ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL100519

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

Linjiong Zhou[1] and Lucas Harris[2]

[1]Cooperative Institute for Modeling Earth Systems, Program on Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA, [2]National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA

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 Geophysical Fluid Dynamics Laboratory System for High-resolution prediction on Earth-to-Local Domains
- Integrated physics shows promise for improved simulation of high-impact weather events such as hurricane

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

L. Zhou,
linjiong.zhou@noaa.gov

Citation:

Zhou, L., & Harris, L. (2022). Integrated dynamics-physics coupling for weather to climate models: GFDL SHiELD with in-line microphysics. *Geophysical Research Letters*, *49*, e2022GL100519. https://doi.org/10.1029/2022GL100519

Received 21 JUL 2022
Accepted 20 OCT 2022

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, revise the thermodynamics to include moist effects, 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 Geophysical Fluid Dynamics Laboratory System for High-resolution prediction on Earth-to-Local Domains 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 1 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 Geophysical Fluid Dynamics Laboratory. 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, 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.

Standpoint 1: 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

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

Model	Dynamics	Turbulent diffusion	Convection	Cloud and precipitation	Orographic sub-grid drag	Radiation	Surface exchange
UM	Fast	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

Note. The concept of fast, intermediate, and slow are relative within each model. "Cloud and precipitation" refers to the cloud and precipitation parameterization. "Surface exchange" refers to the energy and moisture fluxes exchanged between the surface and lowermost atmosphere.

called less frequently. This has been long recognized in dynamical cores, principally due to efficiency reasons and timestep 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., 2011; 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. (2011) and Walters et al. (2017) consider convection a relatively fast process, while cloud and precipitation consist of both fast and slow processes. However, Beljaars et al. (2018) believes both convection and cloud processes consist of both 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.

Standpoint 2: 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. 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 have found that these differences 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.

Standpoint 3: 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), Zhou, Harris, Chen, Gao, et al. (2022), 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, dynamical and physical processes should be in their physical time steps (refer to **Standpoint 1**). That is, the surface exchange, turbulent diffusion, and orographic drag are relatively fast processes that would be moved from the physics loop into the acoustic loop. The convection and cloud and precipitation are intermediate-timescale processes that would be moved from the physics loop into the remapping loop. The slow radiative 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 (refer to **Standpoint 2**). Dry total enthalpy conservation designed for the original physical parameterization would be revised as moist total energy conservation for each integrated physics. Meanwhile, conservation would be changed from being based on constant pressure to being based on constant volume. Finally, the dynamics and non-dynamics processes would be separated in the physics (refer to **Standpoint 3**). For example, the sedimentation of precipitable water in the cloud microphysics scheme, the vertical transport of water and aerosols by the mass fluxes in the convection scheme, and the vertical diffusion of water and aerosols by the turbulent fluxes in the boundary layer scheme would be separated and taken care of by the FV3 numerics (Lin, 2004).

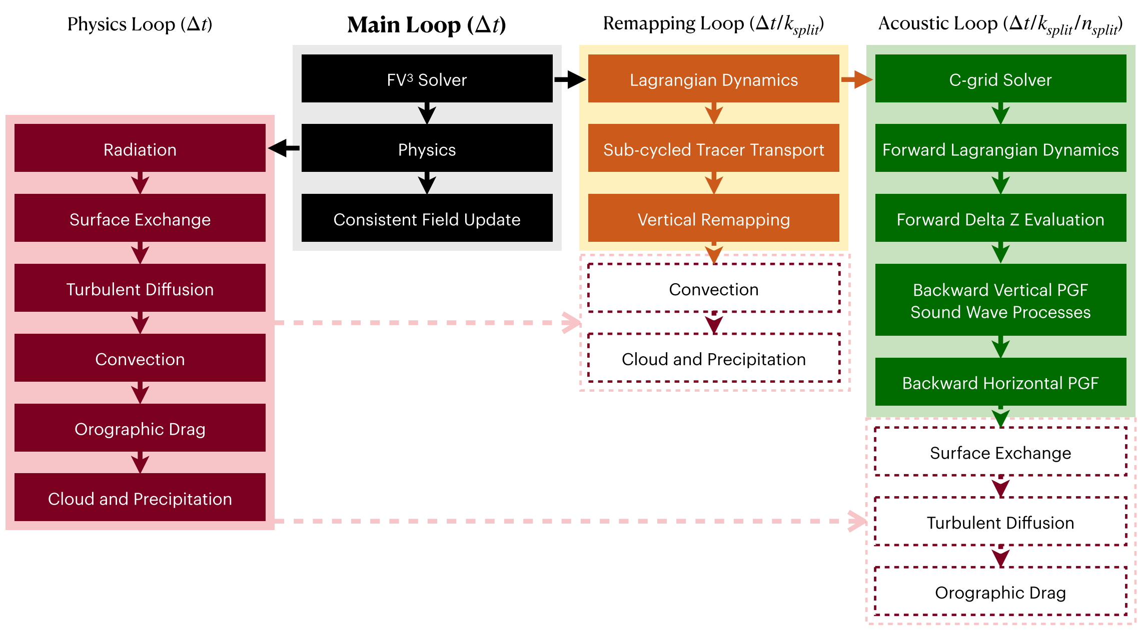

Figure 1. Proposed schematic of the integrated dynamics-physics coupling framework in SHiELD. Black boxes are different model components in the main loop. Red boxes are different physical parameterizations in the physics loop. Orange boxes are dynamics processes in the intermediate-timescale vertical 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). At this point, cloud and precipitation movement is finished and evaluated in this study; the movement of other physical processes is still under development and not included in this study.

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, which conserves moist total energy, 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, Harris, and Chen, 2022; Zhou, Harris, Chen, Gao, et al., 2022) in SHiELD. We call it the in-line GFDL MP (IMP) as it is in-lined within the FV3 dynamical core. As a reference, we call the GFDL MP initially implemented within the physics suite the split GFDL MP (SMP).

The SMP codebase has been recently simultaneously updated to be the same as the IMP codebase except for the following differences: (a) the SMP is called in the physical loop, and the IMP is called in the remapping loop in the dynamical core; (b) latent heating/cooling from the SMP is adjusted following the dry total enthalpy conservation, while there is no such adjustment for the IMP. Two experiments were conducted; one uses the SMP as a control, and the other uses the IMP. The impacts of location change of the microphysics parameterization and revision of the thermodynamics relationship on the model prediction are evaluated in this study, aiming to demonstrate the benefit of the IMP as an example of the benefits of an integrated dynamics-physics coupling strategy for weather and climate models.

The model SHiELD and the GFDL MP are the same as Zhou, Harris, Chen, Gao, et al. (2022). The 13-km horizontal resolution and 91 vertical levels follow Harris et al. (2020). Correspondingly, time step Δt, k_{split}, and n_{split} are 150s, 1, and 8, respectively. Note that $k_{\text{split}} = 1$ is used here, and so the timestep for the microphysical processes is the *same* in both SMP and IMP, and we are thereby only evaluating the direct effect of in-lining the microphysics within the dynamical core. For higher-resolution configurations (Harris et al., 2019, 2020) k_{split} is typically greater than 1, for which more frequent interaction between microphysics and dynamics may be useful. Although there is no extra sub-cycling of the GFDL MP in this configuration, the total SHiELD runtime

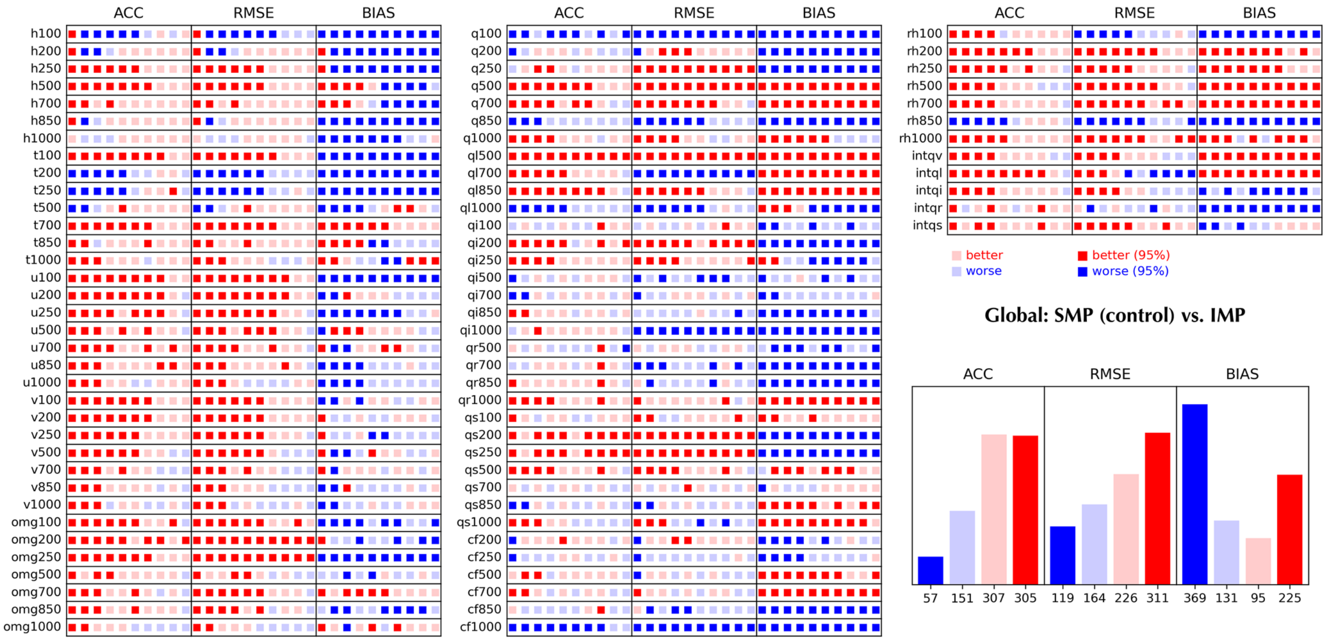

Figure 2. Scorecard showing improvement of the in-line GFDL MP (IMP) over the split GFDL MP (SMP, control) for each meteorological field on the global domain. Totally 372 cases initialized daily from 14 March 2021 to 21 March 2022 are analyzed to produce this scorecard. Improvements (degradation) of 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 in Supporting Information S1. The histograms at the right bottom corner show the counts of squares for (left) ACC, (middle) RMSE, and (right) bias. The percentage of improvement (degradation) can be found in Figure S3 in Supporting Information S1.

increases about 3% due to an extra dynamics-microphysics interface. We perform 10-day long weather forecasts initialized at 00Z every day from 14 March 2021 to 21 March 2022 (372 cases in total). The initial conditions are real-time analyses from the operational Global Forecast System 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 future studies, an in-depth comparison with satellite and station observations will be conducted, especially for top-of-atmosphere and surface variables. This study analyzes the prediction skill of geopotential height, temperature, winds, humidity, and cloud at different pressure levels, as well as vertically integrated cloud species. Statistics used in this study include anomaly correlation coefficient (ACC), root mean square error (RMSE), and bias.

3. Results

The prediction skills of IMP related 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, snow, and relative humidity at most pressure levels are significantly improved in the first few days of the forecast. These improvements result from a faster interaction between the dynamical advection and microphysical heating and cooling, and consistent thermodynamics relationship between the dynamical core and the microphysics parameterization. However, there is some degradation in geopotential height above 200 hPa, temperature above 500 hPa, specific humidity, and relative humidity at 100 and 850 hPa. We do see a significant degradation in the biases of many meteorological fields despite the improved skill and errors. The degraded biases with improved skill (higher ACC and lower RMSE) indicate a different mean state between the model and reanalysis data set in the initial conditions, as discussed in Magnusson et al. (2019). For example, there is a significant negative mean difference in both geopotential height and temperature in the initial conditions of SHiELD compared to ERA5 (not shown). An increment of the mean state results in a reduction of bias, but it does not indicate that the mean state prediction has been improved. Furthermore, it is subject to change using different reference reanalysis (Magnusson et al., 2019).

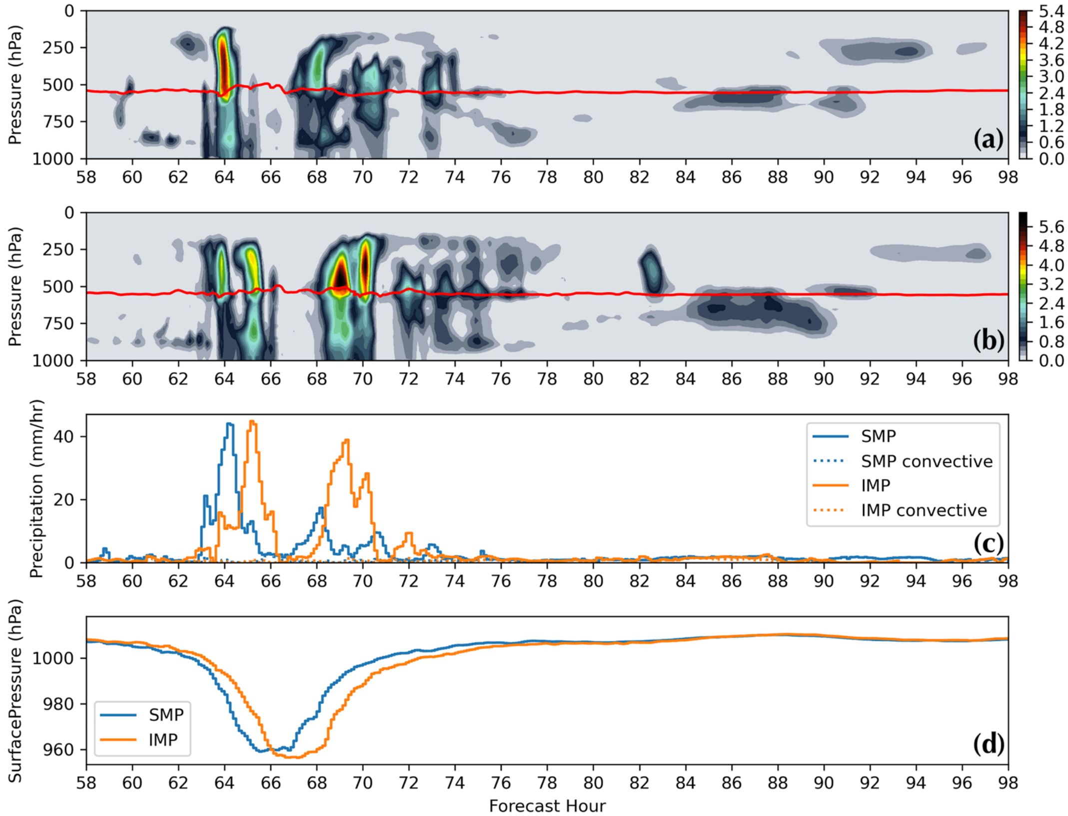

Figure 3. Cloud, precipitation, and surface pressure forecasts of split GFDL MP (SMP) and in-line GFDL MP (IMP) in Hurricane Ida (2021) for a forecast initialized at 00Z on 27 August 2021. Panels show the vertical profiles of combined cloud water, cloud ice, rain, snow, and graupel mass mixing ratio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

Similar findings are also found for the northern and southern hemispheres (see Figures S1–S5 in Supporting Information S1). Despite the questionable degradation of bias prediction, these scorecards clearly show that the new dynamics-physics coupling in SHiELD improves weather prediction skill.

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 Figure S6 in Supporting Information S1). Here we focus on the differences in cloud structures between the SMP and IMP simulations instead of evaluating forecast skill, which depends on many factors. Indeed, Ida's eyewall (seen through both the condensate and rain; Figures 3a–3c) and central pressure (Figure 3d) arrived 1 hour later in IMP than in SMP, and was slightly deeper in IMP. The similarities between the two simulations' total 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 Figure S6 in Supporting Information S1). 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 passing (forecast hour 64–76), suggesting the primacy of mixed-phase processes in these simulations. Another noticeable feature of these simulations is that convective precipitation only accounts for a minimal portion of the total precipitation close to Ida's eyewall. Instead, microphysics-induced precipitation is dominant and is significantly influenced by the coupling of the microphysics scheme.

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 hr, both SMP and IMP produce stratiform cloud and light precipitation for about 6 hr. 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 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) 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. 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. It's worth noting that moving the physical parameterizations into the dynamical core and calling them more frequently inevitably increases the computational cost. We may resolve this issue by simplifying the parameterization and optimizing the code without degrading the forecast skills. 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.

Acknowledgments

The authors thank Dr. Shian-Jiann Lin for his brilliant ideas of dynamical-physics coupling before he retired from GFDL. Many thanks also go to the GFDL FV3 team for their huge support of SHiELD development. Finally, the authors also want to thank Dr. Zhihong Tan, Dr. Yi-Husan Chen, and two anonymous reviewers for their valuable comments and suggestions to improve the quality of this manuscript. Zhou is supported under awards NA18OAR4320123, NA19OAR0220146, and NA19OAR0220147 from the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce.

Data Availability Statement

The source code of SHiELD is the same as that in Zhou, Harris, Chen, Gao, 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.

References

Beljaars, A., Balsamo, G., Bechtold, P., Bozzo, A., Forbes, R., Hogan, R., et al. (2018). The numerics of physical parametrization in the ECMWF model. *Frontiers of Earth Science*, *6*, 137. https://doi.org/10.3389/feart.2018.00137

Donahue, A., & Caldwell, P. (2018). Impact of physics parameterization ordering in a global atmosphere model. *Journal of Advances in Modeling Earth Systems*, *10*(2), 481–499. https://doi.org/10.1002/2017ms001067

10.1029/2022GL100519

Durran, D. (2010). *Numerical methods for fluid dynamics*. Springer.

Emanuel, K. A. (1994). *Atmospheric convection*. Oxford University Press.

Gross, M., Wan, H., Rasch, P., Caldwell, P., Williamson, D., Klocke, D., et al. (2018). Physics–dynamics coupling in weather, climate, and Earth system models: Challenges and recent progress. *Monthly Weather Review*, *146*(11), 3505–3544. https://doi.org/10.1175/MWR-D-17-0345.1

Han, J., Li, W., Yang, F., Strobach, E., Zheng, W., & Sun, R. (2021). Updates in the NCEP GFS cumulus convection, vertical turbulent mixing, and surface layer physics (Tech. Rep.). *National Centers for Environmental Prediction*. https://doi.org/10.25923/cybh-w893

Harris, L., Chen, X., Putman, W., Zhou, L., & Chen, J.-H. (2021). A scientific description of the GFDL finite-volume cubed-sphere dynamical core (Tech. Rep.). *National Oceanic and Atmospheric Administration*. Retrieved from https://repository.library.noaa.gov/view/noaa/30725

Harris, L., Rees, S., Morin, M., Zhou, L., & Stern, W. (2019). Explicit prediction of continental convection in a skillful variable-resolution global model. *Journal of Advances in Modeling Earth Systems*, *11*(6), 1847–1869. https://doi.org/10.1029/2018ms001542

Harris, L., Zhou, L., Lin, S., Chen, J.-H., Chen, X., Gao, K., et al. (2020). GFDL shield: A unified system for weather-to-seasonal prediction. *Journal of Advances in Modeling Earth Systems*, *12*(10), e2020MS002223. https://doi.org/10.1029/2020ms002223

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horanyi, A., Munoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Lin, S.-J. (2004). A "vertically Lagrangian" finite-volume dynamical core for global models. *Monthly Weather Review*, *132*(10), 2293–2307. https://doi.org/10.1175/1520-0493(2004)132<2293:avlfdc>2.0.co;2

Magnusson, L., Chen, J.-H., Lin, S.-J., Zhou, L., & Chen, X. (2019). Dependence on initial conditions versus model formulations for medium-range forecast error variations. *Quarterly Journal of the Royal Meteorological Society*, *145*(722), 2085–2100. https://doi.org/10.1002/qj.3545

Ubbiali, S., Schär, C., Schlemmer, L., & Schulthess, T. (2021). A numerical analysis of six physics-dynamics coupling schemes for atmospheric models. *Journal of Advances in Modeling Earth Systems*, *13*(11), e2020MS002377. https://doi.org/10.1029/2020ms002377

Walters, D., Best, M., Bushell, A., Copsey, D., Edwards, J., Falloon, P., et al. (2011). The met office unified model global atmosphere 3.0/3.1 and Jules global land 3.0/3.1 configurations. *Geoscientific Model Development*, *4*(4), 919–941. https://doi.org/10.5194/gmd-4-919-2011

Walters, D., Boutle, I., Brooks, M., Melvin, T., Stratton, R., Vosper, S., et al. (2017). The met office unified model global atmosphere 6.0/6.1 and Jules global land 6.0/6.1 configurations. *Geoscientific Model Development*, *10*(4), 1487–1520. https://doi.org/10.5194/gmd-10-1487-2017

Zhou, L., Harris, L., & Chen, J.-H. (2022a). The GFDL cloud microphysics parameterization (Tech. Rep.). *National Oceanic and Atmospheric Administration*. Retrieved from https://repository.library.noaa.gov/view/noaa/44636

Zhou, L., Harris, L., Chen, J.-H., Gao, K., Guo, H., Xiang, B., et al. (2022b). Improving global weather prediction in GFDL shield through an upgraded GFDL cloud microphysics scheme. *Journal of Advances in Modeling Earth Systems*, *14*(7), e2021MS002971. https://doi.org/10.1029/2021MS002971

Zhou, L., Lin, S.-J., Chen, J.-H., Harris, L., Chen, X., & Rees, S. (2019). Toward convective-scale prediction within the next generation global prediction system. *Bulletin of the American Meteorological Society*, *100*(7), 1225–1243. https://doi.org/10.1175/bams-d-17-0246.1