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| 14. ABSTRACT The Earth System Prediction Suite (ESPS) is a collection of flagship U.S. weather and climate models and model components that are being instrumented to conform to interoperability conventions, documented to follow metadata standards, and made available either under open source terms or to credentialed users. The ESPS represents a culmination of efforts to create a common Earth system model architecture, and the advent of increasingly coordinated model development activities in the U.S. ESPS component interfaces are based on the Earth System Modeling Framework (ESMF), community-developed software for building and coupling models, and the National Unified Operational Prediction Capability (NUOPC) Layer, a set of ESMF-based component templates and interoperability conventions. This shared infrastructure simplifies the process of model coupling by guaranteeing that components conform to a set of technical and semantic behaviors. The ESPS encourages distributed, multi-agency development of modeling systems, controlled experimentation and testing, and exploration of novel model configurations, such as those motivated by research involving managed and interactive ensembles. ESPS codes include the Navy Global Environmental Model (NavGEM), HYbrid Coordinate Ocean Model (HYCOM), and Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS??); the NOAA Environmental Modeling System (NEMS) and the Modular Ocean Model (MOM); the Community Earth System Model (CESM); and the NASA ModelE climate model and GEOS-5 atmospheric general circulation model. | | | | | |
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THE EARTH SYSTEM PREDICTION SUITE:

Toward a Coordinated U.S. Modeling Capability

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27 **CAPSULE SUMMARY:** Benefits from common modeling infrastructure and component
28 interface standards are being realized in a suite of national weather and climate codes.

29 **ABSTRACT**

30 The Earth System Prediction Suite (ESPS) is a collection of flagship U.S. weather and climate
31 models and model components that are being instrumented to conform to interoperability
32 conventions, documented to follow metadata standards, and made available either under open
33 source terms or to credentialed users.

34 The ESPS represents a culmination of efforts to create a common Earth system model
35 architecture, and the advent of increasingly coordinated model development activities in the U.S.
36 ESPS component interfaces are based on the Earth System Modeling Framework (ESMF),
37 community-developed software for building and coupling models, and the National Unified
38 Operational Prediction Capability (NUOPC) Layer, a set of ESMF-based component templates
39 and interoperability conventions. This shared infrastructure simplifies the process of model
40 coupling by guaranteeing that components conform to a set of technical and semantic behaviors.
41 The ESPS encourages distributed, multi-agency development of modeling systems, controlled
42 experimentation and testing, and exploration of novel model configurations, such as those
43 motivated by research involving managed and interactive ensembles. ESPS codes include the
44 Navy Global Environmental Model (NavGEM), HYbrid Coordinate Ocean Model (HYCOM),

45 and Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS[®]); the NOAA
46 Environmental Modeling System (NEMS) and the Modular Ocean Model (MOM); the
47 Community Earth System Model (CESM); and the NASA ModelE climate model and GEOS-5
48 atmospheric general circulation model.

49 **BODY TEXT**

50 The software infrastructure that underlies Earth system models includes workhorse utilities as
51 well as libraries generated by research efforts in computer science, mathematics, and
52 computational physics. The utilities cover tasks like time management and error handling, while
53 research-driven libraries include areas such as high performance I/O, algorithms for grid
54 remapping, and programming tools for optimizing software on emerging computer architectures.
55 Collectively, this model infrastructure represents a significant investment. As a crude
56 comparison, a comprehensive infrastructure package like the Earth System Modeling Framework
57 (ESMF; Hill et al. 2004, Collins et al. 2005), is comparable in size to the Community Earth
58 System Model (CESM; Hurrell et al. 2013), each at just under a million lines of code.¹

59 In 2002, Dickinson et al. articulated the goal of *common* model infrastructure, a code base that
60 multiple weather and climate modeling centers could share. This idea was shaped by an *ad-hoc*,
61 multi-agency working group that had started meeting several years earlier, and was echoed in
62 reports on the state of U.S. climate modeling (NRC 1998, NRC 2001, Rood et al. 2000). Leads
63 from research and operational centers posited that common infrastructure had the potential to
64 foster collaborative development and transfer of knowledge; lessen redundant code; advance

¹ Codes compared are CESM 1.0.3, at about 820K lines of code (Alexander and Easterbrook 2011), and ESMF 6.3.0rp1, at about 920K lines of code (ESMF metrics available online at: https://www.earthsystemcog.org/projects/esmf/sloc_annual)

65 computational capabilities, model performance and predictive skill; and enable controlled
66 experimentation in coupled systems and ensembles. This vision of shared infrastructure has been
67 revisited in more recent publications and venues; for example, in the 2012 National Research
68 Council report entitled *A National Strategy for Advancing Climate Modeling* (NRC 2012).

69 In this article we describe how the vision of common infrastructure is being realized, and how it
70 is changing the approach to Earth system modeling in the U.S. Central to its implementation is
71 an *Earth System Prediction Suite (ESPS)*, a collection of weather and climate models and model
72 components that are being instrumented to conform to interoperability conventions, documented
73 to follow metadata standards, and made available either under open source terms or to
74 credentialed users.

75 We begin by discussing how the U.S. modeling community has evolved toward a common
76 architecture, and explain the role of the ESMF and related projects in translating that
77 convergence into technical interoperability. We define what we mean by minimal
78 interoperability and the behavioral rules needed to achieve it, and describe the ESPS code suite
79 and its target inclusion criteria. We give examples of the adoption process for different kinds of
80 codes, and of science enabled by common infrastructure. Finally, we examine the potential role
81 of the ESPS in model ensembles, and consider areas for future work.

82 **EMERGENCE OF A COMMON MODEL ARCHITECTURE**

83 Several generations of model infrastructure development, described in the sidebar (**Linked and**
84 **Leveraged** ...) allowed for the evolution and evaluation of design strategies. A community of
85 infrastructure developers emerged, whose members exchanged ideas through a series of
86 international meetings focused on coupling techniques (e.g. Dunlap et al. 2014), comparative

87 analyses such as Valcke et al. (2012), and design reviews and working group discussions hosted
88 by community projects such as CESM and ESMF.

89 Over time, model developers from major U.S. centers implemented similar model coupling
90 approaches, based on a small set of frameworks: ESMF, the CESM Coupler 7 (CESM CPL7;
91 Craig et al. 2012), which uses the lower-level Model Coupling Toolkit for many operations
92 (MCT; Larson et al. 2005, Jacob et al. 2005), and the Flexible Modeling System (FMS; Balaji
93 2012). ESMF, CPL7, and FMS share several key architectural characteristics. First, they are all
94 single executable frameworks, meaning that constituent components are called as subroutines by
95 a top-level driver. Second, major physical domains such as atmosphere, ocean, land, sea ice, and
96 wave models are wrapped with component interfaces, and the component interfaces are
97 structured similarly, with arguments for fields imported, fields exported, and time information.
98 Not all coupling technologies follow these patterns. For example, in the OASIS coupler (Valcke
99 2013) used by many European climate models, components are run as separate, linked programs
100 or “multiple executables” and in general do not require that fields transferred between
101 components pass through a component interface.

102 The design convergence of U.S. models created an opportunity for coordination that a new
103 program was ready to exploit. The National Unified Operational Prediction Capability (NUOPC;
104 see <http://www.nws.noaa.gov/nuopc/>), a consortium of operational weather prediction centers
105 and their research partners, was established in 2007 with goals that included creating a global
106 atmospheric ensemble weather prediction system and promoting collaborative model
107 development. In support of these goals, NUOPC sought further standardization of model
108 infrastructure, and formalized the concept of common model architecture (CMA; Sandgathe et
109 al. 2009; McCarren et al. 2013). The CMA can be defined as a set of conventions that govern

110 the application programming interfaces (APIs) of model components, the “level of
111 componentization,” and the protocols for component interaction. In general terms, models using
112 the ESMF, CPL7, or FMS frameworks could be said to share the same CMA.

113 Despite the similarities in structure, the components under these different frameworks still
114 required the implementation of a common translation layer to achieve a minimal level of
115 interoperability. NUOPC defined this minimal level of interoperability as the ability of a
116 component to execute without code changes within a driver that provides the fields that it
117 requires, and to return with informative messages if its input requirements are not met. Unlike
118 FMS and CESM, which are associated with specific modeling systems, the ESMF software is
119 intended to support multiple modeling systems, and it emerged as the reference architecture and
120 CMA implementation. With ESMF, the NUOPC consortium undertook formal codification of
121 the CMA and its realization in widely usable (e.g. portable, reliable, efficient, documented)
122 software.

123 **ESMF AND THE NUOPC LAYER**

124 ESMF is high performance software for building and coupling Earth system models. It includes
125 a superstructure for representing model and coupler components and an infrastructure of
126 commonly used utilities, including grid remapping, time management, model documentation,
127 and data communications (see <https://www.earthsystemcog.org/projects/esmf/>). It was
128 developed and is governed by a set of multi-agency partners that includes NASA, NOAA, the
129 Department of Defense and the National Science Foundation. ESMF can be used in multiple
130 ways: 1) to create interoperable component-based modeling systems; 2) as a source of libraries
131 for commonly used utilities; 3) as a file-based offline generator of interpolation weights for many
132 different kinds of grids; and 4) as a Python package for grid remapping.

133 The ESMF design, which evolved over a period of years through weekly community reviews and
134 thousands of user support interactions, accommodates a wide range of data structures, grids, and
135 component layout and sequencing options. The main constructs are gridded components
136 (`ESMF_GridComp`) and coupler components (`ESMF_CplComp`). Physical fields are
137 represented using `ESMF_Fields`, which are contained in import and export `ESMF_State`
138 objects in order to be passed between components. ESMF defines three standard methods:
139 initialize, run, and finalize, which can have multiple phases; however, there are no requirements
140 on how these methods should behave. Since ESMF data structures can often reference native
141 model data structures and ESMF methods can invoke model methods without introducing
142 significant performance overhead, the software can serve either as a primary infrastructure or as
143 a wrapper around components in existing coupled models.

144 ESMF provides interfaces and data structures with few constraints about how to use them. This
145 flexibility enabled it to be adopted by many modeling systems,² but limited the interoperability
146 across these systems. To address this issue, the NUOPC consortium developed a set of coupling
147 conventions and generic representations of modeling system elements - drivers, models,
148 connectors, and mediators - called the NUOPC Layer (see
149 <http://www.earthsystemcog.org/projects/nuopc/>). NUOPC drivers and models can be
150 understood in the usual way; connectors handle simple data transformations and transfers, and
151 mediators implement field merges and custom coupling code. Table 1 summarizes NUOPC
152 generic components and their roles. In some cases, the generic components may be used without
153 modification; in others, user code is added at clear specialization points. Calls to NUOPC
154 methods mainly relate to component creation and sequencing, and may be mixed with calls to

² ESMF components are listed here: <https://www.earthsystemcog.org/projects/esmf/components>

155 ESMF time management, grid remapping, and other methods.

156 The NUOPC Layer enables multi-component systems, including hierarchies and ensembles, to
157 be assembled using pre-fabricated code. Figure 1 is a schematic of two simple model
158 configurations built using generic components.

159 While use of the NUOPC Layer cannot guarantee scientific compatibility, it does guarantee a set
160 of component behaviors related to technical interoperability. These are described in the *NUOPC*
161 *Layer Reference* (2014). Specifically, it ensures that a component will provide:

162 (i) A GNU makefile fragment that defines a small set of prescribed variables, which a NUOPC
163 application uses to compile and link with the component.

164 (ii) A single public entry point, called `SetServices`. Standardizing this name enables code that
165 registers components to be written generically.

166 (iii) An *InitializePhaseMap*, which describes a sequence of standard initialize phases drawn
167 from a set of *Initialize Phase Definitions*. For example, one standard phase advertises the
168 fields a component can provide, based on standard names drawn from the Climate and
169 Forecast conventions (CF; Eaton et al. 2011). Field names are checked and mapped to each
170 other using a NUOPC *Field Dictionary*. Another standard phase instantiates the fields that
171 will be used.

172 (iv) A *RunPhaseMap*, in which each phase must check the incoming clock of the driver and the
173 timestamps of incoming fields against its own clock for compatibility. The component
174 returns an error if incompatibilities are detected.

175 (v) Time stamps on its exported fields consistent with the internal clock of the component.

176 (vi) A `finalize` method that cleans up all allocations and file handles.

177 These constraints, involving build dependencies, initialization sequencing, and run sequencing,
178 are the focus of the NUOPC Layer because they are required to satisfy the definition of minimal
179 interoperability: that components will run without code changes if their required field inputs are
180 satisfied, and will return with appropriate warnings if they are not. The constraints nonetheless
181 allow for the representation of many different model control sequences. They also enable
182 negotiation and contingencies to be represented in a structured way, a feature that becomes
183 important in optimization of multi-component systems, where components may compete for
184 resources.

185 The ESMF/NUOPC software distribution is suitable for broad use as it has an open source
186 license, comprehensive user documentation, a suite of about 6500 regression tests that runs
187 nightly on about 30 different platform/compiler combinations, and a user support team.
188 Performance evaluation occurs on an ongoing basis, with reports posted at
189 <https://www.earthsystemcog.org/projects/esmf/performance>. The software has about 6000
190 registered downloads.

191 **THE EARTH SYSTEM PREDICTION SUITE**

192 The National Earth System Prediction Capability (National ESPC; see <http://espc.oar.noaa.gov>)
193 combines the ESPC, initiated in 2010, and NUOPC, to extend the scope of the NUOPC program
194 in several ways. The National ESPC goal is a global Earth system analysis and prediction
195 system that will provide seamless predictions from days to decades, developed with
196 contributions from a broad community. Expanding on NUOPC, the National ESPC includes
197 additional research agency partners (NSF, NASA, and DOE), time scales of prediction that
198 extend beyond short term forecasts, and new modeling components (e.g. cryosphere, space).

199 In order to realize the National ESPC vision, major U.S. models must be able to share and
200 exchange model components. Thus the National ESPC project is coordinating development of an
201 *Earth System Prediction Suite (ESPS)*, a collection of NUOPC-compliant Earth system
202 components and model codes that are technically interoperable, tested, documented, and
203 available for integration and use. At this stage, ESPS focuses on *coupled modeling systems* and
204 *atmosphere, ocean, ice* and *wave* components.

205 ESPS partners are targeting the following inclusion criteria:

- 206 • ESPS components and coupled modeling systems are NUOPC-compliant.
- 207 • ESPS codes are versioned.
- 208 • Model documentation is provided for each version of the ESPS component or
209 modeling system.
- 210 • ESPS codes have clear terms of use (e.g. public domain statement, open source
211 license, proprietary status), and have a way for credentialed ESPC collaborators to
212 request access.
- 213 • Regression tests are provided for each component and modeling system.
- 214 • There is a commitment to continued NUOPC compliance and ESPS participation for
215 new versions of the code.

216 ESPS is intended to formalize the steps in preparing codes for cross-agency application, and
217 the inclusion criteria support this objective. NUOPC compliance guarantees a well-defined,
218 minimal level of interoperability, and enables assembly of codes from multiple contributors.
219 Versioning is essential for traceability. Structured model documentation facilitates model

220 analysis and intercomparison.³ Clear terms of use and a way to request code access are
221 fundamental to the exchange of codes across organizations. Regression tests are needed for
222 verification of correct operation on multiple computer platforms. The commitment to
223 continued participation establishes ESPS as an ongoing, evolving capability.

224 At the time of this writing, not all criteria are satisfied for all candidate codes. Further, the
225 criteria themselves are likely to evolve. The extent of the metadata to be collected still needs
226 to be determined, and specific requirements for regression tests have not yet been
227 established. The process of refining the inclusion criteria and completing it for all codes is
228 likely to occur over a period of years. However, a framework is now in place for moving
229 forward. Current information is presented on the ESPS webpage, see
230 <https://www.earthsystemcog.org/projects/esps/>.

231 CODE DEVELOPMENT, COMPLIANCE CHECKING, AND TRAINING TOOLS

232 The viability of ESPS depends on there being a straightforward path to writing compliant
233 components. Several tools are available to facilitate development and compliance verification of
234 ESPS components and coupled models. These include the command line-based NUOPC
235 Compliance Checker and Component Explorer, both described in the *NUOPC Layer Reference*
236 (2014), and the graphical Cupid Integrated Development Environment (IDE) (Dunlap 2014).

237 The NUOPC Compliance Checker is an analysis tool that intercepts component actions during
238 the execution of a modeling application and assesses whether they conform to standard NUOPC
239 Layer behaviors. It is linked by default to every application that uses ESMF and can be activated
240 by setting an environment variable. When deactivated, it imposes no performance penalty. The

³ Initial, minimal metadata associated with each ESPS model is being collected and displayed using tools from the Earth System Documentation consortium (ES-DOC; Lawrence et al. 2012).

241 Compliance Checker produces a compliance report that includes, for each component in an
242 application, information such as checks for presence of the required initialize, run, and finalize
243 phases, correct timekeeping, how fields are passed between components, and the presence of
244 required component and field metadata.

245 The Component Explorer is a run-time tool that analyzes a *single* model component by acting as
246 its driver. The tool offers a way of evaluating the behavior of the component outside of a coupled
247 modeling application. It steps systematically through the phases defined by the component and
248 performs checks such as whether required makefile fragments are provided, whether a NUOPC
249 driver can link to the component, and whether error messages are generated if the required inputs
250 are not supplied. For additional information, the Compliance Checker can be turned on while the
251 Component Explorer is running. A test of NUOPC compliance is running the candidate
252 component in the Component Explorer and ensuring that it generates no warnings from the
253 Compliance Checker when it is turned on.

254 Cupid provides a comprehensive code editing, compilation, and execution environment with
255 specialized capabilities for working with NUOPC-based codes. It is implemented as a plugin for
256 Eclipse, a widely used IDE. A key feature of Cupid is the ability to create an outline that shows
257 the NUOPC-wrapped components in the application, their initialize, run, and finalize phases, and
258 their compliance status. The outline is presented to the developer side-by-side with a code editor,
259 and a command line interface for compiling and running jobs. Cupid provides contextual
260 guidance and can automatically generate portions of the code needed for compliance. The user
261 can select several prototype codes for training, or can import their own model code into the
262 environment. Figure 2 shows the Cupid graphical user interface.

263 Table 3 summarizes the tools described in this section and their main uses. Static analysis mode
264 refers to the examination of code, while dynamic analysis mode refers to evaluation of
265 component behaviors during run-time.

266 **ADAPTING MODELS FOR ESPS**

267 In this section, we describe the approach to adapting different sorts of codes for ESPS. We look
268 at implementation of single model components, wholly new coupled systems, and existing
269 coupled systems.

270 The realities of implementation required adjustments to some goals and strategies. Most
271 significantly, the idea that a *single* common software framework must replace all others, a
272 solution advanced in the 2012 NRC report, proved unrealistic and unnecessary. In practice, it
273 has been more effective to wrap and combine multiple infrastructure packages, and ESMF often
274 co-exists with native infrastructure within modeling applications. This approach also enables
275 centers to maintain local differences in coupling methodologies; longstanding coupled modeling
276 efforts at NCAR, GFDL, and NASA have established organizational preferences for handling
277 coastlines, conservative transfer of fluxes, and other coupling operations. The details of these
278 operations are not reviewed here; detailed discussion of techniques is available in documents
279 such as Craig (2014). The different approaches encountered to date can be accommodated by the
280 NUOPC Layer rules and software.

281 Single model components are the most straightforward to wrap with NUOPC Layer interfaces.
282 The Modular Ocean Model (MOM5; Griffies 2012) and Hybrid Coordinate Ocean Model
283 (HYCOM; Halliwell et al., 1998, Halliwell et al., 2000, Bleck, 2002) are examples of this case.
284 Both ocean models had previously been wrapped with ESMF interfaces, and had the distinct

285 initialize, run, and finalize standard methods required by the framework. For NUOPC
286 compliance, a standard sequence of initialize phases was added, and conformance with the Field
287 Dictionary checked. The process of wrapping MOM5 and HYCOM with NUOPC Layer code
288 required minimal changes to the existing model infrastructure. For both MOM5 and HYCOM,
289 NUOPC changes can be switched off, and MOM5 can still run with GFDL's in-house FMS
290 framework.

291 The construction of newly coupled systems is a next step in complexity. The Navy global
292 modeling system and the NOAA Environmental Modeling System (NEMS; Iredell et al. 2014)
293 are examples in this category. Navy developers coupled the Navy Operational Global
294 Atmospheric Prediction System (NOGAPS; Rosmond 1992, Bayler and Lewit 1992) and
295 HYCOM by introducing simple NUOPC connectors between the models, and were able to easily
296 switch in the newer Navy Global Environmental Model atmosphere (NavGEM; Hogan et al.
297 2014) when it became available. This work leveraged ESMF component interfaces introduced
298 into NOGAPS as part of the Battlespace Environments Institute (BEI; Campbell et al. 2010). The
299 NUOPC-based HYCOM code from this coupled system was a useful starting point for coupling
300 HYCOM with components in NEMS and the CESM.

301 NEMS is an ambitious effort to organize a growing set of operational models at the National
302 Centers for Environmental Prediction under a unifying framework. Model coupling within
303 NEMS began with coupling the Global Spectral Model or GSM (previously the Global Forecast
304 System or GFS; EMC 2003) to HYCOM and MOM5 ocean components and the CICE sea ice
305 model (Hunke and Lipscomb 2008). A NUOPC mediator and connectors were introduced in
306 order to transfer and transform data on a potentially different grid and distribution than the
307 component models, and to perform merging and other coupling operations. A prototype of the

308 atmosphere-ocean-ice system has been completed, but much work remains to validate the code,
309 introduce additional components, and ready the system for operational use. Other components
310 now being introduced into NEMS include the WaveWatch 3 model (Tolman 2002), the
311 Ionosphere-Plasmasphere Electrodynamics (IPE) model (based on an earlier model described in
312 Fuller-Rowell et al. 1996 and Millward et al. 1996), and a hydraulic component implemented
313 using the WRF-Hydro model (Gochis et al. 2013). The Non-Hydrostatic Mesoscale Model
314 (NMMB; Janjic et al. 2012) will be coupled within NEMS to the Princeton Ocean Model (POM;
315 Blumberg and Mellor 1987) regional ocean for hurricane forecasts, and there are also plans to
316 introduce an alternate ice model, KISS (Grumbine 2013). Shown schematically in Figure 3, all
317 are being constructed as NUOPC components.

318 Adapting an existing coupled modeling system for NUOPC compliance is most challenging,
319 since adoption must work around the native code. The CESM, the Coupled Ocean Atmosphere
320 Mesoscale Prediction System (COAMPS; Hodur 1997, Chen et al. 2003), and ModelE (Schmidt
321 et al. 2006) are examples of this. In CESM, a fully coupled model that includes atmosphere,
322 ocean, sea ice, land ice, land, river and wave components, ESMF interfaces have been supported
323 at the component level since 2010, when it was known as the Community Climate System Model
324 4.0. However, the CESM driver was based on the MCT data type. Recently, the driver was
325 rewritten to accommodate the NUOPC Layer. By introducing a new component data type in the
326 driver, either NUOPC component interfaces or the original component interfaces that use MCT
327 data types can be invoked. These changes did not require significant modifications to the
328 internals of the model components themselves.

329 Incorporating the NUOPC Layer into COAMPS involved refactoring the existing ESMF layer in
330 each of its constituent model components and implementing a new top-level driver/coupler layer.

331 As with the global Navy system, ESMF component interfaces had been introduced as part of
332 BEI. The COAMPS system includes the non-hydrostatic COAMPS atmosphere model coupled
333 to the Navy Coastal Ocean Model (NCOM; Martin et al. 2009) and the Simulating Waves
334 Nearshore model (SWAN; Booij et al. 1999). Refactoring to introduce the NUOPC Layer into
335 each model component involved changing the model ESMF initialize method into multiple
336 standard phases. The representation of import/export fields was also changed to use the NUOPC
337 Field Dictionary. These changes were straightforward and limited to the model ESMF wrapper
338 layer. An effort that is just beginning involves wrapping the NEPTUNE [Navy Environmental
339 Prediction system Utilizing the NUMA (Nonhydrostatic Unified Atmospheric Model) CorE]
340 atmosphere, a non-hydrostatic model which uses an adaptive grid scheme (Kelly and Giraldo
341 2012, Kopera et al. 2014, Giraldo et al. 2013), with a NUOPC Layer interface, as a candidate for
342 the Navy's next-generation regional and global prediction systems..

343 When NUOPC Layer implementation began in ModelE, the degree of coarse-grained
344 modularization was sufficiently complete that the ModelE atmosphere could be run with four
345 different ocean models (data, mixed-layer, and two dynamic versions), and the two dynamic
346 oceans could both be run with a data atmosphere. At this time, atmosphere and mixed layer
347 ocean models are wrapped as NUOPC components, and can be driven using a NUOPC driver.
348 Specification of the multi-phase coupled run sequence was easily handled via NUOPC
349 constructs. Mediators will provide crucial flexibility to apply nontrivial field transformations as
350 more complex coupled configurations are migrated.

351 Developers of the GEOS-5 atmospheric model (Molod et al. 2012) incorporated ESMF into the
352 model design from the start, using the framework to wrap both major components and many sub-
353 processes. In order to fill in gaps in ESMF functionality, the GEOS-5 development team

354 developed software called the Modeling Analysis and Prediction Layer, or MAPL. A challenge
355 for bringing GEOS-5 into ESPS is translating the MAPL rules for components into NUOPC
356 components, and vice versa. A joint analysis by leads from the MAPL and NUOPC groups
357 revealed that the systems are fundamentally similar in structure and capabilities (da Silva et al.
358 2013). The feature that most contributes to this compatibility is that neither NUOPC nor MAPL
359 introduces new component data types - both are based on components that are native ESMF data
360 types (ESMF_GridComp and ESMF_CplComp). MAPL has been integrated into the
361 ESMF/NUOPC software distribution, and set up so that refactoring can reduce redundant code in
362 the two packages. Although the GEOS-5 model is advanced with respect to its adoption of
363 ESMF, most of the work in translating between MAPL and NUOPC still lies ahead.

364 **RESEARCH AND PREDICTION WITH COMMUNITY INFRASTRUCTURE**

365 Community-developed ESMF and NUOPC Layer infrastructure supports scientific research and
366 operational forecasting. This section describes examples of scientific advances that ESPS and
367 related infrastructure have facilitated at individual modeling centers, and the opportunities they
368 bring to the management of multi-model ensembles.

369 **MODELING AND DATA CENTER IMPACTS**

370 The use of ESMF and NUOPC infrastructure at modeling and data centers follows several
371 patterns. The NUOPC Layer allows software components representing major physical realms to
372 be leveraged across agencies; the underlying ESMF architecture wraps and organizes a diversity
373 of components, both large and small; and ESMF grid remapping and other libraries are used
374 extensively with coupled modeling systems and in other contexts such as data visualization.

- 375 • ***Navy NavGEM-HYCOM-CICE:*** The NavGEM-HYCOM-CICE modeling system, coupled

376 using NUOPC Layer infrastructure, is being used for research at the Naval Research
377 Laboratory. An initial study, using just NavGEM and HYCOM, examined the onset of a
378 Madden-Julien Oscillation (MJO) event in 2011 (Peng, 2011). For standalone NavGEM,
379 the onset signature was basically absent. The coupled system was able to reasonably
380 simulate the onset signature compared with TRMM (Tropical Rainfall Measuring
381 Mission) measurements. With the addition of the CICE ice model, this system is now
382 being used to explore the growing and melting of sea ice over the Antarctic and Arctic
383 regions.

384 • **COAMPS and COAMPS-TC:** The COAMPS model is run in research and operations by the
385 Defense Department and others for short-term numerical weather prediction. COAMPS-
386 TC is a configuration of COAMPS specifically designed to improve tropical cyclone
387 (TC) forecasts (Doyle et al. 2014). Both use ESMF and NUOPC software for component
388 coupling. The coupled aspects of COAMPS and COAMPS-TC were recently evaluated
389 using a comprehensive observational data set for Hurricane Ivan (Smith et al. 2013).
390 This activity allowed for the evaluation of model performance based on recent
391 improvements to the atmospheric, oceanic, and wave physics, while gaining a general but
392 improved understanding of the primary effects of ocean–wave model coupling in high-
393 wind conditions. The new wind input and dissipation source terms (Babanin et al. 2010;
394 Rogers et al. 2012) and wave drag coefficient formulation (Hwang, 2011), based on field
395 observations, significantly improved SWAN’s wave forecasts for the simulations of
396 Hurricane Ivan conducted in this study. In addition, the passing of ocean current
397 information from NCOM to SWAN further improved the TC wave field.

398 • **GEOS-5:** The NASA GEOS-5 atmosphere-ocean general circulation model is designed to

399 simulate climate variability on a wide range of time scales, from synoptic time scales to
400 multi-century climate change. Projects underway with the GEOS-5 AOGCM include
401 weakly coupled ocean-atmosphere data assimilation, seasonal climate predictions and
402 decadal climate prediction tests within the framework of Coupled Model Intercomparison
403 Project Phase 5 (CMIP5; Taylor et al. 2012). The decadal climate prediction experiments
404 are being initialized using the weakly coupled atmosphere-ocean data assimilation based
405 on MERRA (Rienecker et al. 2011). All components are coupled together using ESMF
406 interfaces.

407 • **NEMS:** The NEMS modeling system under construction at NOAA is intended to
408 streamline development and create new knowledge and technology transfer paths that
409 bridge the NOAA research and operational centers and other agency efforts. NEMS will
410 encompass multiple coupled models, including future implementations of the Climate
411 Forecast System (CFS; Saha 2014), the Next Generation Global Prediction System
412 (NGGPS; Lapenta 2015), and regional hurricane forecast models. The new CFS will
413 couple global atmosphere, ocean, sea ice and wave components through the NUOPC
414 Layer for advanced probabilistic seasonal and monthly forecasts. NGGPS is being
415 designed to improve and extend weather forecasts to 30 days, and will include ocean and
416 other components coupled to an atmosphere. The NEMS hurricane forecasting capability
417 will have nested mesoscale atmosphere and ocean components coupled through the
418 NUOPC Layer for advanced probabilistic tropical storm track and intensity prediction.
419 Early model outputs from the atmosphere (GSM), ocean (MOM5), and sea ice (CICE)
420 three-way coupled system in NEMS are currently being evaluated.

421 • **CESM:** The CESM coupled global climate model enables state-of-the art simulations of

422 Earth's past, present and future climate states and is one of the primary climate models
423 used for national and international assessments. A recent effort involves coupling
424 HYCOM to CESM components using NUOPC Layer interfaces. A scientific goal of the
425 HYCOM-CESM coupling is to assess the impact of hybrid versus depth coordinates in
426 the representation of our present-day climate and climate variability. The project
427 leverages an effort to couple HYCOM to an earlier version of CESM, CCSM3 (Lu et al.
428 2013; Michael et al. 2013).

429 • **Grid Remapping:** An ongoing collaboration between CESM and ESMF led to joint
430 development of the parallel ESMF grid remapping tools. These are now widely used by
431 modeling groups and visualization and analysis packages including NCL and UV-CDAT,
432 and have enabled projects like CESM to meet critical milestones and opened doors to
433 new research initiatives. For example, leveraging ESMF grid remapping, CESM was able
434 to create offline utilities that permit researchers to run CESM on user-defined grids,
435 including regionally refined grids.⁴ ESMF offline remapping has also enabled the
436 incorporation of the Model for Prediction Across Scales (MPAS) ocean model as a new
437 CESM component. Recent efforts are focusing on migrating the off-line grid remapping
438 into a run time capability in order that more dynamic and adaptive grids can be
439 supported.

440 ESPS OPPORTUNITIES FOR MANAGED AND INTERACTIVE ENSEMBLES

441 In the weather and climate prediction communities ensemble simulations are used to separate
442 signal from noise, reduce some of the model-induced errors and improve forecast skill.

443 Uncertainty and errors come from several sources:

⁴ These utilities have been folded into the publically released version of the model as of CESM1.2.0.

- 444 (i) Initial condition uncertainty associated with errors in our observing systems or in how
445 the observational estimates are used to initialize prediction systems (model
446 uncertainty/errors play a significant role here);
- 447 (ii) Uncertainty or errors in the observed and modeled external forcing. This can be either
448 natural (changes in solar radiation reaching the top of the atmosphere, changes in
449 atmospheric composition due to natural forcing such as volcanic explosions, changes
450 in the shape and topography of continents or ocean basins), or anthropogenic
451 (changes in the atmospheric composition and land surface properties due to human
452 influences);
- 453 (iii) Uncertainties or errors in the formulation of the models used to make the predictions
454 and to assimilate the observations. These uncertainties and errors are associated with
455 a discrete representation of the climate system and the parameterization of sub-grid
456 physical processes. The modeling infrastructure development described here is ideally
457 suited to quantify uncertainty due to errors in model formulation, and where possible
458 reduce this uncertainty.

459 To account for initial condition uncertainty it is standard practice to perform a large ensemble of
460 simulations with a single model by perturbing the initial conditions. The ensemble mean or
461 average is typically thought of as an estimate of the signal and the ensemble spread or even the
462 entire distribution is used to quantify the uncertainty (or noise) due to errors in the initial
463 conditions. In terms of uncertainty in external forcing, the model simulations that are used to
464 inform the Intergovernmental Panel on Climate Change (IPCC) use a number of different
465 scenarios for projected greenhouse gas forcing to bracket possible future changes in the climate.
466 In both of the examples above, it is also standard practice to use multiple models to quantify

467 uncertainty in model formulation and to reduce model-induced errors.

468 The use of multi-model ensembles falls into two general categories both of which are easily
469 accommodated by ESPS. The first category is an *a posteriori* approach where ensemble
470 predictions from different models are combined, after the simulation or prediction has been run,
471 into a multi-model average or probability distribution that takes advantage of complementary
472 skill and errors. This approach is the basis of several international collaborative prediction
473 research efforts (e.g., National Multi-Model Ensemble, ENSEMBLES), climate change
474 projection (CMIP) efforts, and there are numerous examples of how this multi-model approach
475 yields superior results compared to any single model (e.g., Kirtman et al. 2013). In this case, the
476 multi-model average estimates the signal that is robust across different model formulations and
477 initial condition perturbations. The distribution of model states is used to quantify uncertainty
478 due to model formulation and initial condition errors. While this approach has proven to be quite
479 effective, it is generally *ad hoc* in the sense that the chosen models are simply those that are
480 readily available. The ESPS development described here allows for a more systematic approach
481 in that individual component models (e.g., exchanging atmospheric components CAM5 for
482 GEOS-5) can easily be interchanged within the context of the same coupling infrastructure thus
483 making it possible to isolate how the individual component models contribute to uncertainty and
484 complementary skill and errors. For simplicity we refer to the interchanging or exchanging
485 component models as managed ensembles.

486 The second category can be viewed as an *a priori* technique in the sense that the model
487 uncertainty is “modeled” as the model evolves. This approach recognizes that the dynamic and
488 thermodynamic equations have irreducible uncertainty and that this uncertainty should be
489 included as the model evolves. This argument is the scientific underpinning for the multi-model

490 interactive ensemble approach. The basic idea is to take advantage of the fact that the multi-
491 model approach can reduce some of the model-induced error, but with the difference being that
492 this is incorporated as the coupled system evolves. In ESPS we can use the atmospheric
493 component model from say CAM5 and GEOS-5 *simultaneously* as the coupled system evolves,
494 and for example, combine the fluxes (mean or weighted average) from the two atmospheric
495 models to communicate with the single ocean component model. Moreover, it is even possible to
496 sample the atmospheric fluxes in order to introduce state dependent and non-local stochasticity
497 into the coupled system to model the uncertainty due to model formulation. Forerunners of the
498 approach have been implemented within the context of CCSM to study how atmospheric weather
499 noise impacts climate variability (Kirtman et al. 2009, Kirtman et al. 2011) and seasonal
500 forecasts in the NOAA operational prediction system (Stan and Kirtman 2008).

501 **FUTURE DIRECTIONS**

502 Next steps include continued development of NUOPC-based modeling systems, ongoing
503 improvements to ESPS metadata and user access information, exploration of the opportunities
504 ESPS affords in creating new ensemble systems, and addition of capabilities to the infrastructure
505 software itself. Whether to extend the ESPS to other types of components is an open question.
506 Developers have already implemented NUOPC Layer interfaces on components that do not fall
507 into the initial ESPS model categories, including the WRF-Hydro hydrology model, the
508 Community Land Model (CLM), and the Ionosphere-Plasmasphere Electrodynamics (IPE)
509 model.

510 The continued incorporation of additional processes into models, the desire for more seamless
511 prediction across temporal scales, and the demand for more information about the local impacts
512 of climate change are some of the motivations for linking frameworks from multiple disciplines.

513 The NSF-funded Earth System Bridge project is building converters that will enable NUOPC
514 codes to be run within the Community Surface Dynamics Modeling System (CSDMS), which
515 contains many smaller models representing local surface processes, and CSDMS codes to be run
516 within ESMF. The ESMF infrastructure is also being used to develop web service coupling
517 approaches in order to link weather and climate models to frameworks that deliver local and
518 regional information products (Goodall et al. 2013).

519 A critical aspect of future work is the evaluation and evolution of NUOPC and ESMF software
520 for emerging computing architectures. A primary goal is for common infrastructure such as the
521 NUOPC Layer to do no harm, and allow for optimizations within component models. However,
522 NUOPC infrastructure also offers new optimization opportunities for coupled systems. The
523 formalization of initialize and run phases, which allows components to negotiate with each other
524 for resources, holds great potential in dealing with systems that have an increasing number of
525 components, and will need to run efficiently on accelerator-based compute hardware. Among the
526 planned extensions to NUOPC protocols are hardware resource management between
527 components and the negotiation of data placement of distributed objects. Both extensions
528 leverage the ESMF “virtual machine” or hardware interface layer, already extended under the
529 ESPC initiative to be co-processor aware. The awareness of data location can also be used to
530 minimize data movement and reference data where possible during coupling. Finally, there is
531 interest in optimizing the grid remapping operation between component grids in the mediator by
532 choosing an optimal decomposition of the transferred model grid. This optimization requires
533 extra negotiation between the components which could be made part of the existing NUOPC
534 component interactions.

535 **CONCLUSION**

536 Through the actions of a succession of infrastructure projects in the Earth sciences over the last
537 two decades, a common model architecture (CMA) has emerged in the U.S. modeling
538 community. This has enabled high-level model components to be wrapped in community-
539 developed ESMF and NUOPC interfaces with few changes to the model code inside, in a way
540 that retains much of the native model infrastructure. The components in the resulting systems
541 possess a well-defined measure of technical interoperability. The ESPS, a collection of multi-
542 agency coupled weather and climate systems that complies with these standard interfaces, is a
543 tangible outcome of this coordination. It is a direct response to the recommendations of a series
544 of National Research Council and other reports recommending common modeling infrastructure,
545 and a national asset resulting from commitment of the agencies involved in Earth system
546 modeling to work together to address global challenges.

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569 **SIDEBAR I:**

570 **LINKED AND LEVERAGED:**

571 **THE EVOLUTION OF COUPLED MODEL INFRASTRUCTURE**

572 **First generation (1996-2001)** Model coupling technologies were initially targeted for
573 specific modeling systems, often within a single organization. Infrastructure that arose out of
574 model development during this period included the Flexible Modeling System (FMS) at the
575 Geophysical Fluid Dynamics Laboratory, the Goddard Earth Modeling System (GEMS; NASA
576 GSFC 1997), and the Climate System Model (CSM; Boville and Gent 1998) and Parallel
577 Climate Model (PCM; Washington et al. 2000) flux couplers at NCAR. Each of these systems
578 coordinated functions such as timekeeping and I/O across model components contributed by
579 domain specialists, and implemented component interfaces for field transformations and
580 exchanges.

581 **Second generation (2002-2006)** Recognizing similar functions and strategies across first
582 generation model infrastructures, a multi-agency group formed a consortium to jointly develop
583 an Earth System Modeling Framework (ESMF). ESMF was intended to limit redundant code
584 and enable components to be exchanged between modeling centers. Also at this time, within
585 DOE, the Common Component Architecture (CCA; Bernholdt et al. 2006) consortium
586 introduced a more precise definition of components into the high performance computing
587 community, and members of the Model Coupling Toolkit (MCT) project worked with CSM
588 (now CCSM - the Community CSM) to abstract low-level coupling functions into the MCT
589 general-purpose library and develop a new CCSM coupler (CPL7).

590 **Third generation (2007-2014)** A third generation of development began as multi-agency
591 infrastructures began to mature and refactor code, assess their successes and deficiencies, and
592 encounter new scientific and computational challenges. Both NASA, with the Modeling Analysis
593 and Prediction Layer (MAPL; Suarez et al. 2007) and the National Unified Operational
594 Prediction Capability (NUOPC), a group of NOAA, Navy and Air Force operational weather
595 prediction centers and their research partners, added conventions to ESMF to increase
596 component interoperability. Similar refactoring efforts took place in other communities such as
597 surface dynamics (Peckham et al. 2013) and agriculture (David et al. 2010). The demands of
598 high resolution modeling and the advent of unstructured grids pushed ESMF to develop new
599 capabilities and products, and MCT and CCSM – now CESM - to introduce new communication
600 options. In this wave of development, the capabilities of shared infrastructure began to equal or
601 outperform those developed by individual organizations.

602 **What next? (2015 -)** Although some infrastructure projects have disappeared or merged,
603 projects from all three generations of development are still in use, and increasingly their

604 interfaces may coexist in the same modeling system. Future development is likely to include
605 more cross-disciplinary projects like the Earth System Bridge (see Peckham et al. 2014), which
606 is defining a formal characterization of framework elements and behaviors (an Earth System
607 Framework Description Language, or ES-FDL), and using it to explore how to link components
608 that come from different communities that have their own infrastructures (e.g. climate,
609 hydrology, ecosystem modeling).

610 **SIDEBAR II**

611 **LIMITS OF COMPONENT**

Possible image for Sidebar II.

612 **INTEROPERABILITY**

613 NUOPC Layer compliance guarantees certain
614 aspects of technical interoperability, but it does not
615 guarantee that all components of the same type, for
616 instance all NUOPC-wrapped atmosphere models,
617 will be scientifically viable in a given coupled
618 modeling system. A simple example of scientific
619 incompatibility is one in which the exported fields
620 available do not match the imported fields needed for a component to run. Other
621 incompatibilities can originate in how the scope of the component is defined (i.e., which physical
622 processes are included), and in assumptions about how the component will interact with other
623 components.⁵ For example, some modeling systems implement an implicit interaction between



⁵ Alexander and Easterbrook 2011. provide a high-level look at variations in the component architecture of climate models.

624 atmosphere and land models while others take a simpler explicit approach. Whether or not a
625 component can adapt to a range of configurations and architectures is determined as well by
626 whether scientific contingencies are built into it by the developer. The components in the ESPS
627 are limited to major physical domains since many of the models in this category, such as CAM,
628 CICE, and HYCOM have been built with the scientific flexibility needed to operate in multiple
629 modeling systems and coupling configurations.

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