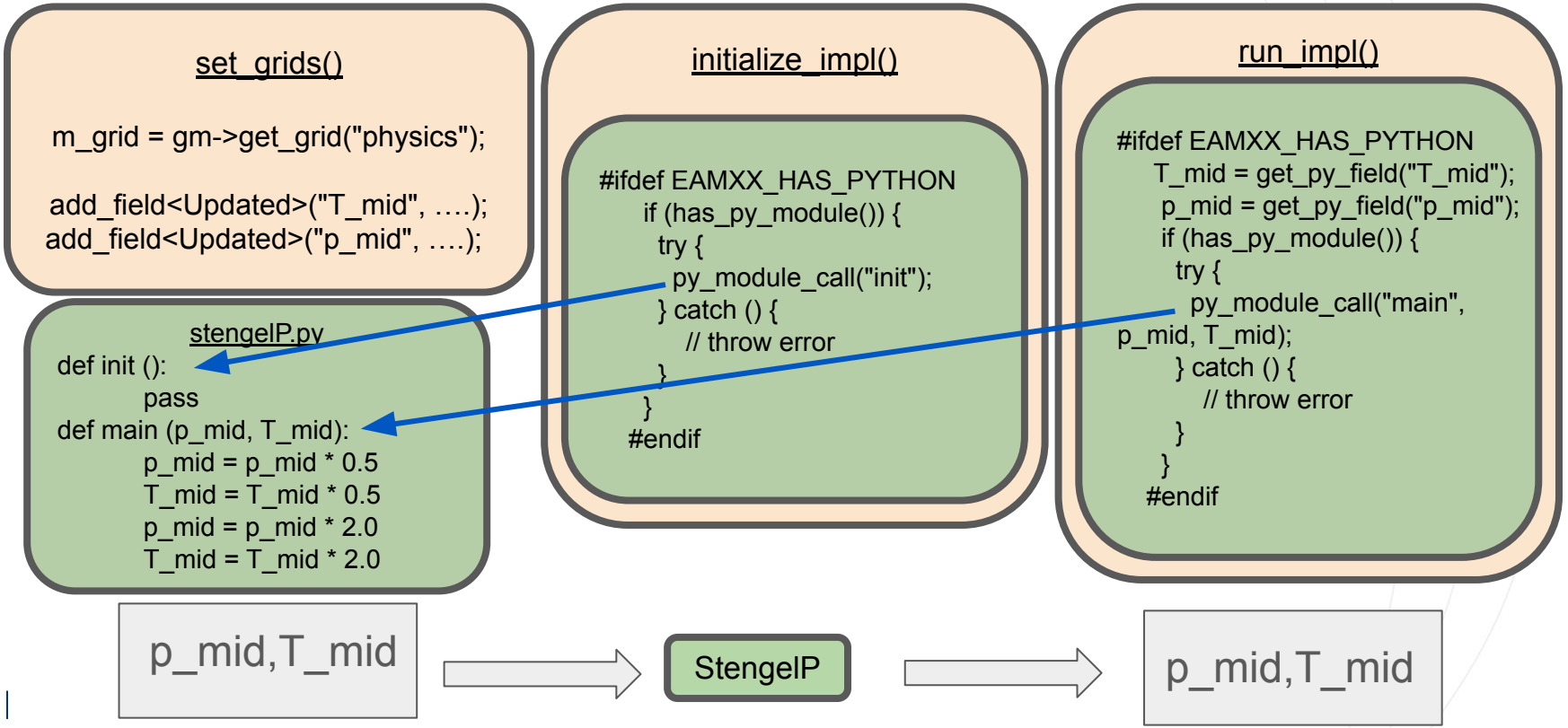
T_mid = get_field_out("T_mid");
p_mid = get_field_out("p_mid");

T_mid.scale(2.0);
p_mid.scale(2.0);

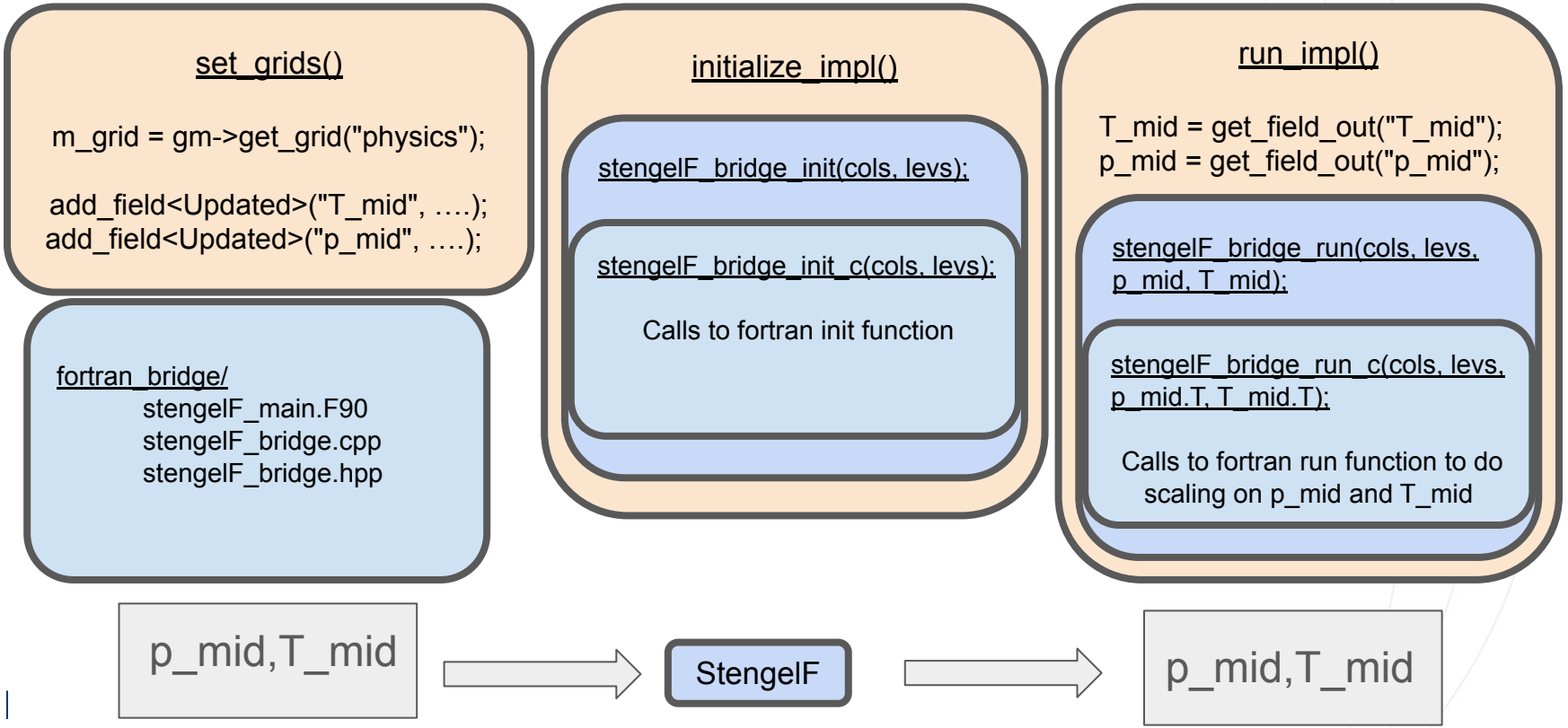
T_mid.scale(0.5);
p_mid.scale(0.5);



EAMxx parameterization interface – Python bridge



EAMxx parameter interface – C++ to Fortran bridge



EAMxx parameterization interface bridges

- C++ and Fortran have different data layouts
  - Requires doing a transpose on fields before going to/from Fortran
  - Use a struct to keep track of C++ and Fortran data fields

- Supports using OpenACC Fortran directives
  - Both the C++ and Fortran code then runs on GPU instead of transferring to CPU for Fortran

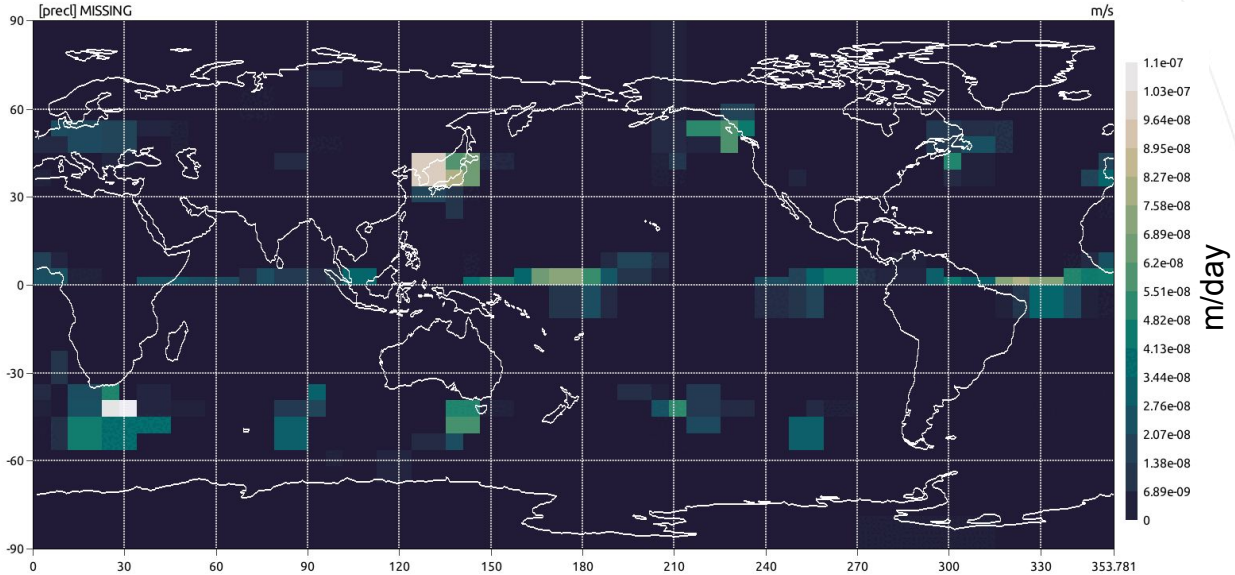
- Can bridge directly to existing code from other repositories! (i.e. CLUBB, PUMAS)

EAMxx with Kessler - WIP

- Kessler from CAM-SIMA
  - Small microphysics parameterization (~783 lines, including meta)
  - CCPP generated code: O(1000s) lines
- EAMxx bridge code written:
  - 1202 lines of C++, including debugging code and comments
  - 179 lines of Fortran for bridge
- Time spent:
  - 2 months for all three Stengel* parameterizations (technical plumbing)
  - Around 2 months for Kessler code
    - I am not a domain expert -> spent a lot of time confused about matching variables, etc
    - Code is currently functional*

Next steps

- Verify Kessler in EAMxx versus FKESSLER in StormSPEED
  - Requires adding analytical conditions capabilities to EAMxx to run the Kessler simulations



Next steps

- Verify Kessler in EAMxx versus FKESSLER in StormSPEED
  - Requires adding analytical conditions capabilities to EAMxx to run the Kessler simulations
- Additional CAM physics parameterizations in EAMxx framework
  - CLUBB
  - PUMAS
- Explore additional language bridge functionality
  - Python/JAX
  - Rust
  - Julia
- Automating bridge code generation

Next steps - portability & performance

- Finish GPU enabling Kessler using OpenACC directives
- Compare memory footprint for EAMxx w/Kessler versus FKESSLER
- Compare memory footprint & transfers and performance for EAMxx Kessler on CPU, CPU/GPU, and GPU

Questions?

Contact: kstengel@ucar.edu

Github branch for the Stengel* example parameters
*Contains Stengel (C++ only), StengelF (Fortran w/OpenACC support), and StengelP (Python) as subdirectories

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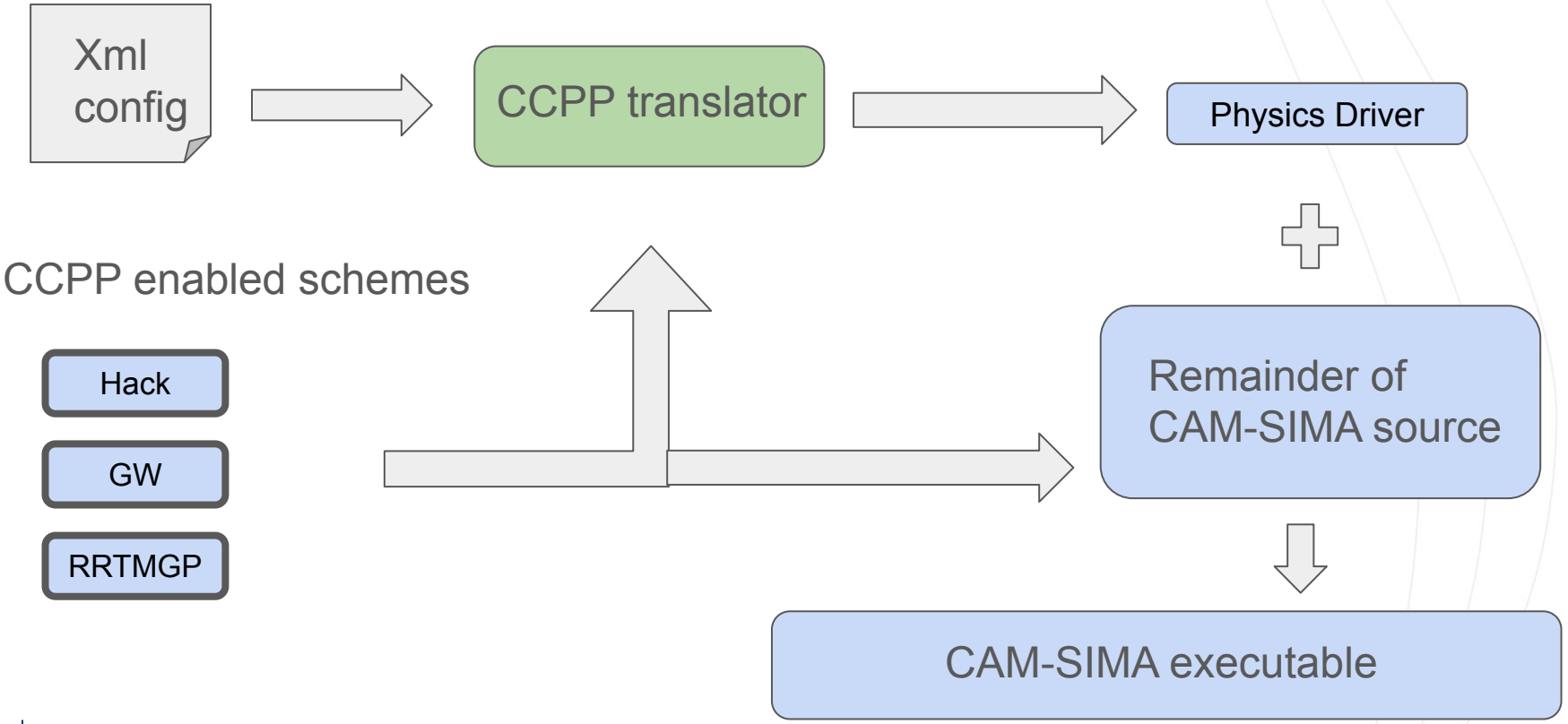
CAM-SIMA change atmospheric processes



EAMxx parameter interface – C++ to python bridge

set_grids()

```
m_grid = gm->get_grid("physics");

add_field<Updated>("T_mid", ….);
add_field<Updated>("p_mid", ….);
```

initialize_impl()

```
#ifdef EAMXX_HAS_PYTHON
      if (has_py_module()) {
        try {
          py_module_call("init");
        } catch () {
            // throw error
        }
      }
    #endif
```

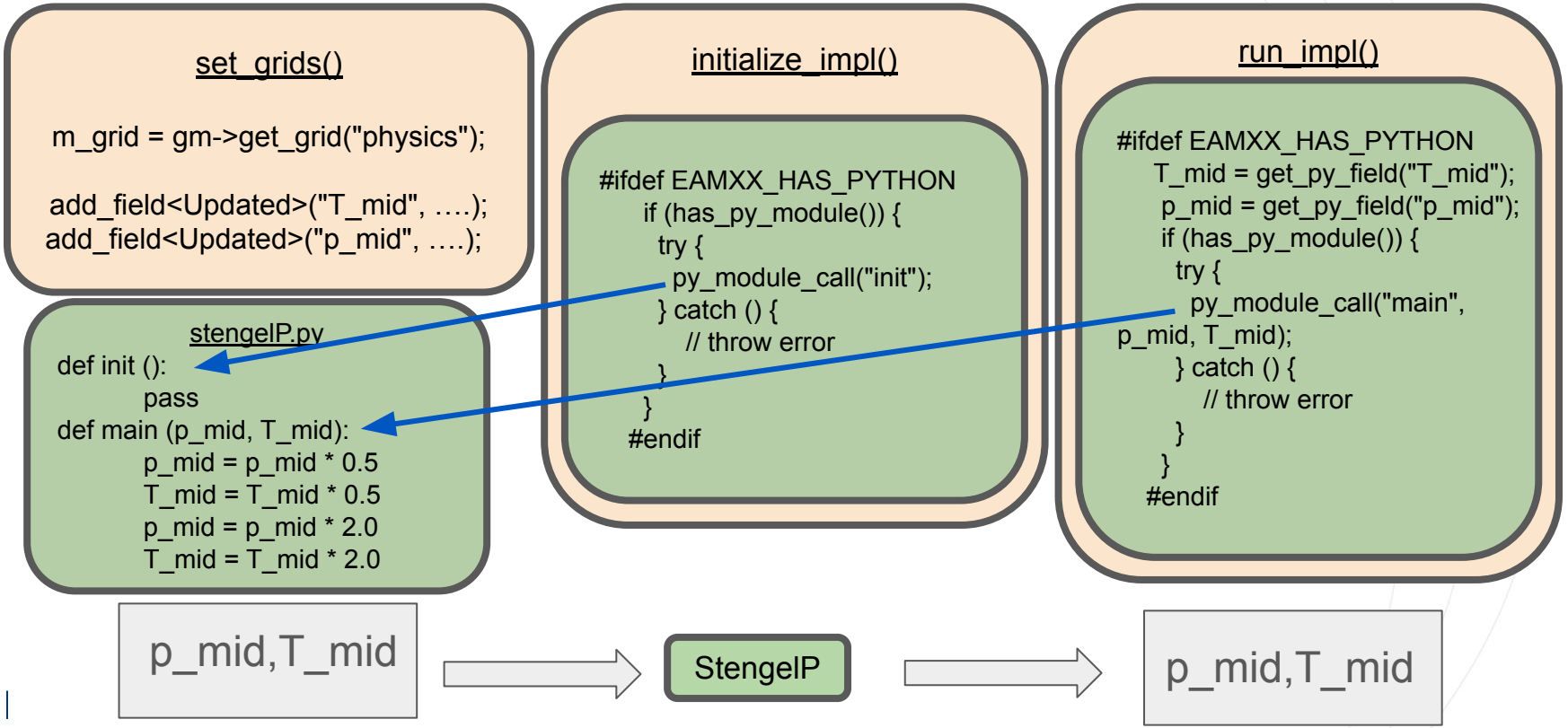
run_impl()

```
#ifdef EAMXX_HAS_PYTHON
      T_mid = get_py_field("T_mid");
       p_mid = get_py_field("p_mid");
       if (has_py_module()) {
         try {
           py_module_call("main",
p_mid, T_mid);
        } catch () {
            // throw error
        }
      }
    #endif
```

stengelP.py

```
def init ():
        pass
def main (p_mid, T_mid):
        p_mid = p_mid * 0.5
        T_mid = T_mid * 0.5
        p_mid = p_mid * 2.0
        T_mid = T_mid * 2.0
```

EAMxx parameter interface - C++ to python bridge



EAMxx with Kessler – GPU results

- Put in CPU and GPU figures if we have them; would want CPU only, CPU/GPU, and all on GPU if possible. Want to show matching results between the three

EAMxx change atmospheric process settings

- Use the **`./atmchange`** functionality to change atmospheric process settings at runtime:
  - Change logging levels:
    - **`./atmchange atm_log_level=debug`**
  - Change overall physics processes:
    - **`./atmchange physics::atm_procs_list=mac_aero_mic,rrtmgp`**
  - Change the parameterizations & their ordering:
    - **`./atmchange mac_aero_mic::atm_procs_list=shoc,cld_fraction,spa,kessler`**
    - **`./atmchange mac_aero_mic::atm_procs_list=shoc,cld_fraction,spa,mam4_aci,p3`**

- Can also be used to set topography file or change initial conditions, etc

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