Integrated Dynamics-Physics Coupling for Weather to Climate Models: GFDL SHiELD with In-Line Microphysics

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Key Points:

- A new integrated dynamics-physics coupling framework is designed to enhance dynamics-physics interaction and thermodynamic consistency
- In-line microphysics coupling shows significant improvements to weather prediction skills in GFDL SHiELD
- Integrated physics shows promise for improved simulation of high-impact weather events such as hurricane

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Abstract

We propose an integrated dynamics-physics coupling framework for weather and climate-scale models. Each physical parameterization would be advanced on its natural time scale, revised to include a moist thermodynamic relationship, and finally integrated into the relevant components of the dynamical core. We show results using a cloud microphysics scheme integrated within the dynamical core of the GFDL SHiELD weather model to demonstrate the promise of this concept. We call it the in-line microphysics as it is in-lined within the dynamical core. Statistics gathered from one year of weather forecasts show significantly better prediction skills when the model is upgraded to use the in-line microphysics. However, we do find that some biases are degraded with the in-line microphysics. The in-line microphysics also shows larger-amplitude and higher-frequency variations in cloud structures within a tropical cyclone than the traditionally-coupled microphysics. Finally, we discuss the prospects for further development of this integrated dynamics-physics coupling.

Plain Language Summary

Resolved-scale air flow ("dynamics") and sub-grid parameterizations ("physics") are two essential components of a weather or climate model. They work together through dynamics-physics coupling in weather and climate models. However, traditionally dynamics and physics are engineered in isolation and developed independently in models, and many parts of the physics run at a physically-inappropriate time frequency, or with heat transfers that are inconsistent with the dynamics, leading to errors. This paper proposes an integrated dynamics-physics coupling framework that can significantly improve weather prediction skills. A concrete example is the cloud and precipitation physics integrated within the dynamics in a global weather model developed at GFDL. When a large number of 10-day forecasts are run, the version with integrated cloud and precipitation physics shows significantly lower errors and higher skill, especially for large-scale weather patterns and near-surface temperatures, compared to a traditionally-coupled physics scheme. The integrated physics also shows promise for improved simulation of high-impact weather events such as hurricanes. The prospects for the integration of other physics processes are also discussed.

1 Introduction

Atmospheric models consist of two main parts: dynamical core and physical parameterizations. Traditionally, dynamical cores and physical parameterizations have been engineered in isolation for the sake of tractability (Donahue and Caldwell (2018); Gross et al. (2018) and references therein). These two independent components are coupled and advanced using the same time step, either parallel or sequentially split (Ubbiali et al., 2021). Ubbiali et al. (2021) analyzed six strategies of dynamics-physics coupling in atmospheric models. They emphasized that the coupling remained an open problem in atmospheric modeling and were conscious that significantly more effort is required to fully understand the implications for a full-fledged model. Gross et al. (2018) described many challenging aspects of dynamics-physics, including the time-stepping of different components, an incomplete understanding of the role of coupling, thermodynamic incompatibility between components, the extension to ocean and land coupling to the atmosphere, and more.

Dynamics-physics coupling is complicated, mainly by the three following aspects. First, dynamical and physical processes have different physical time scales, and the design of the dynamical core and dynamics-physics coupling should reflect this. Fast processes should be computed on a shorter time step and called more frequently, while slow processes should be computed on a longer time step and called less frequently. This has been long recognized in dynamical cores, principally due to efficiency reasons and timestep

Table 1. The time scales of dynamics and different physical parameterizations in Met Office's UM model, ECMWF's IFS model, and GFDL's SHiELD model. The concept of fast, intermediate, and slow are relative within each model. "Surface exchange" refers to the energy and moisture fluxes exchanged between the surface and lowermost atmosphere.

Model	Dynamics	Turbulent Diffusion	Convection	Cloud and Precipitation	Orographic Sub-grid Drag	Radiation	Surface Exchange
UM	Fast	Fast	Fast	Slow	Slow	Slow	Fast
IFS	Fast	Fast	Fast + Slow	Fast + Slow	Fast	Slow	Fast
SHiELD	Fast	Fast	Intermediate	Intermediate	Fast	Slow	Fast

limitations (Durran, 2010). However, there is much less appreciation of this fact in the design of physical parameterizations and there is little consensus on the relative timescales of many parameterizations. Table 1 lists the time scale of each model process in Met Office's Unified Model (UM, Walters et al. (2017)), European Centre for Medium-Range Weather Forecasts (ECMWF)'s Integrated Forecast System (IFS, Beljaars et al. (2018)), and our consideration in Geophysical Fluid Dynamics Laboratory (GFDL)'s System for High-resolution prediction on Earth-to-Local Domains (SHiELD, Harris et al. (2020)). We all agree that the dynamics, turbulent diffusion, and surface exchange between the Earth's surface and the lowest atmosphere are relatively fast processes, but the radiative heating and cooling are relatively slow. In UM, Walters et al. (2017) considers convection a relatively fast process, cloud and precipitation relatively slow processes. However, Beljaars et al. (2018) believes both convection and cloud processes consist of fast and slow processes in IFS. For example, the convective available potential energy's time scale is resolution-dependent in the convection scheme. Condensation is fast, and ice deposition is slow. We agree with Beljaars et al. (2018) and consider them intermediate processes. As for the orographic drag, we agree with Beljaars et al. (2018) that this is a relatively fast process.

Second, the definitions of thermodynamic quantities and their conservation laws can differ between the dynamical core and physical parameterization. For example, in GFDL SHiELD, the nonhydrostatic Finite-Volume Cubed-Sphere Dynamical Core (FV3) defines prognostic variables in a grid box consisting of dry air, water vapor, liquid water, and solid water ("total mass") and assumes that physical processes take place at constant volume. As a result, the dynamical core in SHiELD conserves, up to discretization error, moist total energy (TE_m) defined following Emanuel (1994) as:

$$\mathrm{TE}_m = c_v T + L_v q_v - L_f q_s + \Phi + K, \tag{1}$$

$$c_v = c_{vd} + q_v c_{vv} + q_l c_{vl} + q_s c_{vs}, \tag{2}$$

$$L_v = L_{v0} - (c_{vv} - c_{vl}) T_0, \tag{3}$$

$$L_f = L_{f0} - (c_{vl} - c_{vs}) T_0. \tag{4}$$

Here, c_{vd}, c_{vv}, c_{vl}, and c_{vs} are the heat capacities of dry air, water vapor, liquid water, and solid water, respectively, at constant volume. q_v, q_l, and q_s are mass mixing ratios of water vapor, liquid water, and solid water. T_0 and T are freezing temperature and temperature. L_{v0} and L_{f0} are latent heat coefficients of evaporation and fusion at freezing temperature. c_v can be treated as the moist heat capacities at constant volume. L_v and L_f are the latent heat coefficients at absolute temperature. The last two terms on the right-hand side, Φ and K, are potential energy and kinetic energy, respectively. On the other hand, the physical parameterizations in SHiELD define prognostic variables in a grid box with dry air and water vapor ("moist mass") only, and that thermodynamic processes take place at constant pressure. Like most physical parameterizations in other models, SHiELD's physical parameterizations conserve dry total enthalpy (TE_d) as:

$$\mathrm{TE}_d = c_{pd}T + L_{v0}q_v - L_{f0}q_s + \Phi + K, \tag{5}$$

where c_{pd} is the heat capacity of dry air at constant pressure, we called this "dry total enthalpy". The major differences between moist total energy and dry total enthalpy conservation are whether the heat capacity and latent heat coefficients consider the heat capacities of water vapor and condensates and whether the heat capacity is defined at constant volume or constant pressure. We found that this difference would lead to significant changes in the intensity and propagation of convective- to meso-scale storms. However, this finding is beyond the scope of this study.

Third, the dynamical core and physical parameterizations have traditionally been separated in models. Physical parameterizations consist of un-resolved dynamical and all non-dynamical processes. Here we define convective updrafts, sedimentation or precipitation, orographic drag, and turbulence as sub-grid dynamical processes, but phase changes of water and aerosols, radiative transfer, and aerosol-cloud interactions are non-dynamical processes. Many physical parameterizations combine both dynamical and non-dynamical processes. For example, the convection scheme usually consists of convective updrafts, downdrafts, and phase changes of water. Cloud and precipitation schemes usually consist of sedimentation of precipitating species and phase changes of water. We believe there are compelling reasons that dynamical processes, if resolved, should be taken care of by the dynamical core. Horizontal and vertical transport can be performed by dynamical advection, consistent with the advection of other dynamical quantities and often more accurately owing to the greater sophistication of numerical algorithms within dynamical cores. This is particularly true when the model's resolution reaches a few kilometers or less, and deep convective updrafts can be explicitly represented. Non-dynamical processes, like water phase change, still need to be parameterized. However, the model can benefit from a closer coupling to the dynamics: higher-frequency interaction between the microphysics and the dynamics could permit a faster dynamical response to latent heat release allowing moist dynamical processes to react much more quickly to moist thermodynamic changes.

This paper proposes a novel integrated dynamics-physics coupling framework within the GFDL SHiELD (Harris et al., 2020) that promises to resolve the above issues. The GFDL cloud and precipitation microphysics scheme has already been integrated within the FV3 dynamical core and has proven effective for a variety of weather prediction applications, as described in (Harris et al., 2020) and references therein. Section 2 describes the proposed dynamics-physics framework in detail. Section 3 shows some preliminary results using this framework to implement in-line microphysics within SHiELD. Finally, a summary and discussion are presented in Section 4.

2 Framework

As shown in Figure 1, the primary structure of SHiELD is controlled by the main loop, where the Δt is the main loop time step (or physics time step) used for both the FV3 solver and the SHiELD physics suite. In SHiELD, the dynamics and physics are executed sequentially. The FV3 solver is divided into several vertical remapping loops by k_{split}. Inside the vertical remapping loop, the Lagrangian dynamics are further divided into several acoustic loops by n_{split}. Details of the FV3 solver have been documented thoroughly in Harris et al. (2021). The physics suite, executed in the physics loop, consists of radiation, surface exchange, turbulent diffusion, convection, orographic drag, and cloud and precipitation (Harris et al., 2020). In the proposed integrated dynamics-physics coupling framework, the surface exchange, turbulent diffusion, and orographic drag are relatively fast processes that would be moved from the physics into the acoustic loop. The convection and cloud and precipitation microphysics are intermediate-timescale processes that would be moved from the physics into the remapping loop. The slow radia-

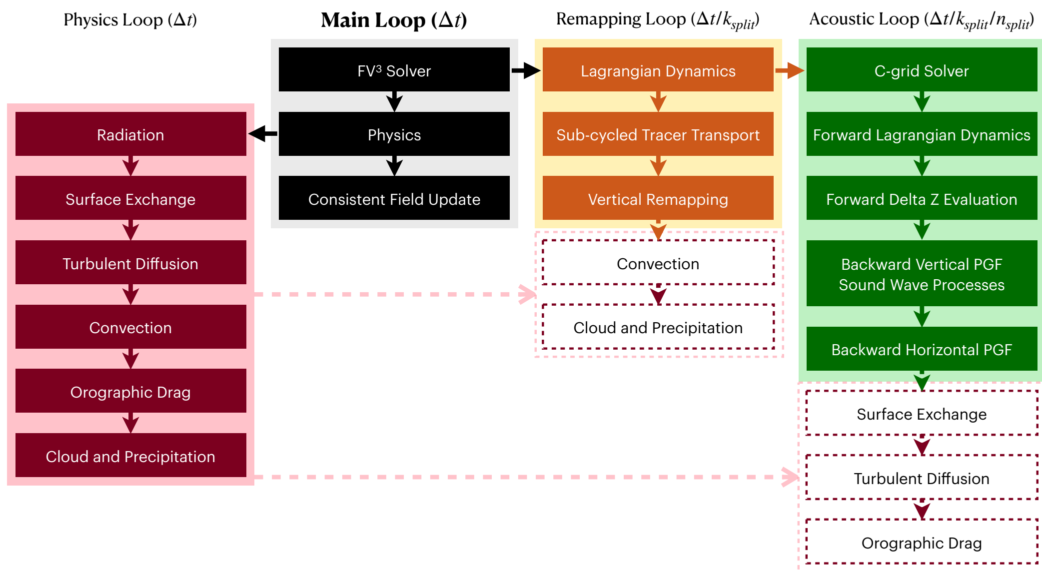

Figure 1. Proposed schematic of the integrated dynamics-physics coupling framework in SHiELD. Black boxes are different model components in the main loop. Red boxes are different physical parameterizations in the physics suite. Orange boxes are dynamics processes in the intermediate-timescale vertical remapping loop. Green boxes are dynamics processes in the fast-timescale acoustic loop. Δt is the time step used in the main and physics loops, k_{split} is the cycle of vertical remapping in a physics time step, n_{split} is the cycle of acoustic dynamics in a vertical remapping loop. This schematic figure is an extension of Figure 2.1 of Harris et al. (2021).

tive heating and cooling would remain within the physics loop. Achieving this new structure is not simply a code relocation. The integrated dynamics-physics coupling framework also requires revising the physics' thermodynamics definitions and conservation laws, and separating the dynamics and non-dynamics processes in the physics.

The dynamics-physics coupling reconstruction in SHiELD requires significant software engineering effort and a thorough understanding of each physical parameterization. Currently, only the cloud and precipitation processes have been completely moved from the physics suite into the dynamical core. In the relocation of cloud and precipitation processes, the time step is changed from physics time step to time step of vertical remapping, the thermodynamic relationships are revised to be consistent with the FV3 dynamical core, and the sedimentation of precipitating species is separated from other microphysical processes and conducted by a time-implicit upwind advection scheme or alternatively FV3's Lagrangian vertical remapping. The cloud and precipitation processes are parameterized by the GFDL single-moment five-category cloud microphysics scheme (GFDL MP, Zhou et al. (2019); Harris et al. (2020); Zhou et al. (2022)) in SHiELD. We call it the in-line GFDL MP as it is in-lined within the FV3 dynamical core. On the contrary, as a reference, we call the GFDL MP implemented within the physics suite the split GFDL MP. Both the in-line and split GFDL MP use the same codebase. The split GFDL MP here is implemented the same way as that described in (Zhou et al., 2019; Harris et al., 2020), except that the fast saturation adjustment or fast phase changes called within FV3 is turned off, and the whole microphysics is used within the physics loop for a clean demonstration of the impact of the in-line microphysics. This paper aims to demonstrate the benefit of the in-line GFDL MP as an example of the benefits of an integrated dynamics-physics coupling strategy for weather and climate models.

3 Results

Two experiments were conducted for this study, using the same GFDL MP codebase; one uses the split GFDL MP (SMP, as a control), the other uses the in-line GFDL MP (IMP). The codebase of SHiELD and the GFDL MP is the same as Zhou et al. (2022). The horizontal resolution and vertical levels follow Harris et al. (2020). Δt, k_{split}, and n_{split} are 150s, 1, and 8, respectively. Note that $k_{split} = 1$ is used here, but it is usually greater than 1 in higher resolution configurations. Therefore, the impact of time-step change on physics-dynamics coupling is not considered here. We perform ten-day long weather forecasts initialized at 00Z every day from March 14th, 2021 to March 21st, 2022 (372 cases in total). The initial conditions are real-time analyses from the operational Global Forecast System (GFS) version 16 (Han et al., 2021). All model results are verified against the ERA5 Reanalysis (Hersbach et al., 2020) for its high-quality dynamical fields and consistent spatial and temporal coverage with our model output. In-depth comparison with satellite and station observations will be conducted in future studies. This study analyzes the prediction skill of geopotential height, temperature, winds, humidity, cloud at different pressure levels, surface temperature, winds, heat flux, radiation fluxes, top of atmosphere radiation fluxes, etc. Statistics used in this study include anomaly correlation coefficient (ACC), root mean square error (RMSE), and bias.

The prediction skills of IMP related to to SMP are shown in Figure 2. It is evident from the scorecard and the summary histograms that the IMP yields significantly higher skill and lower error than the SMP in many meteorological fields. For example, the 10-day ACC and RMSE of geopotential height, temperature, zonal wind, meridional wind, vertical velocity, specific humidity, cloud water, and relative humidity at most pressure levels are significantly improved in the first few days of the forecast. On the other hand, there is some degradation in geopotential height above 200 hPa, temperature above 500 hPa, cloud water above 250 hPa, specific humidity, and relative humidity at 100 and 850 hPa. Most surface, top-of-atmosphere, and vertically integrated variables show significant improvement, except for the high, mid, and total cloud fraction prediction. We do see a significant degradation in the biases of many meteorological fields despite the improved skill and errors. We suspect that the degraded biases with improved skill indicate a different mean state between the model and reanalyses dataset (Magnusson et al., 2019). Similar findings are also found for the northern and southern hemispheres (see supplemental Figures S1, S2). These scorecards clearly show that the new dynamics-physics coupling in SHiELD improves weather prediction skills.

Next, We performed forecasts of Hurricane Ida (2021) to show the tangible effects of the in-line cloud microphysics. Figure 3 shows the time evolution of cloud structures, precipitation, and surface pressure at a location off the Louisiana coast through which Ida's eyewall passed (see supplemental Figure S3). Here we focus on the differences in cloud structures between the IMP and SMP simulations instead of evaluating forecast skill, which depends on many factors. Indeed, Ida's eyewall (seen through both the condensate and rain; Figure 3a-c) and central pressure (Figure 3d) arrived one hour later in IMP than in SMP, and was slightly deeper in IMP. The similarities between the two simulations' precipitation (Figure 3c) are striking in the leading side of Ida's eyewall, although the precipitation on the trailing side is considerably greater in the IMP simulation. This shows that, other than the differing time of arrival, the larger-scale circulation and cloud structures are very similar between the two simulations. However, the smaller-scale structures are considerably different. Most notably, the cloud structures in the IMP simulation vary on a faster timescale compared to those in the SMP simulation, which is consistent with the patchy horizontal cloud distribution (see supplemental Figure S3). This may indicate the effect of calling the microphysics before other parameterizations, rather than afterward (Figure 1). Note that in both SMP and IMP, more clouds are generated above the freezing level than below the freezing level when Hurricane Ida was pass-

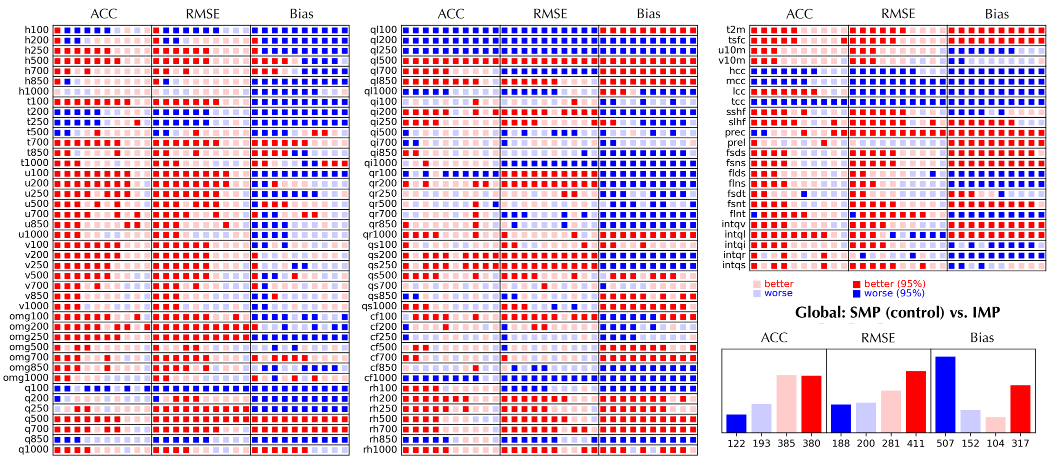

Figure 2. Scorecard showing improvement of the in-line GFDL MP (IMP) over the split GFDL MP (SMP, control) for each meteorological field on the global domain. Totally 372 cases initialized daily from March 14th, 2021 to March 21st, 2022 are analyzed to produce this scorecard. Improvements (degradation) of IMP are indicated in red (blue) squares: higher (lower) ACC, lower (higher) RMSE, or less (larger) absolute bias. Darker colors mean the difference exceeds the 95% significance level. Square boxes in each grid cell from left to right are for the forecasts at 00Z from day 1 to day 10. Abbreviations are defined in Table S1. The histograms at the right bottom corner show the counts of squares for (left) ACC, (middle) RMSE, and (right) bias.

ing (forecast hour 64-76), suggesting the primacy of mixed-phase processes in these simulations.

After the eyewall passes, the middle layer mixed-phase cloud associated with the rainbands persists longer in IMP than SMP. After the forecast lead time of 84 hours, both SMP and IMP produce stratiform cloud and light precipitation for about 6 hours. Still, there is more cloud in IMP than SMP. These results, taken together, show clear changes to cloud and precipitation when switching from split cloud microphysics to in-line microphysics, although all microphysical processes are the same and the simulations are otherwise identical. It is apparent that the thermodynamics of clouds and precipitation parameterizations and how they interact with the dynamics significantly impact the structure and distribution of clouds.

4 Summary and Discussion

This paper proposes an integrated dynamics-physics coupling framework for weather and climate models. The general concept of integrated coupling is to reconstruct each physical parameterization based on their natural time scale, implement the parameterizations within the dynamics, and rewrite the thermodynamics to be more consistent with that in the dynamics. The idea of integrated dynamics-physics coupling is being applied to the Geophysical Fluid Dynamics Laboratory (GFDL) System for High-resolution prediction on Earth-to-Local Domains (SHiELD). This paper demonstrates our first successful example, the integration of the cloud microphysics parameterization into the dynamical core. Ten-day forecasts initialized every day at 00 UTC, covering an entire year, are performed and validated. Statistics from these forecasts are examined. The comparison between split cloud microphysics (cloud microphysics in the physical parameterization suite) and in-line cloud microphysics (cloud microphysics in the dynamical core)

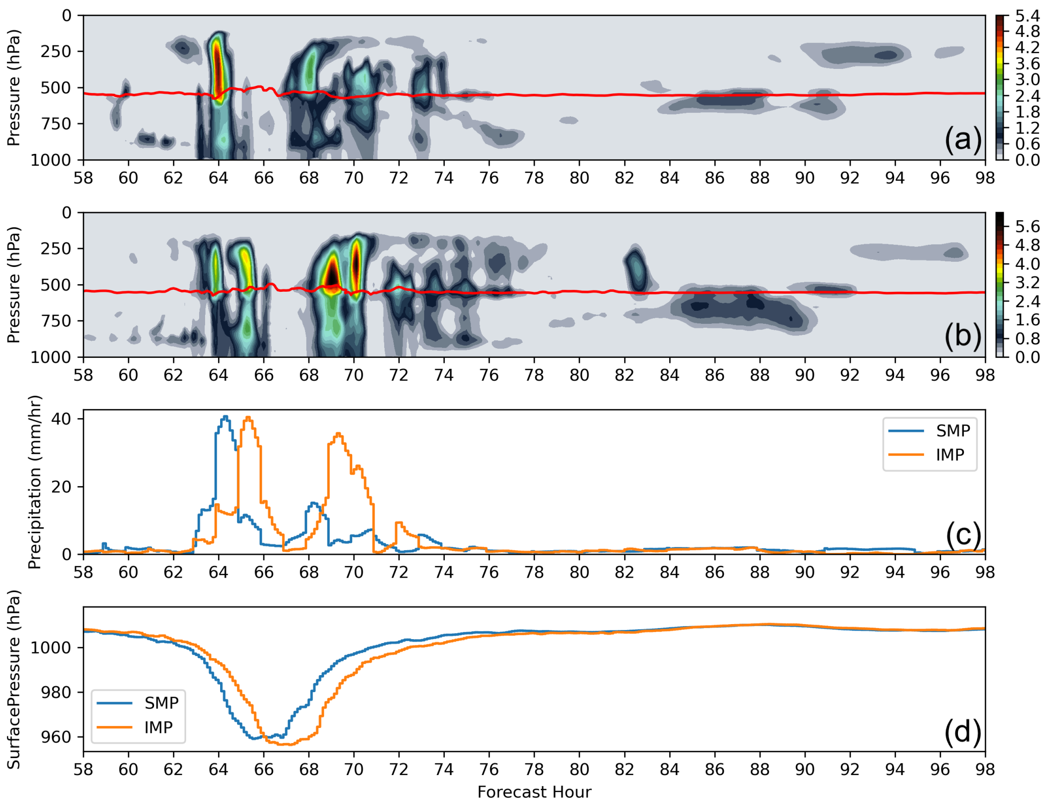

Figure 3. Cloud, precipitation, and surface pressure forecasts of split GFDL MP (SMP) and in-line GFDL MP (IMP) in Hurricane Ida for a forecast initialized at 00Z on August 27, 2021. Panels show the vertical profiles of combined cloud water, cloud ice, rain, snow, and graupel mass mixing ratio (g/kg) of (a) SMP and (b) IMP, the time evolution of (c) precipitation (mm/hr) and (d) surface pressure (hPa), from forecast lead time of 58 to 98 hours at 28.5314°N, 91.139°W. The eye of 2021 Hurricane Ida passed this location around 18Z on August 29, 2021. The red lines in panels (a) and (b) indicate the height of freezing temperature (0°C).

clearly shows that the global prediction model has significantly better forecast skill when the cloud microphysics is integrated into the dynamical core. Most notably, anomaly correlation coefficients are higher and errors are lower for all dynamical variables (height, temperature, winds, vertical velocity, and humidity) at all levels up to about 250 hPa, out to at least day 5, with a minimal exception. There are also significant improvements in near-surface temperature, winds, radiative and turbulent fluxes, and column-integrated hydrometeors. We do see degradation in the biases of many fields with the in-line cloud microphysics compared to the split cloud microphysics; since the skills and errors are significantly improved in most cases, this suggests a difference in mean states between SHiELD and the validating ERA5 reanalysis. Forecasts of Hurricane Ida with the in-line and split cloud microphysics provide a concrete example of the differing impacts of the two methods for coupling the physics. While the large-scale structures are similar in the two simulations, there are distinct differences to the small-scale cloud structures within the hurricane, most notably in the presence of clouds above the freezing level.

Integrating the cloud and precipitation processes into the dynamical core is the first step toward improved dynamics-physics coupling. With this success, we are integrating the convection, surface exchange, turbulent diffusion, and orographic drag into the FV3 dynamical core of SHiELD. We are confident that expanding the integrated dynamics-physics coupling framework to include the other parameterizations will further improve the prediction skill of the weather model. While we have demonstrated the feasibility of this framework in a global weather model, it should also be beneficial in climate models and regional models because the dynamics-physics coupling techniques are similar.

Open Research

The source code of SHiELD is the same as that in Zhou et al. (2022) and is available at `https://doi.org/10.5281/zenodo.5800223`. The ERA5 data on pressure levels can be obtained from `https://doi.org/10.24381/cds.bd0915c6`, while that on the single level can be obtained from `https://doi.org/10.24381/cds.adbb2d47`.

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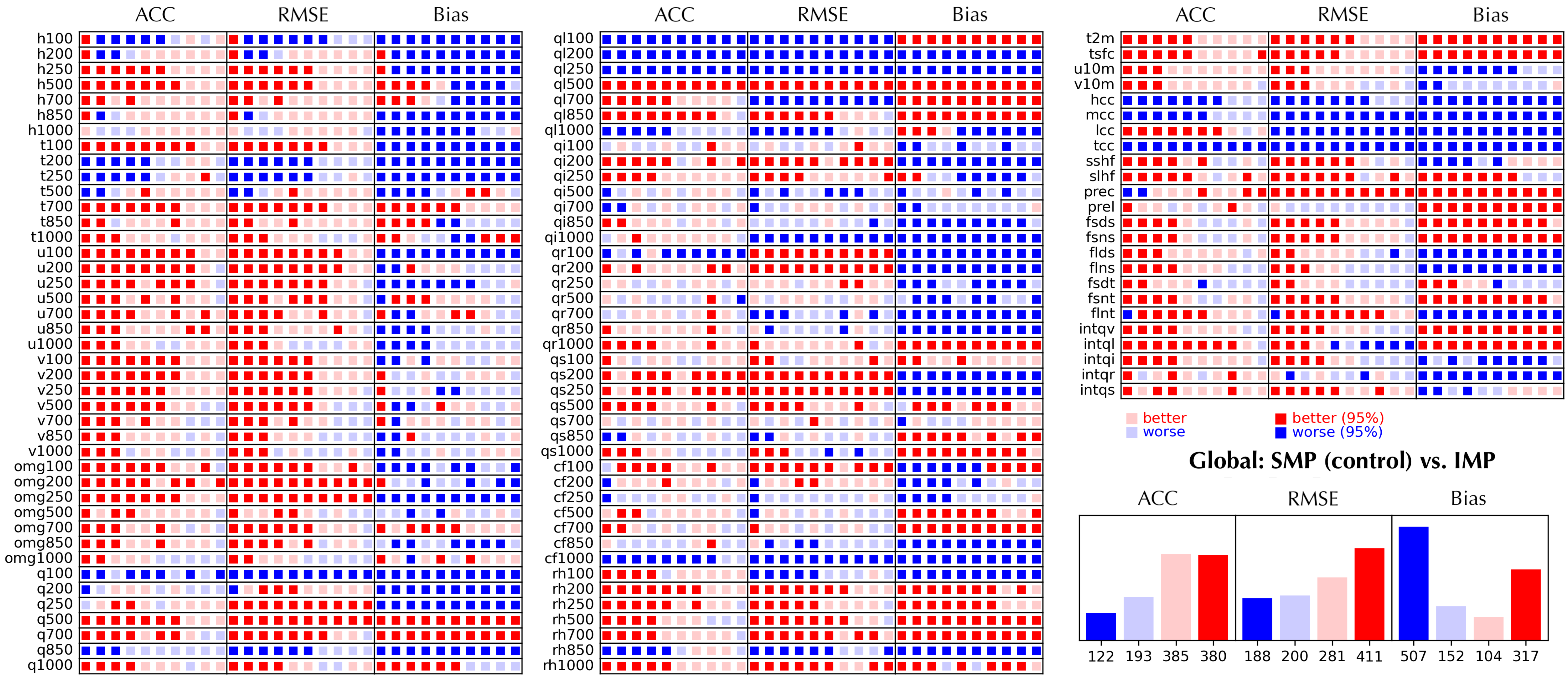
Figure 1.

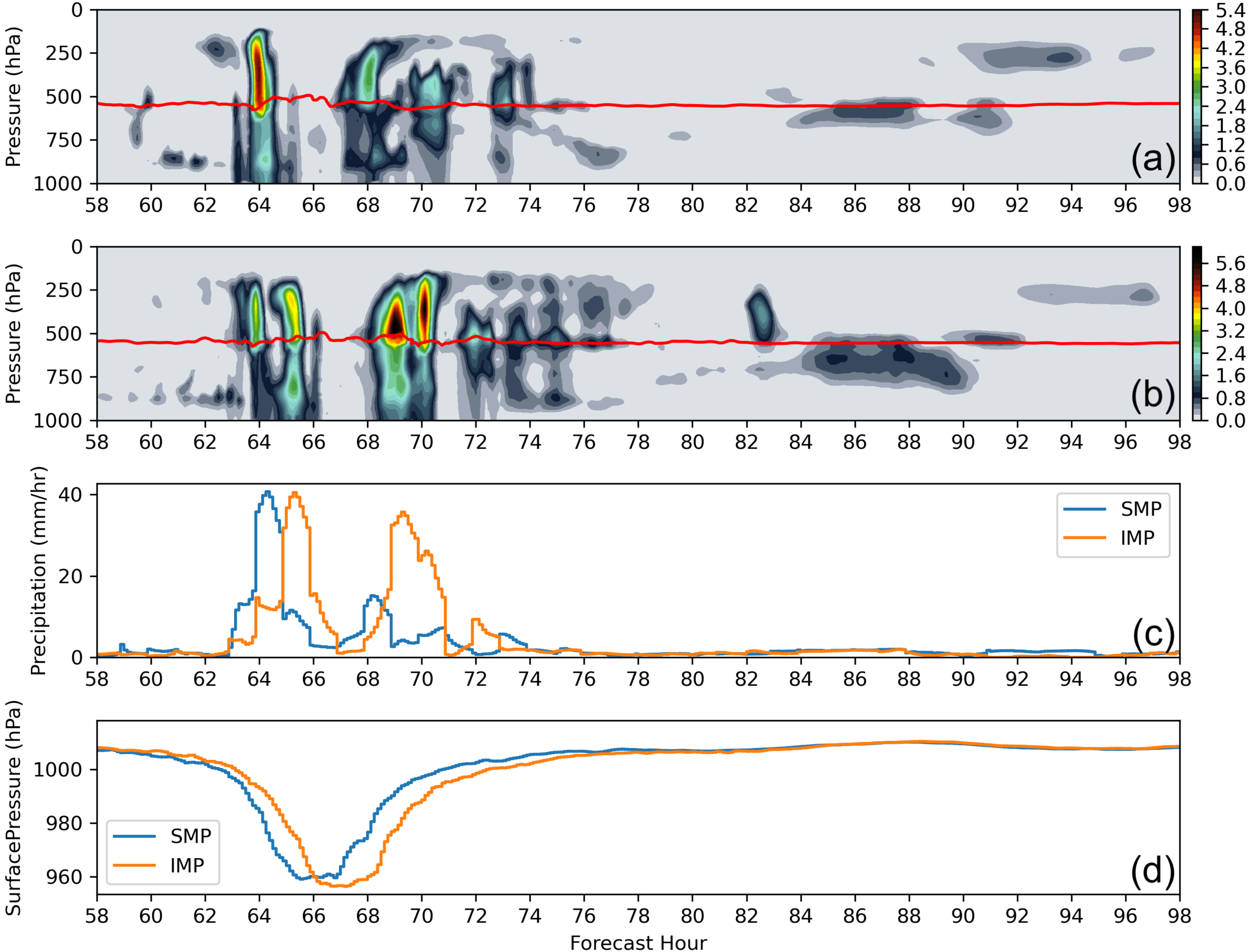
Physics Loop (Δt)
Main Loop (Δt)
Remapping Loop ($\Delta t/k_{split}$)
Acoustic Loop ($\Delta t/k_{split}/n_{split}$)
FV³ Solver
Physics
Consistent Field Update
Lagrangian Dynamics
Sub-cycled Tracer Transport
Vertical Remapping
Convection
Cloud and Precipitation
C-grid Solver
Forward Lagrangian Dynamics
Forward Delta Z Evaluation
Backward Vertical PGF
Sound Wave Processes
Backward Horizontal PGF
Surface Exchange
Turbulent Diffusion
Orographic Drag
Radiation
Surface Exchange
Turbulent Diffusion
Convection
Orographic Drag
Cloud and Precipitation

Figure 2.



ACC
RMSE
Bias
h100 h200 h250 h500 h700 h850 h1000 t100 t200 t250 t500 t700 t850 t1000 u100 u200 u250 u500 u700 u850 u1000 v100 v200 v250 v500 v700 v850 v1000 omg100 omg200 omg250 omg500 omg700 omg850 omg1000 q100 q200 q250 q500 q700 q850 q1000
ql100 ql200 ql250 ql500 ql700 ql850 ql1000 qi100 qi200 qi250 qi500 qi700 qi850 qi1000 qr100 qr200 qr250 qr500 qr700 qr850 qr1000 qs100 qs200 qs250 qs500 qs700 qs850 qs1000 cf100 cf200 cf250 cf500 cf700 cf850 cf1000 rh100 rh200 rh250 rh500 rh700 rh850 rh1000
t2m tsfc u10m v10m hcc mcc lcc tcc sshf slhf prec prel fsds fsns flds flns fsdt fsnt flnt intqv intql intqi intqr intqs
better
worse
better (95%)
worse (95%)
Global: SMP (control) vs. IMP
122 193 385 380
188 200 281 411
507 152 104 317

Figure 3.



Pressure (hPa)
(a)
Pressure (hPa)
(b)
Precipitation (mm/hr)
SMP
IMP
(c)
SurfacePressure (hPa)
SMP
IMP
(d)
Forecast Hour