Scientific Final Report

1. IDENTIFICATIONS

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Name of Recipient: Piotr K. Smolarkiewicz
Project Title: COLLABORATIVE RESEARCH: CONTINUOUS DYNAMIC GRID ADAPTATION IN A GLOBAL ATMOSPHERIC MODEL – APPLICATION AND REFINEMENT
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2. AUTORIZED DISTRIBUTION LIMITATIONS NOTICES

N.A.

3. EXECUTIVE SUMMARY

This project had goals of advancing the performance capabilities of the numerical general circulation model EULAG and using it to produce a fully operational atmospheric global climate model (AGCM) that can employ either static or dynamic grid stretching for targeted phenomena. The resulting AGCM combined EULAG's advanced dynamics core with the "physics" of the NCAR Community Atmospheric Model (CAM). Effort discussed below shows how we improved model performance and tested both EULAG and the coupled CAM-EULAG in several ways to demonstrate the grid stretching and ability to simulate very well a wide range of scales, that is, multi-scale capability. We leveraged our effort through interaction with an international EULAG community that has collectively developed new features and applications of EULAG, which we exploited for our own work summarized here. Overall, the work contributed to over 40 peer-reviewed publications and over 70 conference/workshop/seminar presentations, many of them invited.

3a. EULAG Advances

EULAG is a non-hydrostatic, parallel computational model for all-scale geophysical flows. EULAG's name derives from its two computational options: EULerian (flux form) or semi-LAGrangian (advective form). The model combines nonoscillatory forward-in-time (NFT) numerical algorithms with a robust elliptic Krylov solver. A signature feature of EULAG is that it is formulated in generalized time-dependent curvilinear coordinates. In particular, this enables grid adaptivity. In total, these features give EULAG novel advantages over many existing dynamical cores.

For EULAG itself, numerical advances included refining boundary conditions and filters for optimizing model performance in polar regions. We also added flexibility to the model's underlying formulation, allowing it to work with the pseudo-compressible equation set of Durran in addition to EULAG's standard anelastic formulation. (Both forms eliminate sound waves, hence their "soundproof" form.) Work in collaboration with others also extended the demonstrated range of validity of soundproof models, showing that they are more broadly applicable than some had previously thought. Coupled with these developments was a relaxing of restrictions on the baseline environmental state used to construct the equation sets, allowing for more states that adhere more closely to physical characteristics of the targeted simulation domain.

Substantial testing of EULAG included application and extension of the Jablonowski-Williamson baroclinic wave test – an archetype of planetary weather – and further analysis of multi-scale interactions arising from collapse of temperature fronts in both the baroclinic wave test and simulations of the Held-Suarez idealized climate. These analyses revealed properties of atmospheric gravity waves not seen in previous work and further demonstrated the ability of EULAG to simulate realistic behavior over several orders of magnitude of length scales. Tests like these originated with hydrostatic atmospheric models. At high resolutions where nonhydrostatic effects emerge, such tests can be computationally demanding. PI Smolarkiewicz in collaboration with Nils Wedi (ECMWF) developed a framework for efficient testing of nonhydrostatic global models by specifying a "small planet" analogue. Additional collaborative work enhanced capability for modeling atmospheric flows with adaptive moving meshes and demonstrated the ability of EULAG to move into petascale computing.

3b. CAM-EULAG Advances

We have developed CAM-EULAG in collaboration with former project postdoc, now University of Cape Town Assistant Professor, Babatunde Abiodun. Initial study documented good model performance in aqua-planet simulations. In particular, we showed that the grid adaptivity (stretching) implemented in CAM-EULAG allows higher resolution in selected regions without causing anomalous behavior such as spurious wave reflection. We exploited the grid-stretching to study factors influencing the Intertropical Convergence Zone (ITCZ). We demonstrated that tropical waves coupled to atmospheric convection strongly influence whether the ITCZ has a single or double maximum in the tropics. We also used the grid stretching to show that the strength of the ITCZ is governed by extratropical waves through their influence on tropical overturning circulation (Hadley Cell).

Additional simulation used observed distributions of land, ocean and sea ice and static grid stretching, with highest resolution (0.5 deg) focused on West Africa. The initial intent was to study genesis of tropical cyclones by mesoscale convective systems propagating from West Africa into the Atlantic. However, analysis of the circulation over the Atlantic showed that the model was producing excessive vertical shear in the horizontal wind, which suppressed cyclogenesis. This occurred whether we used EULAG or CAM's standard dynamics routines, indicating that modeling factors outside our immediate expertise (the model "physics") were the cause. We shifted focus more directly on West Africa, and showed that the EULAG dynamics and grid-stretching both contributed to improved simulation of West African climate compared to simulations using standard CAM. We then used the stretched-grid version to analyze simulated extreme precipitation events in West Africa, comparing the precipitation and event environment with observed behavior. The model simulates fairly well the spatial scale and the interannual and intraseasonal variability of the extreme events, although its extreme precipitation intensity is weaker than observed. The observed extreme events appear to be often an outcome of intense squall lines, which the model, using half-degree resolution, does not simulate well. The model's vertical wind and humidity fields on simulated extreme-event days correspond to observed fields on observed extreme-event days. In addition, both observations and the simulations show possible forcing of extreme events by African easterly waves.

3c. Other Contributions

Through our collaborations, we have made contributions to a wide range of outcomes. For research focused on terrestrial behavior, these have included (1) upwind schemes for gas dynamics, (2) a nonlinear perspective on the dynamics of the Madden-Julian Oscillation, (3) numerical realism of thermal convection, (4) extreme precipitation processes, (5) unstructured meshes, (6) porous-media analogies for simulating flow in urban environments, (7) Monge-Ampere enhancements of semi-Lagrangian methods and (8) further extensions of the generality of EULAG applications to geophysical problems.

The generality of EULAG for multi-scale flow was also demonstrated through solar applications. Simulations of solar magnetohydrodynamics showed that EULAG produces the solar cycle fairly well. Although the model's solar cycle is significantly longer than observed, it shows remarkable agreement with observations in features of spatial evolution. These efforts in environments that are extreme from a geophysical perspective have helped to establish the robustness of EULAG as an all-scale code for geophysical applications.

4. GOALS AND ACCOMPLISHMENTS

	GOAL	**ACCOMPLISHMENT**
1.	Produce a fully operational AGCM from our CAM-EULAG coupling that employs static or dynamic grid stretching for targeted phenomena.	Completed. (e.g., Abiodun et al. 2011)
2.	Optimize the performance of the model and increase further its overall numerical accuracy while activating and improving the dynamic adaptation	Improved model's behavior and efficiency in polar regions. Achieved appropriate scaling of total CPU time with global grid size for sub-degree global grids. Expanded flexibility of model through improved numerical formulation (e.g., more flexible ambient profiles). Improved pressure recovery and pressure velocity algorithms in CEU. Developed new transformations for grid adaptivity. Verified quality of global anelastic model in replicating baroclinic instability test case. Demonstrated multi-scale (planetary ⟷ mesoscale) wave interactions in global simulations that closely matched linear/WKB analyses where appropriate.
3.	Work with personnel at the National Center for Atmospheric Research to	Discussions held with D. Williamson (NCAR), with appropriate diagnostics provided to him. Performed extensive simulation and analysis of the JW baroclinic

	satisfy their criteria for accepting a new dynamics code in their operational climate model.	wave test, demonstrating multi-scale capability of EULAG and deepening understanding of the test's sensitivity to initial conditions and solver accuracy. Completed testing of aqua-planet simulations, another test of dynamics codes. Presentations given at meetings of the Atmospheric Model Working Group.
4.	Demonstrate CAM-EULAG's capability in application to a timely problem in climate-change research, genesis of Atlantic tropical cyclones (TCs).	Developed resolution-appropriate diagnostics for reanalysis and simulated TCs using dynamic grid adaptivity capability to track TCs with region of enhanced resolution. Conducted numerous test simulations, ultimately showing that CAM physics were producing overly strong zonal jet shear, substantially inhibiting TC formation and rendering current model inappropriate for TC study.
5.	Focus on the behavior of West African mesoscale convective systems and their intermittent triggering of tropical storms over the Atlantic Ocean.	Focus shifted to West African systems themselves, due to problems with TC simulation (above). Demonstrated model's ability to replicate climatology and underlying physical causes of extreme precipitation events, which involve convective systems. Demonstrated where model improvements will yield improved replication of extreme precipitation events.
6.	Interact with other potential users of CAM-EULAG, thereby leveraging our funds to allow further validation and improvements in the model's performance.	Numerous advances occurred: (a) developed a framework for testing global nonhydrostatic models; (b) produced large-eddy simulations on the sphere; (c) extended the range of validity of soundproof atmospheric models; (d) Extended EULAG's capability for simulating atmospheric flows with adaptive, moving meshes; (e) developed petascale computing capability in EULAG; (f) produced a new perspective on MJO dynamics; (g) developed unstructured mesh capability for EULAG; (h) adapted EULAG for porous-media simulation; (i) developed a Monge-Ampere enhancement for semi-Lagrangian methods; (j) produced a model for solar magneto-hydrodynamics and validated its ability to simulate solar convection and magnetic cycles.

5. SUMMARY OF PROJECT ACTIVITIES

5a. Modeling Advances in EULAG

EULAG is a non-hydrostatic, parallel computational model for all-scale geophysical flows. EULAG's name derives from its two computational options: EULerian (flux form) or semi-LAGrangian (advective form). The model combines nonoscillatory forward-in-time (NFT) numerical algorithms with a robust elliptic Krylov solver. A signature feature of EULAG is that it is formulated in generalized time-dependent curvilinear coordinates. In particular, this enables grid adaptivity. In total, these features give EULAG novel advantages over many existing dynamical cores.

***Polar Boundary Conditions*:**

Historically, there were two versions of the model code, EULAG and EULAS, designated for local-area and global simulation, respectively. The signature of EULAS was a sophisticated design of polar boundary conditions (hereafter ``differencing across the poles'', DiACP for brevity) custom-designed for both the underlying tensorial formulation and unique numerical design of the code. DiACP was consistently incorporated throughout the entire model code from advection and elliptic pressure solver, through definition of various differential operators, to details of parallelization. In the early 2000s, work started on unifying EULAG and EULAS, and in the interest of developing a more efficient, general code, DiACP was removed, leaving either rigid wall or open boundary condition options for the meridional coordinate near the poles. These options worked well for many global applications, yet it was found, in the context of high-resolution aqua-planet and solar magneto-convection, that DiACP might be needed to achieve high fidelity results in complex multi-scale problems.

During this project, DiACP was (re)introduced into the advanced unified EULAG as an additional option for global simulations. Initially DiACP was only available for the co-located finite-volume (Eulerian), default option of the model code. Later, we extended it to the semi-Lagrangian option of EULAG.

A suite of dynamical tests, from wave propagation through baroclinic instability to idealized climates, has documented excellent performance of the newly developed DiACP boundary condition. For example, the superiority of DiACP has been documented with computations of idealized Held-Suarez climates.

Polar Filters:

The excellent performance of DiACP, alluded to above, results when no polar filters are utilized in a global simulation. Solutions generated by EULAG in the local neighborhood of a pole are seen to satisfy horizontal vector invariance properties to a high degree. However, the potential temperature perturbation and vertical wind fields tend to be quite noisy, and the solution stability (compared to the previous rigid wall polar boundary) tends to be diminished. By implementing polar filters, these adverse effects can be mitigated.

Implementing the DiACP boundary condition enabled meaningful research on control-volume polar filters, in the spirit of LES, the role of which is to remove "super-resolving" modes in the neighborhoods of the poles. These ultra short modes, appearing due to the longitude lines convergence to a point at the poles, are physically unimportant but numerically cumbersome, as they increase the condition number of the elliptic problem and degrade convergence of the Krylov solver for larger grids. The ultimate goal is to develop a range of polar filters using as a basis spectral preconditioners in the Krylov solver that already exist in EULAG.

During the current project, we made progress with flexible filters posed in the physical space, using: a) newly developed options of finite-volume MPDATA advection (cf. Appendix in Smolarkiewicz and Szmelter 2009), b) the generalized, anisotropic Fickean module of EULAG.; and variable Rayleigh attenuation toward prescribed states in close vicinity of the poles. In particular, new filters were developed based on vector invariance of the horizontal wind field over the poles that (in the limit of dx,dy >> dz) gives a unique Fourier description for the horizontal wind in the neighborhood of a pole.

Regardless of these advances, the CFL limit for computational models based upon geospherical coordinates remains formidable for large grids. For example, with a 15 ms^{-1} horizontal flow over a pole, a Courant number of one results in timestep of 32 s for the nominally uniform 0.7-degree global grid. The use of heavy filters to offset the CFL limit is a poor remedy, as it compromises solution fidelity in the polar neighborhoods. Instead, EULAG's grid adaptivity technology can be utilized to move the computational grid further from the poles. The usefulness of this technique in allowing significantly larger timesteps is already well established from previous aqua-planet and Held-Suarez simulations. This technique was successfully employed, in combination with the invariance and anisotropic Fickean filters, to allow efficient Held-Suarez simulations to be made well into the quasi-stationary state for the nominally uniform 0.7-degree grid. The increase in allowed timestep mirrored a doubling of distance of nearest nodes from the poles – contributing to an overall decrease in CPU time of ~ 4x compared to DiACP alone.

Environmental Profile Developments:

At present, the default global environmental states in the idealized climate simulations have been restricted to vertically varying profiles only for potential temperature (pressure, and density) and zero wind. There is nothing intrinsic to EULAG that requires this. In the interest of employing more realistic geostrophically balanced states, we developed the anelastic nonhydrostatic variant of the test put forward in Jablonowski & Williamson (2006) that evinces baroclinic instability of mid-latitude jets. The crux of our development is to refine the geostrophically balanced ambient state of Jablonowski & Williamson, such that it forms the compatibility condition of EULAG; i.e., it satisfies the analytic model equations at the discretization level. In order to achieve this, we adapted their definition of the ambient thermal structure by converting it to the ambient potential temperature used in EULAG, and evaluated ambient wind by integrating on the grid EULAG's thermal wind balance on the sphere. The results obtained document excellent stability of unperturbed ambient flow, whereas perturbed jets develop instability with characteristics in the range of those reported in Jablonowski & Williamson (2006). The ability to make precise pressure and temperature comparisons with those results resulted in a modification of the physical pressure recovery algorithm (as used in previous Held-Suarez and aqua-planet simulations), whereby the environmental pressure is viewed as an independent field and specified *a priori*.

Further simulations demonstrated that unperturbed flows remain balanced for approximately 20 days; whereas for perturbed flows, baroclinic instability growth closely matches Jablonowski & Williamson phase speeds, with similar disturbance amplitudes (allowing for differences in grid sizes), throughout the linear growth regime. Once vigorous baroclinic wavebreaking begins, EULAG results remain similar to those in Jablonowski & Williamson, but do not follow particular details closely. Those details are sensitive to grid resolution and perhaps the radiation of small gravity wave packets from baroclinic wavebreaking regions.

Other new developments on environmental profiles included adding to EULAG a variant based on adiabatic, pseudo-incompressible equations, the implementation of which has been documented in Smolarkiewicz and Dornbrack (2008). Unlike the anelastic set of the governing equations, the results evince strong sensitivity to the boundary conditions in the vertical, thus adding another dimension to the design of environmental profiles.

A framework for testing global nonhydrostatic models:

Nils Wedi (ECMWF) and Piotr Smolarkiewicz (NCAR) developed an approach for testing the emerging nonhydrostatic global dynamical cores. Building on the concepts of Smolarkiewicz et al (1999), the planetary radius is suitably reduced to capture nonhydrostatic phenomena without incurring the computational cost of actual simulations of weather and climate at nonhydrostatic resolution. The procedure is simple and tests various aspects of the discretised hydrostatic and nonhydrostatic equations in the same setting on the sphere. Furthermore, it facilitates verification against analytic solutions and against LES benchmarks. They developed formal scale-analysis, and used both EULAG and a nonhydrostatic variant of the Integrated Forecast System (IFS) to illustrate the theoretical arguments with simulations of inertia-gravity wave dynamics in linear and nonlinear regimes, including flows past idealized mountains, stratified shear flows, and critical layers. Finally, they presented an intercomparison of the Held and Suarez (1994) climate variability on reduced-size planets, which provides a path for future investigations on the dynamics of convective boundary layers on the sphere. This assesses the ability to adequately capture interactions of large-scale dynamics with intermittent turbulent structures, an important aspect of future weather and climate predictions.

Large-eddy simulations on the sphere:

We developed an approximate Smagorinsky subgrid-scale turbulence model for explicit large eddy simulation (LES) on the sphere. The model combines a rigorous formulation of the stress tensor in generalized time-dependent curvilinear coordinates of EULAG with an approximate evaluation of the eddy-viscosity coefficient based on local Cartesian components of the deformation tensor. The benchmark LES of convective planetary boundary layer (PBL) evolution on a reduced planet (Wedi & Smolarkiewicz 2009) reproduces classical scaling results documented in the literature (cf. Margolin, Smolarkiewicz & Sorbjan 1999). This spherical Smagorinsky model is versatile in terms of the filter-size definition, and is thus well equipped to study subgrid-scale models optimal for global flows. Furthermore, it opens a new avenue in the research of control-volume polar filters.

JW baroclinic instability test:

We discussed above the basic agreement of EULAG simulations with the baroclinic instability test of Jablonowski and Williamson (2006). These results were presented and published at the ECCOMAS meeting in Lisbon, Portugal in June 2010 (Prusa and Gutowski 2010). Additional computations further probed the test case for sensitivities due to vertical grid resolution, time resolution, numerics, and initial condition. Sensitivities due to vertical grid and time resolution are small. Sensitivity to numerics was probed by running EULAG in Semi-Lagrangian (SL) mode (all other simulations were done in Eulerian (EL) mode. Consistent with other studies

(Smolarkiewicz and Prusa 2002), we found the SL simulation to be more dissipative than the EL simulation with the same setup. While this caused only relatively minor changes in the baroclinic wave structures during the linear growth phase, it caused dramatic changes during the wave-breaking phase. An EL simulation with reduced amplitude initial disturbance corroborated this result. A number of other simulations (still ongoing) are testing the effects of changes in the initial state. The baroclinic instability test is proving to be sensitive to small changes in the initial state. These experiments are demonstrating that details of setup and numerical schemes/ implementation are as important as the choice of model equations in simulating baroclinic dynamics. These results are presently being organized into a paper to be submitted to *Journal of the Atmospheric Sciences*.

Regime of validity of soundproof atmospheric flow models:

The collaborative work between Rupert Klein (Free University of Berlin), Piotr Smolarkiewicz and colleagues (Klein et al. 2010) provided a multiple scale analysis showing that the regime of validity of the two soundproof models (the anelastic Lipps-Hemler and pseudo-incompressible Durran models) covers stratification strengths corresponding to realistic variations of potential temperature < 30 degrees across the pressure scale height. This extends the classical results of Ogura and Phillips (1962) by two orders of magnitude. Specifically, Klein and colleagues have shown that within this range of stratification the atmosphere features three asymptotically distinct time scales, namely, those of advection, internal gravity waves, and sound waves, and that these two soundproof models yield very good approximations to the linearized internal wave dynamics in a compressible flow on length scales comparable to the pressure and density scale heights.

Resolution of smaller scale gravity waves in Held-Suarez simulations:

Previous global application of EULAG demonstrated orographic waves using grid adaptivity with a maximum resolution of 0.9 degrees over an idealized Andes mountain range in Held-Suarez climates (Prusa and Gutowski 2006). Work supported by the current grant complemented that study by continuing to examine gravity wave generation and propagation in global Held-Suarez simulations. In particular, we examined gravity waves generated from baroclinic wave instabilities of frontal collapse/jet oscillations. Published in Prusa and Gutowski (2011), the global simulations show gravity wave packets ranging from larger scale inertia-gravity waves to pure internal waves small enough that Coriolis effects are negligible, even with modest (uniform) 1.4-degree global resolution. Approximately 3 to 5 smaller scale (domain size < synoptic) wave packets were observed to form in each hemisphere per week at mid-latitudes in the quasi-geostrophic regime. These wave packets are more localized than typical inertia-gravity waves, and have horizontal scales of 1000 – 2500 km and time scales of 1– 2 days. Analysis of one representative wave packet reveals wavelengths, frequency, and phase speeds that are found to fit the linear dispersion for classical inertia-gravity waves to within 4%, suggesting an excellent fit. However, the group velocities matched poorly. This latter result was not consistent with the quality of the numerical data as indicated by a propagation of uncertainty analysis. WKB theory was employed to demonstrate the existence of a critical surface to the southwest of the wave packet that prevented the packet motion predicted by the linear modal analysis. The wave packet properties appear distinct from those of inertia-gravity waves appearing in baroclinic instability studies previously published in the literature. Analysis suggests these smaller scale wave packets may be generated by blocking events arising from barotropic dynamics/instabilities. Clearly, EULAG is proven capable of resolving small-scale internal waves in global simulations being driven by planetary wave instability, that is, the results are clearly multiscale. We believe this capability is due to model design (non-oscillatory forward-in-time numerics and implicit treatment of potential temperature perturbation) as well as an inherent ability of the anelastic model to successfully capture multiscale effects between synoptic and mesoscale waves (Klein et al. 2010).

Modeling atmospheric flows with adaptive moving meshes:

In a collaborative study, Christian Kuehnlein (University of Munich), Piotr Smolarkiewicz, and Andreas Doernbrack (DLR, Oberpfaffenhofen, Germany) extended EULAG's proficiency by combining semi-implicit nonoscillatory forward-in-time numerics with a solution-adaptive mesh capability. A key feature of the extended solver is the unification of a mesh adaptation apparatus, based on moving mesh partial differential equations (MMPDEs), with the rigorous formulation of the governing anelastic PDEs in generalised time-dependent curvilinear coordinates. The new development includes an enhancement of the flux-form multidimensional positive definite advection transport algorithm (MPDATA) — employed in the integration of the underlying anelastic PDEs — that ensures full compatibility with mass continuity under moving meshes. In addition, to satisfy the geometric conservation law (GCL) tensor identity under general moving meshes, a diagnostic approach is proposed based on the treatment of the GCL as an elliptic problem. The benefits of the solution-adaptive moving mesh technique for the simulation of multiscale atmospheric flows are demonstrated. The developed solver is verified for two idealised flow problems with distinct levels of complexity: passive scalar advection in a prescribed deformational flow, and the life cycle of a large-scale atmospheric baroclinic wave instability showing fine-scale phenomena of fronts and internal gravity waves.

Towards petascale simulation of atmospheric circulations with soundproof equations:

This collaborative work of Zbigniew Piotrowski (NCAR GTP postdoc) Piotr Smolarkiewicz and Andrzej Wyszogrodzki furthered development of a petascale implementation of EULAG for anelastic atmospheric flows in the range of scales from micro to planetary. The new model-domain decomposition into a three dimensional processor array has been implemented to increase model performance and scalability. The performance of the new code was demonstrated on the IBM BlueGene/L and Cray XT4/XT5 supercomputers. The results document significant improvement of the model efficacy (showing, e.g., excellent strong scalability of the new scheme up to the maximum available 32769 cores for a canonical problem of the decaying turbulence on a 1024x1024x1024 grid) compared to the original decomposition into a two-dimensional processor array in the horizontal — a standard in meteorological models.

5b. Modeling Advances in CAM-EULAG

CAM-EULAG is a new global climate model produced by combining the EULAG dynamics core with the physics package of the National Center for Atmospheric Research (NCAR) Community Climate Model (CAM). We have done this work in collaboration with former project postdoc, now University of Cape Town Assistant Professor, Babatunde Abiodun. Development and performance of the coupled model has been documented in Abiodun et al. (2008a, 2008b, 2011). Initial study documented good model performance in aqua-planet simulations that also demonstrated the utility of the model's grid stretching for diagnosing circulation behavior under changing resolutions. Later analysis focused on using CAM-EULAG in simulations with specified sea-surface temperature and ocean ice ("time-slice" simulations).

Aqua-planet:

As part of our step-wise development, we implemented EULAG as a dynamical core in the Community Atmospheric Model, Version 3 (CAM3), which was the latest version of CAM at the time of this work. In Abiodun et al. (2008a), we used a series of aqua-planet simulations to demonstrate that CAM-EULAG results compare favorably with those from CAM simulations at standard CAM resolution that use current finite volume or Eulerian-spectral dynamical core options. We also showed that the grid adaptivity implemented in CAM3-EULAG allows higher resolution in selected regions without causing anomalous behavior such as spurious wave reflection.

Further aqua-planet simulations, reported in Abioudun et al. (2008b) used the model's proven grid-stretching capability to diagnose conditions for good simulation of tropical waves and the Inter-tropical Convergence Zone (ITCZ). Previous aqua-planet simulations reported in the literature showed the existence of both single and double ITCZs. In this study, horizontal grid resolution strongly affected ITCZ morphology as well as the amount of tropical precipitation through its influence on resolved dynamics. The grid adaptation capability of CAM-EULAG enabled simulations that separated the influence of tropical and extratropical dynamics on both the ITCZ and tropical precipitation.

The presence of single versus double ITCZs in our aqua-planet simulations depends on the resolution of convectively coupled equatorial waves. When the tropical resolution is sufficiently high to resolve prominent equatorial waves a double ITCZ occurs, otherwise a single ITCZ occurs. In contrast, tropical resolution does not affect the magnitude of tropical precipitation in our aqua-planet simulations. Instead the magnitude is sensitive to extratropical resolution, through its influence on the strength of baroclinic eddies and their forcing of the Hadley circulation.

Global climate model with observed land-ocean-ice distributions:

Further development yielded an atmospheric global climate model based on CAM-EULAG. Part of our original plan was to evaluate the capacity of CAM-EULAG to simulate the coupling of West African convection and tropical cyclones. However, after extensive analysis, we concluded that biases in the CAM physics thwart tropical cyclogenesis in the Atlantic because of excessive vertical shear in the simulated horizontal wind over the tropical Atlantic. For this reason, we shifted our focus to analyzing features of the CAM-EULAG's climatology over West Africa, where the model performs much better and yet where the roots of the shear problem may lie. In particular, the land scheme appears to produce a warm bias in West African surface temperatures, which in turn creates an overly strong south-north temperature gradient and, hence, overly strong shear in the zonal wind.

In Abioudun et al. (2011), we evaluated the capability of our non-hydrostatic climate model with grid stretching (CAM-EULAG). We compared CEU rainfall with that produced by CAM using finite volume dynamics (CAM-FV). Both models simulated climate from 1996 to 2000, using the same parameterization schemes. Our focus was West Africa, for several reasons: climatic processes there can influence North American weather, such as through tropical cyclones; the monsoonal circulation and mesoscale convective processes represent important challenges to good climate simulation; and persistent heating of the atmosphere through convection in this region may influence climate on broader scales.

We examined the precipitation climatology simulated by CAM for West Africa in three versions of the model: CAM-EULAG with uniform 2 deg (lat) x 2.5 deg (lon) resolution (CEU-UNI), CAM-EULAG with 0.5 deg (lat) x 0.5 deg (lon) resolution over West Africa, stretching to the coarser 2 deg (lat) x 2.5 deg (lon) resolution elsewhere (CEU-SG), and a standard version of CAM using a finite volume dynamics core (CAM-FV) that has the same uniform resolution as CEU-UNI. We ran the models using sea-surface temperatures specified from observations, starting with the year 1996 and continuing forward in time. We compared multi-year output from the three versions with each other and with corresponding observations.

The simulations show that, relative to observations, CEU-SG and CEU-UNI tend to perform better over West Africa than CAM-FV, even though we are using the same physical parameterizations in all three cases. The summer precipitation patterns in all three are similar to the patterns in the Global Precipitation Climatology Program's (GPCP's) data set, though CEU-SG tends to have more intense precipitation, which agrees better with observations. CEU-SG and CEU-UNI show a better annual cycle of precipitation, versus observations, than CAM-FV. The improvement is especially better in August, when the monsoonal circulation extends farthest inland. Again, CEU-SG simulates more intense precipitation than CEU-UNI, in better agreement with observations. Contributing reasons for the better performance of the CEU versions is that they produce an African easterly jet and monsoon circulation that generally agree better than CAM-FV with observations, as depicted by the ERA-Interim reanalysis.

More detailed evaluation appeared in a Master's Thesis (Abatan, 2011), whose results are in preparation for submission to a peer-reviewed journal. CEU-SG simulates the mean rainfall at the peak of the West African summer rainy season (July–September), and captures the rainbelt associated with the ITCZ around 12°N. Both CEU-SG and CEU-UNI show excellent agreement with TRMM satellite observations in the timing of the strong diurnal cycle of precipitation in West Africa. Capturing the correct phase of the diurnal cycle of precipitation is often a challenge for global climate models. In this instance as well, CEU-SG's diurnal cycle has larger amplitude than CEU-UNI's, and the larger amplitude is in better agreement with observations. Examination of the intraseasonal variability of rainfall shows that the model captures the three distinct phases of the West African monsoon circulation: onset, peak, and cessation phases. Furthermore, the meridional migration of the rainfall shows that the rainbelt propagates northward, reaching its northward limit in August. The seasonal migration of the rainbelt is linked to the northward excursion and weakening of the African Easterly Jet (AEJ) and the appearance and intensification of the Tropical Easterly Jet (TEJ). The model shows that the core of the rainbelt coincides with the core of the deep ascent lying between the axes of the AEJ and the TEJ. However, there exist notable discrepancies between the simulations and observations. The model shows a tendency to underestimate rainfall over orographic regions. Also, it simulates too little summer rainfall over the Guinean coast while it simulates too much rainfall over the Soudano-Sahel region.

West African precipitation extremes in CAM-EULAG simulation:

Extreme precipitation and its possible alteration by climate change can have substantial societal impact. In the Abatan (2011) M.S. thesis and paper in preparation for publication, we evaluated the ability of a CAM-EULAG with grid-stretching (CEU-SG) to simulate extreme precipitation and its physical causes. As above, we ran the model with 0.5 deg (lat) x 0.5 deg (lon) resolution over West Africa, stretching to the coarser 2 deg (lat) x 2.5 deg (lon) resolution elsewhere. We analyzed observed and simulated extreme daily precipitation and its underlying processes in observations and in a ten-year (1998-2007) CEU-SG simulation.

We focused on a core monsoonal region in West Africa: (6°-16°N, 5°W-5°E). In both the onset (April-May-June; AMJ) and mature-monsoon (July-August-September; JAS) seasons, the model reproduces well the observed climatological annual and diurnal cycles of precipitation in this region, though with somewhat greater than observed time-average precipitation. Daily precipitation extremes at the 99% level and higher are stronger in the observations, but the spatial scale of extreme events in the model is comparable to the observed scale.

The model also simulates fairly well the interannual and intra-seasonal variability of the extreme events. The model's anomaly vertical wind and humidity fields on simulated extreme-event days correspond to ERA-Interim anomaly fields on observed extreme-event days. In addition, both observations and the simulations show possible forcing of extreme events by African easterly waves. However, the three-hourly maximum precipitation on extreme-event days in the observations for both AMJ and JAS varies with extreme event, typically appearing during a period ranging from the late afternoon to early morning, in contrast to the late afternoon maximum in the overall, observed ten-year climatology. The model has difficulty replicating diurnal behavior of the extreme precipitation, tending to show a three-hourly maximum that appears only in the late afternoon. A chief reason for the difference appears to be the model's inability to simulate squall lines at the 0.5-deg resolution. Squall lines produce much of the observed extreme precipitation.

5c. Other Contributions: Terrestrial

EULAG workshop:

We participated in the First and Second International Workshops of EULAG Users (respectively, October 2008, Bad Tölz, Germany and September 2010, Sopot, Poland). The workshops assembled EULAG users to assess progress and discuss future directions with the code. We gave two keynote lectures (Smolarkiewicz, 2008; Prusa, 2008) and two additional presentations (Gutowski et al., 2008a, Smolarkiewicz 2010). There is a strong, active, and growing EULAG community that is exploiting its multi-scale capability by applying it to simulations ranging from cloud microphysics to fluid flow in the Sun. Both meetings were stimulating exchanges of experiences and promoted broader use of EULAG. The Third International EULAG Workshop will be held June 25-28 2012 at the University of Loughborough, UK.

CCSP report:

One of us (Gutowski) co-authored the U.S. Climate Change Science Program (CCSP) Synthesis and Assessment Product 3-1 (Bader et al., 2008). The report is an assessment of current climate modeling, with a focus on U.S. global climate models. It is part of the set of twenty-one Synthesis and Assessment Products being produced for the CCSP.

Iterated upwind schemes for gas dynamics:

Smolarkiewicz and Szmelter (Loughborough University, UK) extended a class of high-resolution schemes established in integration of anelastic equations to fully compressible flows, and documented for unsteady (and steady) problems through a span of Mach numbers from zero to supersonic. The schemes stem from iterated upwind technology of the multidimensional positive definite advection transport algorithm (MPDATA). The derived algorithms employ standard and modified forms of the equations of gas dynamics for conservation of mass, momentum and either total or internal energy as well as potential temperature. Numerical examples from elementary wave-propagation, through computational aerodynamics benchmarks, to atmospheric small-and large-amplitude acoustics with intricate wave-flow interactions verify the approach for both structured and unstructured meshes, and demonstrate its flexibility and robustness.

A nonlinear perspective on the dynamics of the MJO:

Diabatic processes associated with tropical convection and two-way atmosphere-ocean interaction are generally believed to be crucial in explaining the origin of the Madden-Julian oscillation (MJO). However, reliable deterministic forecasting of the MJO in global circulation models and understanding its mechanism remains unsatisfactory. Nils Wedi (ECMWF) and Piotr Smolarkiewicz took a different approach and tested the hypothesis that eastward propagating MJO-like structures originate fundamentally as a result of nonlinear (dry) Rossby-wave dynamics. They presented evidence for the occurrences of such structures in a series of idealized Held-Suarez climate simulations with two entirely different global circulation models, EULAG and the Integrated Forecast System (IFS). They also constructed a beta-plane version of EULAG where the generation of solitary structures is excited and maintained via zonally propagating meanders of the meridional boundaries of a rotating, zonally-periodic beta-plane. The simulations capture details of the formation of solitary structures and their impact on the convective organization.

Numerical realizability of thermal convection:

This work developed a cooperative Ph.D. thesis by Zbigniew Piotrowski (Department of Physics, University of Warsaw, Poland) under supervision of Piotr Smolarkiewicz. The research studied thermal convection as realized in large-scale, high-resolution numerical models. With rapid progress in computer technology, global NWP with 10 km horizontal resolution (or better) will become standard in foreseeable future. While such resolutions are impressive by the standards of NWP, they are still too coarse (by two orders of magnitude at least) to represent convection up to the standards of cloud-resolving models. In effect, NWP is entering a new regime where traditional convection parameterization is obsolete, but large-eddy simulation is still beyond reach. In this regime the convection realization is extremely sensitive to filtering embedded in the numerical model (e.g., via subgrid-scale models and/or numerical approximations used) and can take a variety of forms. This in turn influences simulated weather and climate due to their dependence on cloud field structure via precipitation and radiation. This study investigated numerical effects that influence the structure of simulated convection at its roots; i.e., planetary boundary layer. It focused on effective viscosity and diffusivity representative of contemporary numerical models. Flow responses were compared and classified for various realizations of viscous effects, and examined against predictions of linear theories. Looking forward toward petascale computing, conclusions were drawn regarding potential utility of selected modern numerical approaches for cloud-resolving NWP.

Extreme precipitation:

We also completed publication of papers that were partly supported by the grant. In Gutowski et al. (2008b), we analyzed regional climate model (RCM) simulations of daily, spatially distributed extreme precipitation events, using co-operative network observations and output from 10-year RCM simulations of present and future-scenario climates. We examined an Upper Mississippi River Basin region during October–March for daily amounts that exceed the 99.95th percentile and that occur simultaneously at several observation sites or model grid points. For the observations and each simulation, nearly all such extreme regional events occur when a slow moving, cut-off-low system develops over the Rockies and Great Plains and steadily pumps moisture into the Upper Mississippi region from the Gulf of Mexico. The threshold for the extreme events increases in the future scenario by an amount similar to the increase in saturation specific humidity. The results suggest robust circulation behavior for such extremes in the face of climate change.

The constraint found by Gutowski et al. (2007) on how precipitation intensity versus frequency changes in North America under global warming was also found in simulations of global warming effects in Korea (Im et al.; 2008) and Europe (Boberg et al.; 2008).

An Edge Based Unstructured Mesh Discretisation in Geospherical Framework:

Smolarkiewicz and Szmelter (Loughborough University, UK) developed an arbitrary finite volume approach for discretising partial differential equations governing fluid flows on the sphere. Unconventionally for unstructured-mesh global models, the governing equations are cast in the anholonomic geospherical framework established in computational meteorology. The resulting discretisation retains proven properties of the geospherical formulation, while offering the flexibility of unstructured meshes in enabling irregular spatial resolution. The latter allows for an approximately uniform physical resolution globally, as well as for a local mesh refinement. They developed a class of non-oscillatory forward in time edge-based solvers, and applied them to numerical examples of three-dimensional hydrostatic flows, including shallow-water benchmarks, on a rotating sphere.

Large-eddy simulation of urban flows: Porous-media analogy:

In analogy to theoretical formulation for the microscopic fluid flows in porous media (Smolarkiewicz & Winter 2010), Andrzej Wyszogrodzki and Piotr Smolarkiewicz performed a series of numerical simulations of urban boundary layer flows through realistic street-level building structures of the Oklahoma City downtown area. The corresponding numerical solutions relate the morphology of the real building structures to topological and geometrical properties of the physical media. They analyzed the results in statistical terms of random porous media, seeking the relation between the momentum flux and the macroscopic pressure gradient; i.e., a high-Reynolds-number analogy of the Darcy's law. They related urban ``pore-space'' spatial properties (e.g., homogeneity and anisotropy) to the estimates of permeability and tortuosity. The aim of this work is to evaluate the utility of a porous-media analogy for parameterizing urban effects in the mesoscale weather and air-quality prediction models as well as in the climate models.

A Monge-Ampere enhancement for semi-Lagrangian methods:

During the project period, this long-term project (constituting a part of Jean-Francois Cossette's cooperative Ph.D. Thesis between NCAR and the University of Montreal, with Piotr Smolarkiewicz co-advisor) gained substantial momentum. Numerical experience indicates that semi-Lagrangian large-eddy simulations (LES) of turbulent flows are less effective than equivalent finite-volume (FV) Eulerian calculations. Concomitantly, standard semi-Lagrangian schemes pay little attention to the topological realizability of the computed trajectories, and this contrasts with FV Eulerian methods, in which advecting velocities most often comply with the discrete mass continuity. Demanding the compatibility of semi-Lagrangian (SL) trajectory schemes with the fundamental Euler expansion formula leads to the Monge-Ampere (MA) non-linear second-order partial differential equation. Given standard estimates of the departure points of flow trajectories, solving the associated MA problem provides a corrected solution satisfying a discrete Lagrangian form of the mass-continuity equation to round-off error. The impact of the MA enhancement is well illustrated in the context of implicit LES of a 2D fully developed turbulent incompressible flow (an archetype of large-scale atmospheric circulations). The results show that the "-3" power law dependence associated with the inverse energy cascade at the large scales of the energy spectrum is better maintained when compatibility is enforced. A convergence study using different initial conditions and various resolutions establishes the robustness of this result, which suggests that the MA-enhanced SL scheme better represents the dynamics of 2D turbulence than does the classical SL approximation.

A Nonhydrostatic Unstructured-Mesh Soundproof Model for Simulation of Internal Gravity Waves:

Piotr Smolarkiewicz and Joanna Szmelter (Loughborough University, UK) have developed a semi-implicit edge-based unstructured-mesh model that integrates nonhydrostatic soundproof equations, including the anelastic and pseudo-incompressible systems of PDEs. The model builds on nonoscillatory forward-in-time MPDATA approach using finite-volume discretization and unstructured meshes with arbitrarily shaped cells. Implicit treatment of gravity waves benefits both accuracy and stability of the model. The unstructured-mesh, anelastic and pseudo-incompressible solutions were compared to equivalent structured-grid EULAG results for an intricate, multiscale internal wave phenomenon of non-Boussinesq amplification and breaking of deep stratospheric gravity wave. The departures between the anelastic and pseudo-incompressible results were quantified in reference to the theoretical analysis of Achatz et al. (2010, J. Fluid Mech.).

Additional Efforts Extending the Generality of EULAG Applications to Geophysical Problems:

- *Cloud-Clear Air Interfacial Mixing: Homogeneous versus Inhomogeneous Mixing:* This is a long term collaboration with Mirek Andrejczuk (University of Leeds), Szymon Malinowski (University of Warsaw) and Wojtek Grabowski (NCAR). The fourth paper in the series (see Journal/Proceedings Publications below) presents analysis of several dozens of direct numerical simulations of the cloud-clear air mixing in a setup of decaying moist turbulence with bin microphysics. The goal is to assess the instantaneous relationship between the homogeneity of mixing and the ratio of the time scales of droplet evaporation and turbulent homogenization. Such a relationship is important for developing improved microphysical parameterizations for large-eddy simulation of clouds.

- *Coupling the Dynamics of Boundary Layers and Evolutionary Dunes:* In collaboration with Pablo Ortiz (University of Granada), Smolarkiewicz accomplished a study on dynamics of evolutionary land forms. A novel theoretical formulation and corresponding numerical solutions are documented for fluid flow and sediment transport past evolutionary sand dunes.

- *Scale-Invariant Estimates for Permeabilities of Porous Media:* In this collaborative work between Jeffrey Hyman and Larrabee Winter (University of Arizona) and Piotr Smolarkiewicz, three phenomenological power law models for the permeability of porous media are derived from computational experiments on flow through explicit pore spaces. The power laws relate permeability to (i) porosity, (ii) squared mean hydraulic radius of pores, and (iii) their product, which has dimensions of length raised to the fifth power. Their performance is compared to estimates derived via the Kozeny equation, which also uses the product of porosity with squared mean pore radius to estimate permeability. The power laws provide tighter estimates than the Kozeny. The best fit is with the power law based on the Kozeny predictor, that is, the product of porosity with the square of mean pore radius. This work aims at combining meteorology and hydrology models.

5d. Other Contributions: Solar

PI Smolarkiewicz has extended the breadth of EULAG applicability to physical problems. These efforts in environments that are extreme from a geophysical perspective help to establish the robustness of EULAG as an all-scale code for geophysical applications.

Magnetic cycles in global large-eddy simulations of solar convection:

A decade long collaboration between Piotr Smolarkiewicz and Paul Charbonneau (and his group at the Department of Physics, University of Montreal) on the development of the solar variant of the EULAG model has reached a breakthrough. In Ghizaru et al. (2010) they have reported on an unprecedented global magnetohydrodynamical implicit large-eddy simulation of the solar convection zone, which succeeded in generating a large-scale axisymmetric magnetic component, antisymmetric about the equatorial plane and undergoing regular polarity reversals on decadal timescales. They focused on a specific simulation run covering 255 years, during which 8 polarity reversals were observed, with a mean period of 30 years. Time–latitude slices of the zonally averaged toroidal magnetic component at the base of the convecting envelope showed a well-organized toroidal flux system building up in each solar hemisphere, peaking at mid-latitudes and migrating toward the equator in the course of each cycle, in remarkable agreement with inferences based on the sunspot butterfly diagram. Their simulation also produced a large-scale dipole moment, varying in phase with the internal toroidal component, suggesting that the simulation may be operating as what is known in mean-field theory as an alpha-Omega dynamo . The unique numerics of the MHD clone of EULAG has been documented recently in Charbonneau and Smolarkiewicz (2012).

A mode of dynamo action in a global large-eddy simulation of solar convection:

This follow up work of the astrophysical group at the University of Montreal and Piotr Smolarkiewicz examines the mode of dynamo action in the implicit large-eddy magnetohydrodynamical simulation of solar convection reported upon in Ghizaru et al. (2010). Motivated by the presence of a strong and well-defined, large-scale axisymmetric magnetic component undergoing regular polarity reversals, the fluctuating component of the magnetic field is defined as the difference between the total field and it zonal average. The subsequent analysis follows the physical logic and mathematical formulation of mean-field electrodynamics, whereby a turbulent electromotive force (EMF) is computed by suitable averaging of cross-correlations between fluctuating flow and field components, and expressed in terms of the mean-field via a linear truncated tensorial expansion. The use of singular value decomposition to perform a linear least-squares fit of the temporal variation of the EMF to that of the large-scale magnetic component, yields the components of the full alpha-tensor. The alpha-tensor so calculated reproduces a number of features already identified in local, Cartesian simulations of magnetohydrodynamical rotating convection. It is also found that the EMF contributes significantly to the regeneration of the large-scale toroidal magnetic component, which from the point of view of mean-field dynamo models would imply that the simulation operates as an alpha2-Omega dynamo. In more general term, this work verifies implicit large-eddy simulation property of EULAG for magnetohydrodynamics.

Spontaneous formation of current sheets: Untwisted magnetic fields:

This collaborative effort between R. Bhattacharyya (Udaipur Solar Observatory, Physical Research Laboratory, Dewali, India) and NCAR researchers B. C. Low and P. K. Smolarkiewicz studies the spontaneous formation of electric current sheets in an incompressible viscous fluid with perfect electrical conductivity, governed by the magnetohydrodynamic Navier–Stokes equations. Numerical solutions for a 3D periodic, untwisted magnetic field evolving, with no change in magnetic topology under the frozen-in condition and at characteristic fluid Reynolds numbers of the order of 500, demonstrate that current sheets must form during the evolution despite the geometric simplicity of the prescribed initial fields. In addition to the current sheets associated with magnetic neutral points and field reversal layers, other sheets not associated with such magnetic features are also in evidence. These current sheets form on magnetic flux surfaces. This property is used to achieve a high degree of the frozen-in condition in the simulations, by describing the magnetic field entirely in terms of the advection of its flux surfaces and integrating the resulting governing equations with a customized version of EULAG. Incompressibility imposes the additional global constraint that the flux surfaces must evolve with no change in the spatial volumes they enclose. The principal results are related to the Parker theory of current-sheet formation and dissipation in the solar corona.

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6. PRODUCTS DEVELOPED AND TECHNOLOGY TRANSFER ACTIVITIES UNDER THE AWARD

6.a Technologies/Techniques Product Development Overview

Substantial technologies/techniques were developed in this project that are based upon improving capabilities for solving systems of partial differential equations subject to various physical couplings, with particular emphasis on global atmospheric modeling (wherein the coupling is with atmospheric thermodynamics). The current effort (2008 → 2011+) contributed to ~ 40 refereed publications and ~ 70 papers delivered in national and international venues (see following section for detailed list). The resulting technologies/ techniques ranged from mathematical developments in advanced solvers for advection and elliptic boundary value problems through development of advanced coding algorithms for execution on massively parallel computer architectures through global climate modeling with static and dynamic stretched grids. These developments moved the computational capabilities of EULAG, our global atmospheric model, from terascale capability to petascale capability. In turn, this opened up new opportunities for studies on model approximations (sound proof vs. elastic), multiscale wave interactions in global atmospheric simulations (planetary-mesoscale interactions) as well in global atmospheric climate simulations with grid adaptation technology applied to achieve regionally improved climate simulations (African monsoon).

6b. Publications

i. Journal/Proceedings Publications: 2008

Abiodun, B.J., J.M. Prusa and W.J. Gutowski, 2008: Implementation of a Non-hydrostatic, Adaptive-Grid Dynamics Core in CAM3. Part I: Comparison of Dynamics Cores in Aqua-Planet Simulations. *Clim. Dynamics*, **31**, 795-810, [DOI: 10.1007/s00382-008-0381-y].

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Smolarkiewicz, P. K., and J. Szmelter, 2008: An MPDATA-based solver for compressible flows. *Int. J. Numer. Meth. Fluids,* **56,** 1529-1534.

Waite, M. L., and P. K. Smolarkiewicz, 2008: Instability and breakdown of a vertical vortex pair in a strongly stratified fluid. *J. Fluid Mech.,* **606,** 239-273.

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ii. Journal/Proceedings Publications: 2009

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v. Papers/Posters/Seminars Presented: 2008

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Gutowski, W.J., 2008: Review of Multi-model RCM Projects: Recommendations for a Coordinated RCM Program in Africa & Beyond. *Fourth ICTP workshop in the Theory and Use of Regional Climate Models*, Trieste, Italy, 3-14 March 2008. [invited]

Gutowski, W.J, 2008: Experiences and challenges from other regional multi-model programs. *Greater Horn of Africa Regional Model Intercomparison Project (AFRMIP) - First Planning Meeting*, Rutgers University, 27-28 March 2008. [invited]

Gutowski, W.J., 2008: Regional Climate Modeling: Past, Present and Future. *Environment Roundtable,* Institute on the Environment, St. Paul Campus, University of Minnesota, 24 April, 2008. [invited]

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Prusa, J. M., 2008: Adaptive Grid Transformations and Generalized Coordinates in EULAG. *First International Workshop of EULAG Users,* Bad Tölz, Germany, October 2008. [keynote paper]

Smolarkiewicz, P.K., 2008: Building resolving large-eddy simulations. *NCAR Urban Research Meeting*, Boulder, CO, 10 January 2008. [invited]

Smolarkiewicz, P.K., 2008: Modeling atmospheric circulations with soundproof equations, ECMWF, Reading UK, 10 April 2008. [invited]

Smolarkiewicz, P.,K. 2008: Modeling atmospheric circulations with soundproof equations, European Geosciences Union General Assembly 2008, Vienna, Austria, 15 - 18 April 2008, Geophysical Research Abstracts, Vol. 10, 01865, 2008 SRef-ID: 1607-7962/gra/EGU2008-A-01865. [invited]

Smolarkiewicz, P.K., 2008: EULAG, a Computational Model for Multiscale Flows. COSMO General Meeting, Cracow, Poland, 15-19 September 2008. [invited]

Smolarkiewicz, P.K., 2008: Modeling atmospheric circulations with soundproof equations, DLR, Institut fur Physik der Atmosphere, Oberpfaffenhofen, 21 April 2008. [invited]

Smolarkiewicz, P.K., 2008: Modeling atmospheric circulations with soundproof equations. *Workshop on Petascale Computing: Its Impact on Geophysical Modeling and Simulation*, NCAR, 6 May 2008. [invited]

Smolarkiewicz, P.K., 2008: EULAG: high-resolution computational model for research of multi-scale geophysical fluid dynamics . *First International Workshop of EULAG Users,* Bad Tölz, Germany, October 2008. [keynote paper]

Wedi, N.P., and P. Smolarkiewicz, 2008: A framework for testing global nonhydrostatic models, European Geosciences Union General Assembly 2008, Vienna, Austria, 15 - 18 April 2008, Geophysical Research Abstracts, Vol. 10, 01901, 2008 SRef-ID: 1607-7962/gra/EGU2008-A-01901

vi. Papers/Posters/Seminars Presented: 2009

Cosette J-F., and P.K. Smolarkiewicz, 2009: Monge-Ampere solvers for semi-Lagrangian trajectory schemes. *Workshop on Monge-Kantorovich Optimal Transport: Theory and Applications*, Santa Fe, New Mexico, USA October 19 - 21, 2009.

Gutowski, W. J., 2009: Changes in Extremes and Projections of Future Changes, *Twenty First Conference on Climate Variability and Change*, at *Annual Meeting*, American Meteorological Society, Phoenix, AZ, January 2009 [special CCSP 3-3 session].

Gutowski, W. J., J. M. Prusa, P. K. Smolarkiewicz, B. J. Abiodun and A. A. Abatan, 2009: A Global Atmospheric Model: Application and Refinement, *US. Department of Energy Climate Change Prediction Program, PI Meeting*, Bethesda, MD, April 2009.

Gutowski, W. J., and the NARCCAP Team, 2009: Simulations of regional, extreme monthly precipitation by the NARCCAP RCMs. *CRCMD Network Annual Science Meeting*, Mont Gabriel, Quebec, Canada, May 2009. [invited]

Gutowski, W.J., B. J. Abiodun, J. M. Prusa and P. Smolarkiewicz, 2009: Development of a climate model with dynamic grid adaptation. *Second International Lund RCM Workshop,* Lund, Sweden, May 2009. [keynote lecture]

Gutowski, W. J., G. Hegerl, G. J. Holland, T. R. Knutson, L. O. Mearns, R. J. Stouffer, P. J. Webster, M. F. Wehner, and F. W. Zwiers, 2009: CCSP 3-3: Causes of Observed

Gutowski, W.J., 2009: Progress in analysis of climate risk at regional scale. *XXIX MIT Global Change Forum*, Rome, Italy, June 2009. [invited]

Gutowski, W.J., 2009: The Coordinated Regional Climate Downscaling Experiment: CORDEX, presented at Goddard Institute for Space Studies, New York, New York (July 2009), *Arctic System Model Workshop III*, Montreal, Quebec, Canada (July 2009), University of Cape Town, Cape Town, South Africa (August 2009).

Gutowski, W.J., 2009: The Arctic Atmosphere's Water Cycle: Scales, Tales and Hail. *Synthesizing International Understanding of Changes in the Arctic Hydrological System,* Stockholm, Sweden, October 2009. [invited keynote]

Piotrowski, Z.P., S.P. Malinowski, P.K. Smolarkiewicz, A.A. Wyszogrodzki, 2009: Under-Resolved Simulation of Mesoscale Atmospheric Convection, *8th International SRNWP-Workshop on Non-Hydrostatic Modelling*, Bad Orb, 26 – 28 October 2009

Piotrowski Z.P., P.K. Smolarkiewicz, S.P. Malinowski and A.A. Wyszogrodzki, 2009: Spurious Rayleigh-Benard effects in under-resolved simulation of atmospheric convection. European Geosciences Union General Assembly 2009, Vienna, Austria, 19 - 24 April 2009, *Geophysical Research Abstracts,* **Vol. 11,** EGU2009-11574-1.

Smolarkiewicz P.K., 2009: EULAG: High-resolution computational model for research of multi-scale geophysical fluid dynamics. Institute for Scientific Computing & Applied Mathematics, Indiana University - Bloomington, January 2009. [invited]

Smolarkiewicz P.K., 2009: Multidimensional Positive Definite Advection Transport Algorithm (MPDATA): An Overview. FB Mathematik & Informatik, Freie Universitaet Berlin, February 2009. [invited]

Smolarkiewicz P.K., 2009: Building Resolving Large-Eddy Simulations and Comparison with Wind Tunnel Experiments, Center for Environmental Fluid Dynamics, Arizona State University, Phoenix, February 2009. [invited]

Smolarkiewicz P.K., 2009: Modeling atmospheric circulations with high-resolution methods, Frontiers of Geophysical Simulation, The Institute for Mathematics Applied to Geosciences (IMAGe) workshop, 18 - 20 August 2009 NCAR, Boulder, CO. [invited]

Smolarkiewicz P.K., 2009: Coupling the dynamics of boundary layers with evolutionary dunes. The Institute for Mathematics Applied to Geosciences (IMAGe) workshop on Free Boundary Problems, 24 - 25 August 2009, NCAR, Boulder, Colorado. [invited]

Smolarkiewicz P.K., 2009: Modeling atmospheric circulations with soundproof equations. Institute of Meteorology and Water Management, 22 October 2009, Warsaw, Poland. [invited]

Smolarkiewicz P.K., 2009: Modeling atmospheric circulations with high-resolution methods. Institute of Geophysics, University of Warsaw, 23 October 2009, Warsaw, Poland. [invited]

Smolarkiewicz P.K., 2009: Coupling the dynamics of boundary layers with evolutionary dunes. DLR, Institut fur Physik der Atmosphere, Oberpfaffenhofen, 2 November 2009. [invited]

Smolarkiewicz P.K., 2009: Modeling atmospheric circulations with high-resolution methods. University of Munich, 26 November 2009, Munich. [invited]

Smolarkiewicz P.K., J. Szmelter, 2009: An unstructured mesh framework for simulating rotating stratified flows. *Solution of Partial Differential Equations on the Sphere*, April 27 - April 30, 2009, Santa Fe, New Mexico, USA; Proceeding Book LA-UR-09-02384, Los Alamos National Laboratory.

Wedi N.P. and P.K. Smolarkiewicz, 2009: Framework for testing global nonhydrostatic models. *Solution of Partial Differential Equations on the Sphere*, April 27 - April 30, 2009, Santa Fe, New Mexico, USA; Proceeding Book LA-UR-09-02384, Los Alamos National Laboratory.

Wyszogrodzki A.A., and P.K. Smolarkiewicz, 2009: Building resolving large-eddy simulations (LES) with EULAG. *Academy Colloquium on Immersed Boundary Methods: Current Status and Future Research Directions*, 15-17 June 2009, Academy Building, Amsterdam, the Netherlands

vii. Papers/Posters/Seminars Presented: 2010

Cosette, J-F, P.K. Smolarkiewicz, A Monge-Ampere enhancement for semi-Lagrangian methods, *Proceedings of ICFD 2010 Conference on Numerical Methods in Fluid Mechanics,* Reading, UK, April 2010

Dörnbrack A, C. Kühnlein, PK Smolarkiewicz, Modelling Flows through Canopies with Immersed Boundary Methods. *ECCOMAS, CFD 2010, Fifth European Conference on Computational Fluid Dynamics,* Lisbon, Portugal, June 14-17, 2010 .

Gutowski, W.J., 2010: The Coordinated Regional Downscaling Experiment (CORDEX): A framework for mitigation and adaptation information. *Fall Meeting,* American Geophysical Union, San Francisco, CA, December 2010. [invited]

Gutowski, W. J., J. M. Prusa, P. K. Smolarkiewicz, B. J. Abiodun and A. A. Abatan, 2010: A Global Atmospheric Model: Application and Refinement. *US. Department of Energy Earth System Modeling Program, PI Meeting*, Gaithersburg, MD, March 2010.

Gutowski, W.J., 2010: Emerging Technologies in Climate Prediction. *Iowa State Climate Forum: Climate Change and Its Impact on Food Production and Biofuels,* Ames, Iowa, March 2010.

Gutowski, W.J., B.J. Abiodun, J.M. Prusa, P.K. Smolarkiewicz, 2010: Implementation of a non-hydrostatic, adaptive-grid dynamics core in CAM. *CCSM Atmosphere Model Working Group Meeting,* National Center for Atmospheric Research, Boulder, Colorado, February 2010 [http://www.ccsm.ucar.edu/working_groups/Atmosphere/]

Gutowski, W.J., 2010: U.S. and International Opportunities for Collaborating and Moving the Science Forward. *Climate Science Workshop: Regional Climate Modelling Capacity in Ontario,* Toronto, Canada, February 2010. [invited]

Gutowski, W.J., 2010: RMIP Opportunities: CORDEX and Beyond. *Building Asian Climate Change Scenarios by Multi-Regional Climate Models Ensemble: The First Project Workshop,* Tsukuba, Japan, January 2010.

Piotrowski Z, PK Smolarkiewicz: Rayleigh-Benard convection - effects of Prandtl number anisotropy. *2010 EULAG Model Users' Workshop* 13-16 September, 2010, Poland

Prusa, J.M., and W.J. Gutowski, 2010: Multi-scale features of baroclinic waves in sound-proof, global simulations with EULAG. *Proc. fitfth European Conference on Computational Fluid Dynamics*, Lisbon, Portugal, 14-17 June, 2010. [invited]

Smolarkiewicz P.K., 2010: Numerical merits of anelastic models . *2010 EULAG Model Users' Workshop* 13-16 September, 2010, Poland.

Smolarkiewicz P.K., 2010: Modeling atmospheric circulations with high-resolution methods. University of Loughborough, 27 January 2010, Loughborough, UK. [invited]

Smolarkiewicz P.K., 2010: Modeling atmospheric circulations with high-resolution methods. ECCOMAS, CFD, 2010, *Fifth European Conference on Computational Fluid Dynamics*, Lisbon, Portugal, June 14-17, 2010. [invited]

Smolarkiewicz P.K., 2010: Modeling atmospheric circulations with high-resolution methods. 19th Polish National Fluid Dynamics Conference, Poznan, September 5-9, 2010. [invited]

Smolarkiewicz P.K., 2010: Modelling atmospheric circulations with sound-proof equations, *ECMWF Workshop on Nonhydrostatic Modelling*, November 8-10, 2010, Reading. [invited]

Szmelter J., PK Smolarkiewicz, 2010: An unstructured mesh framework for simulation of all scale atmospheric flows. *ECCOMAS, CFD 2010, Fifth European Conference on Computational Fluid Dynamics*, Lisbon, Portugal, June 14-17, 2010. [invited]

Szmelter J., PK Smolarkiewicz., 2010: Forward-in-time differencing on a sphere: an edge-based discretisation. *The 2010 Workshop on the Solution of Partial Differential Equations on the Sphere,* Alfred Wegener Institute, Potsdam, August 24-27, 2010.

Szmelter J, PK. Smolarkiewicz, 2010: An unstructured mesh model for rotating stratified fluids. *2010 EULAG Model Users' Workshop* 13-16 September, 2010, Poland.

Wyszogrodzki, A.A., P.K. Smolarkiewicz, 2010: Large-eddy Simulation of Urban Flows: A Porous-media Analogy. *3rd Joint US-European Fluids Engineering Summer Meeting*, August 1-5, Montreal, Canada. paper no. FEDSM-ICNMM2010-30157.

Wyszogrodzki AA, PK. Smolarkiewicz, 2010: Development and applications of implicit Immersed Boundary Methods for flows in complex media. *2010 EULAG Model Users' Workshop* 13-16 September, 2010, Poland.

viii. Papers/Posters/Seminars Presented: 2011 - current

Abiodun BJ, W.J. Gutowski, J.M. Prusa, A.A. Abatan, 2011: CAM EULAG: A Non-Hydrostatic Atmospheric Climate Model with Grid Stretching. *US Department of Energy Earth System Modeling Program, PI Meeting*, Washington DC, September 2011.

Cossette, J.-F. and Smolarkiewicz, P. Monge-Ampere correction for semi-Lagrangian large-eddy simulations of turbulent flows. *13 European Turbulence Conference*, 12 - 15 September 2011, Warsaw, Poland.

Gutowski, W.J., J.M. Prusa, P.K. Smolarkiewicz, B.J. Abiodun, A.A. Abatan, 2011: Continuous Dynamic Grid Adaptation in a Global Atmospheric Model:

Application and Refinement. *US Department of Energy Earth System Modeling Program, PI Meeting,* Washington DC, September 2011.

Prusa JM, Gutowski, W.J., 2011: Baroclinic Instability in Sound-Proof Global Simulations. *2011 SIAM Conference on Mathematical & Computational Issues in the Geosciences,* Long Beach, CA, March 21-24, 2011. [invited]

Ogier D., B.J. Abiodun, J.M. Prusa, 2011: Mapping Gravity Wave Regions Over Southern Africa Using CAM EULAG. *US Department of Energy Earth System Modeling Program, PI Meeting*, Washington DC, September 2011.

Piotrowski Z. P., and P. K. Smolarkiewicz, Under-resolved LES of Rayleigh-Bénard convection; effects of Prandtl number anisotropy, *9th International SRNWP-Workshop on Non-Hydrostatic Modelling*, Bad Orb, 16 - 18 May 2011, Deutscher Wetterdienst.

Piotrowski, Z. and Smolarkiewicz, P. Under-resolved simulations of Rayleigh-Benard convection: effects of anisotropic viscosity and Prandtl number. *13 European Turbulence Conference*, 12 - 15 September 2011, Warsaw, Poland.

Smolarkiewicz P.K.,2011: Modeling atmospheric circulations with soundproof equations. *Proceedings of the ECMWF Workshop on Nonhydrostatic Modelling*, November 8-10, 2010, Reading, UK, 15 pp. http://www.ecmwf.int/publications/library/do/references/list/201010

Smolarkiewicz P.K.,2011: Pores resolving simulation of Darcy flows. University of Loughborough, 9 February 2011, Loughborough, UK. [invited]

Smolarkiewicz P.K.,2011: Algorithms for Implicit Solvers. NCAR/UKMO/NCAS Workshop on Next Generation Weather and Climate Models 7-9 March 2011 NCAR, Boulder, Colorado. [invited]

Smolarkiewicz P.K.,2011: Sound-proof Simulations of Atmospheric Wave Phenomena, SIAM Conference on Mathematical & Computational Issues in the Geosciences, March 21-24, 2011, Long Beach, California. [invited]

Smolarkiewicz P.K.,2011: Sound-proof simulations of atmospheric wave phenomena. October 14, 2011, Department of Mathematics, Colorado State University, Fort Collins. [invited]

Smolarkiewicz P.K.,2011: EULAG, a Computational Model for Multiscale Flows in Geo- and Solar-Physics, November 7, 2011, Stanford University, HEPL, Kavli Institute for Particle Astrophysics and Cosmology. [invited]

Smolarkiewicz, P.K., and J. Szmelter 2011: Sound-Proof Simulations of Atmospheric Wave Phenomena. *2011 SIAM Conference on Mathematical & Computational Issues in the Geosciences,* Long Beach, CA, March 21-24, 2011.

Smolarkiewicz P. K., and J. Szmelter, 2011: A Nonhydrostatic Unstructured-Mesh Soundproof Model for Simulation of Internal Gravity Waves, *9th International*

SRNWP-Workshop on Non-Hydrostatic Modelling, Bad Orb, 16 - 18 May 2011, Deutscher Wetterdienst.

Smolarkiewicz P.K.,2011: Winter L., J. Hyman, P. Smolarkiewicz, 2011: An Empirical Equation for Effective Conductivity. *European Geosciences Union General Assembly* 2011, Vienna, Austria, 04-08 April, Geophysical Research Abstracts, Vol. 13, EGU2011-1192

6b. Student thesis

Abayomi Abatan, 2011, M.S., Meteorology, West African extreme daily precipitation in observations and stretched-grid simulations by CAM-EULAG, 128 pp.

6c. Web site

Master web site for EULAG. Lists publications, provides code access and user support.
http://www.mmm.ucar.edu/eulag

6d. Collaborative networks fostered

A large number of national and international collaborations have been fostered during the current project as indicated by the list of publications. Our journal/proceedings publications for 2008 alone list over 30 connections with other colleagues mostly at other institutions. A list of affiliations of collaborators/coauthors other than between the PI's over the duration of the grant follows:

- Danish Meteorological Institute – (WJG)
- Department of Mechanical Engineering, The Johns Hopkins University, Baltimore, Maryland – (PKS)
- Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany – (PKS)
- European Centre for Medium Range Waether Forecasts (ECMWF), Reading, UK – (PKS)
- Institute of Geophysics, University of Warsaw, Poland – (PKS)
- Institute of Meteorology and Water Management, Warsaw, Poland – (PKS)
- Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland – (PKS)
- International Center for Theoretical Physics – (WJG)

- LAMA, CNRS, Universite de Savoie, Chambery, France – (PKS)
- Los Alamos National Laboratory – (PKS)
- Mathematik und Informatik, Freie Universitat Berlin, Berlin, Germany – (PKS)
- Meteorologie, Goethe-Universitat, Frankfurt, Germany – (PKS)
- Udaipur Solar Observatory, Physical Research Laboratory, Dewali, India – (PKS)
- University of Arizona, Tucson, USA – (PKS)
- University of Cape Town, South Africa – (WJG, JMP)
- University of Colorado – (WJG)
- University of Granada, Ed. Politecnico, Granada, Spain – (PKS)
- University of Iowa – (WJG)
- University of Leeds, UK – (PKS)
- University of Loughborough, UK – (PKS)
- University of Montreal, Canada – (PKS)
- University of Victoria, Canada – (PKS)

In addition to these explicit collaborative networks are the series of International EULAG Workshops. The first such workshop was held in Bad Tolz, Germany in 2008; the second in Sopot, Poland, 2010; and the third is in Loughborough, UK in 2012. The focus of these workshops is very much aimed towards collaborations with an extended international community.

7. COMPUTATIONAL MODEL OVERVIEW

The primary focus of the project was development of an advanced global atmospheric climate model, CAM-EULAG, or CEU for short. Here CAM means the Community Atmospheric Model v.3, which is a well-documented publically available global atmospheric model. The purpose of our research was to develop a much more advanced dynamical core for CAM than was available. To this end we employed the high performance research model EULAG. To the extent that the dynamical core for CAM determines the qualities of the overall model, the enhanced capabilities of CEU are in large part, those of EULAG.

More realistic simulation of climate has vast implications for our society because it can be used to help answer a series of "what if" scenarios, such as what happens to climate if fossil fuel burning grows or declines.

The mathematical details are extensive, have been developed over many years and span numerous peer-reviewed publications. Including them here would add considerable volume to this report. The reader interested in mathematical details should consult the overview paper as well as documents listed below describing mathematical and numerical details under specific topics.

7a. EULAG

The advanced dynamics core for CEU is a multiscale, nonhydrostatic, sound proof global model that employs a structured grid (default) and the Lipps-Hemler anelastic approximation (default) to filter sound waves out of the solution. EULAG also has built in options for using either an Ogura-Phillips anelastic model or a Boussinesq approximation. Experimental versions using the Durran pseudo-incompressible approximation and the fully compressible exact equations have also been developed and reveal that, for many global atmospheric phenomena of importance, the anelastic sound proof equations give very good results compared to the primitive equations and other types of equation sets. An experimental version of EULAG using an unstructured grid has also been developed.

Nonoscillatory, forward in time integration methods are central to the model design. The nonoscillatory aspect is based upon the convexity of upwind advection. Although based upon upwind differences, the advection schemes are formally second order accurate as correction terms have been added (also via upwind methods) to eliminate the first order error terms. Semi-Lagrangian (SL) and Eulerian (EU) advection options exist in EULAG. The upwind advection scheme that underlies the EU advection is MPDATA (the seminal 1984 paper on MPDATA – listed below – has been cited in the literature 435 times). The correction scheme for MPDATA preserves scale similarity of turbulence. Thus EULAG (with MPDATA EU advection) can effectively resolve scales relatively closely to the Nyquist wavenumber and can be characterized as a “high resolution” model. SL advection requires a remapping interpolator to move the updated field values from their new grid point positions back onto the assigned grid. MPDATA also underlies this interpolator via a clever connection between SL remapping and EU advection (the key SL paper has been cited 150 times). The overall time stepping can be either Crank-Nicholson, Runge-Kutta or Adams-Bashforth. Various levels of accuracy in both the time stepping and spatial discretizations are options; although the default (which our experience generally shows is best) is second order in both space and time. An elliptic pressure equation is formed by projecting the implicit finite difference solution for the dependent variables onto the continuity equation. The overall default scheme treats all dynamical variables (winds and potential temperature) implicitly in the pressure equation; an overall iteration may be required. The pressure equation is solved using a nonsymmetric Krylov solver, that can in principle converge the elliptic iterations to machine round off error even with large grids typical of climate simulation. The advection and pressure solvers in EULAG were designed with accurate representation of gravity waves in mind. The overall result is that EULAG is often much less diffusive than other models, and competitive with spectral codes.

EULAG is formulated in generalized coordinates. This enables continuous dynamic grid deformation while simultaneously maintaining strong conservation form.

Strong conservation, when using grid adaptivity, is enforced by careful adherence to tensor identities. The value of this capability is that it allows the advanced global climate model CEU to continuously adapt its grid by deforming in time and space to focus resolution in particular regions of the atmosphere or to follow atmospheric flow features of interest (vorticity, temperatures, precipitation, etc.; as well as extreme events, heat waves, droughts, excessive rain, tropical storms, etc.). This capability for grid adaptation readily allows local enhancements of resolution permitting up to an order of magnitude reduction in local truncation errors compared to uniform grids with the same overall number of nodes. Potentially this results in a great savings of CPU time because grid adaptivity *per se* adds only a minor component to the overall CPU time. Since the grid size does not change, the only significant increase occurs due to more stringent CFL/Lipschitz number limits as higher resolution allows wind fields to develop greater amplitudes/gradients (for EU/SL advection options, respectively). First developments in dynamic grid adaptivity were enabled in 2001 (perhaps the first such global atmospheric model).

EULAG offers the possibility of direct numerical simulation (DNS) of soft turbulence. For hard turbulence, the nonoscillatory aspect of EULAG (see numerics below) offers what is termed implicit large eddy simulation, or ILES. Basically, the nonoscillatory machinery of the code ensures that no two streamtubes intersect. This is the important property of flow realizability for turbulent flows that is not easily recognized at a glance since turbulent trajectories are complicated. Fundamentally, ILES allows a nonlinear turbulence closure wherein EULAG adds just enough dissipation at the finest scales to keep the solution numerically stable, and thus, EULAG does not require an overall filter as is typically employed in other models for this purpose. ILES has the property that it is "turned on" only as needed. For example, in a DNS simulation with ILES also “active”, ILES will not modify the simulation. With ILES alone and in the case of turbulent "bursts", the ILES machinery will not be active in quiescent regions of flow. EULAG also has options for standard Smagorinksy or TKE type large eddy simulation (LES). EULAG treats contributions from moisture variables as explicit additions to the pressure equation forcing. EULAG also has options for multiple chemical species advection/reactions. A large body of published literature exists that demonstrates EULAG’s high performance capabilities with many atmospheric phenomena key to the performance of a global atmospheric model.

A single model code is capable of running on a number of computer architectures, from the scale of laptops and workstations up to that of petascale massively parallel systems. Recent developments in extending the domain decomposition of the model allow it to scale well to tens of thousands of processor cores.

The wide range of scales and physics (for example, EULAG is being used for cloud microphysics as well as for solar dynamo studies), accuracy, grid adaptivity, and computational flexibility of EULAG makes the model attractive for adaptation in a wide range of academic and industrial environments. Archival publications in the literature that feature the above-mentioned capabilities of EULAG follow, organized according to features and arranged chronologically. These publications (and many others not listed here – see website http://www.mmm.ucar.edu/eulag) demonstrate that all aspects of the model have been rigorously reviewed and tested and furthermore are undergoing continuous development and refinement.

Example EULAG Verification Study: Global Baroclinic Instability Test (See Section 5a):

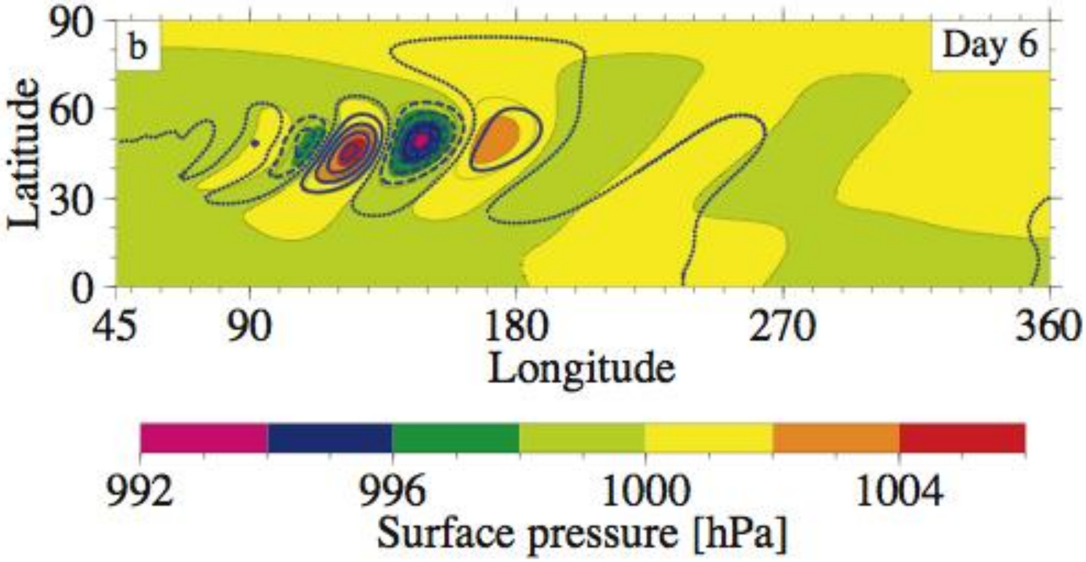

Figure 1. Baroclinic instability test results – linear growth regime. The contours (dotted = 1000 hPa, solid are 1000+ and the dashed are 1000- hPa at 2 hPa intervals) show EULAG results using a globally uniform 1.4^o x 1.4^o grid. Colors depict finite volume results of Jablonowski and Williamson (2006) with 0.5^o x 0.625^o grid, herein JW. EULAG's simulation of the central region of the wave packet matches the JW phase speed within 0.5%. The EULAG result does show dispersion in the outer regions of the wave packet, however this diminishes with increasing resolution: using a 0.7^o x 0.7^o grid EULAG results match JW much better at the leading and trailing edges of the wave packet. See Prusa and Gutowski (2010).

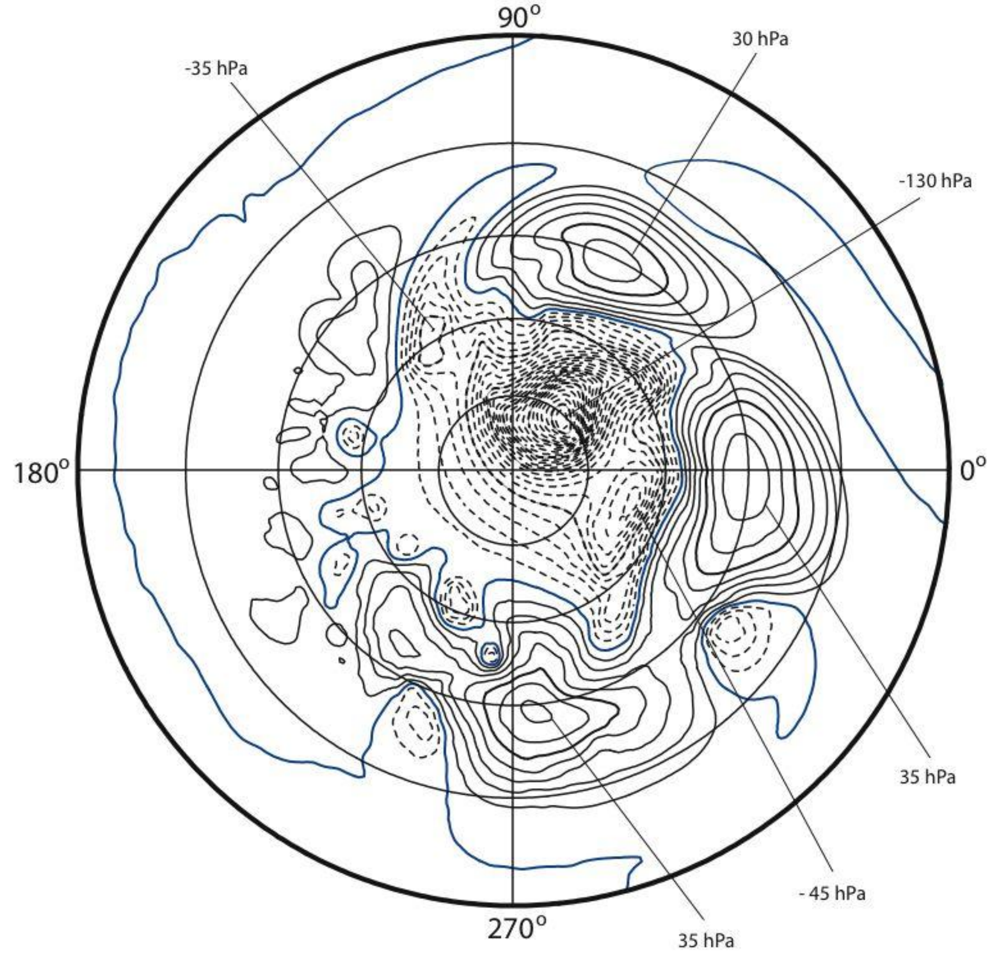

Figure 2. Baroclinic instability test results – nonlinear wave-breaking regime. Polar projection of pressure field at 16.0 days. The contours (bold blue = 1000 hPa, solid are 1000+ and the dashed are 1000- hPa at 5 hPa intervals) show EULAG results generated with a globally uniform 0.7^o x 0.7^o grid. The overall qualitative structure and amplitudes of the highs and lows are similar to those of JW, but differ in details, particularly in the trailing wake region and in ridges connecting highs. Such features are quite sensitive to initial conditions as well as model details. See Prusa and Gutowski (2010) for additional discussion.

Supporting Documentation Published In Archival Literature:

overview

Prusa, J. M., P. K. Smolarkiewicz, and A. A. Wyszogrodzki, 2008: EULAG, a Computational Model for Multiscale Flows. *Comput. Fluids*, **37,** 1193-1207.

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elliptic solver

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Smolarkiewicz P.K., Grubisic V., and Margolin L.G., 1997: On Forward-in-time differencing for fluids: stopping criteria for iterative solutions of anelastic pressure equations. *Mon. Weather Rev.*, **125**, 647-654.

grid adaptivity

Iselin, J.P., Prusa, J.M., Gutowski, W.J., 2002: Dynamic grid adaptation using the MPDATA scheme, *Mon. Weather Rev.*, **130**, 1026–1039.

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Wedi, N., Smolarkiewicz P.K., 2004: Extending Gal-Chen and Somerville terrain-following coordinate transformation on time-dependent curvilinear boundaries. *J. Comput. Phys*., **193**, 1-20.

Prusa J.M., Smolarkiewicz P.K., 2004: Dynamic grid deformation: continuous mapping approach. *Proceedings ECMWF Seminar on Recent Developments in Numerical Methods for Atmospheric and Ocean Modeling*, 6–10 September, Reading, UK, ECMWF, 267–283.

Smolarkiewicz P.K., Prusa J.M., 2005: Towards mesh adaptivity for geophysical turbulence: continuous mapping approach. *Int. J. Numer. Methods in Fluids*, **47**, 789–801.

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7b. CEU

CEU is a full atmospheric global climate model that utilizes CAM3 routines for parameterizations of sub-grid scale physics (radiative transfer, moisture condensation, moist convection, planetary boundary layer turbulence, surface-atmosphere exchanges of heat, moisture and momentum) and EULAG as the dynamical core that advects momentum, energy, and moisture fields and computes the pressure field. EULAG explicitly computes the vertical wind field using geometric coordinates. CAM3, by contrast, is built upon hydrostatic dynamical cores that use pressure for the vertical coordinate and pressure velocity as the "vertical wind". These differences present challenges to the interfacing of EULAG with CAM3. Among these are that CAM3 has no explicit vertical wind field; and that interpolations need to be made between pressure and altitude coordinates as information is transferred from EULAG to CAM3 and back again. Fortunately, the tensor formalism underlying EULAG provides an excellent tool to construct invariance preserving mappings between the two models for the needed fields. The present configuration is that CAM3 provides tendencies for the horizontal wind, potential temperature, and moisture fields for EULAG, and that EULAG in turn provides updated fields for horizontal wind, temperature (computed from the potential temperature and pressure fields), geopotential height (an inversion of pressure field), and pressure velocity (defined as the total derivative of pressure with respect to time and computed in via a chain rule) to CAM3. Physical pressure is computed from EULAG’s pressure perturbation field by inverting the definition of pressure perturbation using a compatibility condition. The most significant biases that we have indentified to date are those due to CAM3 parameterizations, which for example, have precluded the use of CEU to study tropical cyclogenesis (see section 5b. Modeling advances in CAM-EULAG).

Example CEU verification study: West African monsoon (see section 5b):

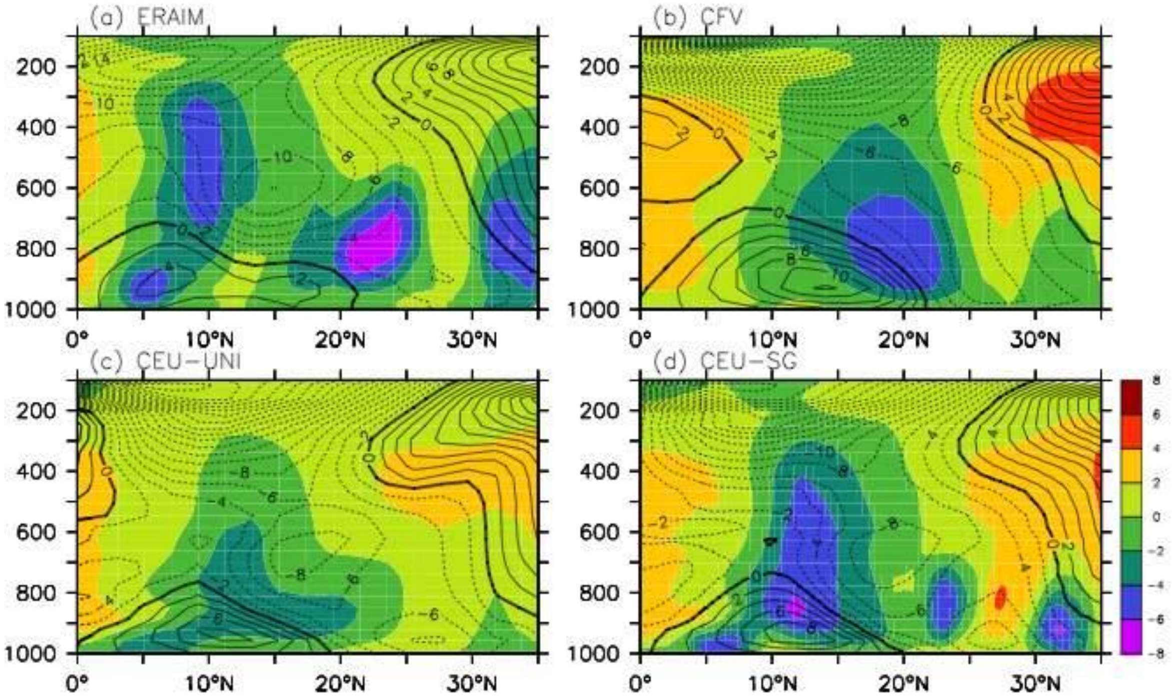

Figure 3. Vertical structure of the African monsoon system in August. Vertical altitude denoted in mb vs. latitude. Time derivative of pressure (pressure velocity, in mb s^{-1}) shown in color and zonal wind depicted in contours (m s^{-1}). Panel A: reanalysis data based upon observations (*ground truth*). Panel B: CAM3 simulation using built in (*hydrostatic*) finite volume dynamics core (*control simulation*) with 2.0° x 2.5° grid. Panel C: simulation result using new CEU model with same resolution as for CAM3-finite volume simulation. Compared to Panel B, note better qualitative form of Easterly jet near 10° latitude and big reduction in erroneous upper level westerly jet near 35° latitude. Panel D: simulation result using new CEU model using grid adapativity over West Africa to produce a local 0.5° x 0.5° grid. Note big improvement in easterly jet structure near 10° latitude. See Abiodun et.al (2011) for more details.

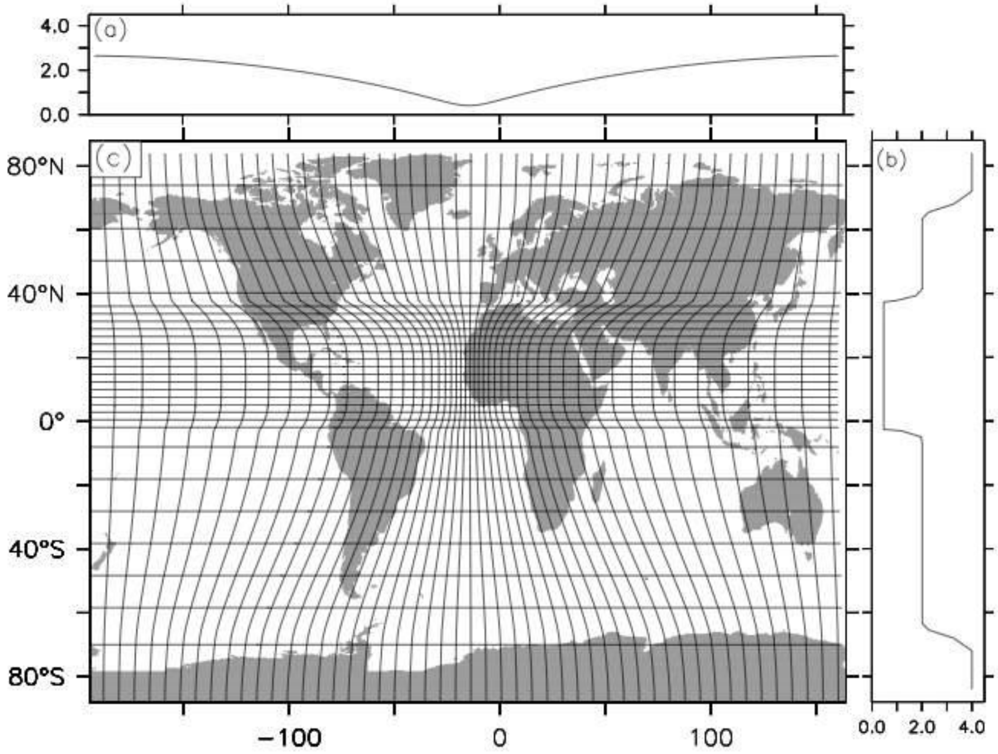

Figure 4. Stretched grid employed for simulation in Panel D of Figure 3 using grid adaptive technology of CEU. Figure shows only every 5th grid line. This grid transitions to courser resolution away from the targeted 0.5^o x 0.5^o region and uses only ~ 2x as many grid points as in uniform 2.0^o x 2.5^o grid. Of ultimate significance, it requires an *order of magnitude less CPU time* than for a globally uniform 0.5^o x 0.5^o grid. From Abiodun et.al (2011).

Supporting Documentation Published In Archival Literature:

<u>EULAG – CAM coupling & aqua-planet</u>

Abiodun, B.J., J.M. Prusa and W.J. Gutowski, 2008: Implementation of a Non-hydrostatic, Adaptive-Grid Dynamics Core in CAM3. Part I: Comparison of Dynamics Cores in Aqua-Planet Simulations. *Clim. Dynamics,* **31**, 795-810, [DOI: 10.1007/s00382-008-0381-y].

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