Considerations for coupled model development at GFDL

GFDL Coupled Model Development Study Team

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Draft **October 31, 2000**

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1 Purpose of this team and this report

As stated in The GFDL White Paper (April 2000) and The Millennium Panel Report (August 2000), building and using state-of-the-art coupled models represents a *core* aspect of GFDL's future research goals. How do we reach a stage where the lab's intellectual and computational resources are centered on this vision? This question provides a mandate for this study team and this document. In particular, this team was established in August 2000 by Mahlman "to evaluate the best ways that we at GFDL can proceed to work together across the Laboratory's Groups to produce the next-generation coupled model." This purpose has evolved to what we see as our central mission: *To focus the laboratory towards the aim of constructing the pre-eminent class of coupled models for studies of climate mean, variability, and change ranging from intra-seasonal to centennial time scales.*

This document represents the outcome of our deliberations. It consists of two main elements. First, it introduces some of the key scientific, engineering, and computational requirements necessary to develop the next generation GFDL coupled models. Our list is preliminary and will evolve. Additionally, we focus on the main *trunk* of a particular coupled model. However, it is anticipated that various *branches* will naturally grow in the process of investigating selected phenomena and developing improved algorithms.

Second, it raises questions regarding how to optimize the development of numerical models. The answers to these questions are many and varied. We present a sample of those which were discussed amongst the team. Differences arise from variations in experience, understanding, intuition, emphasis, and philosophy. In trying to articulate one approach or another, the associated debates often become emotional. This might be expected given the difficult questions addressed and the importance and ramifications of the decisions. However, it is hoped that a rational approach will prevail.

At this time, there is not an optimal approach to coupled model development. Nor is there an approach which has borne fruit for the development of the next generation coupled model at GFDL. What is clear is that the development of models in general, and coupled models in particular, *is a process rather than an event.* In order to achieve our goals in coupled modeling, this process must become the central aspect of GFDL's research and development.

To evolve an optimal development strategy requires a healthy debate amongst *all* the relevant players. A basic goal of these debates should be to lead us towards the cohesion and focus called for by the White Paper and Millennium Panel. In particular, these debates *should aim to design a sound and detailed action plan for coupled model development.* It is hoped that this report provides a useful vehicle for the development of such a plan.

2 Overall goals

2.1 GFDL White Paper and Climate Initiative

Spring 2000 saw many in the lab asking questions about how we should focus research and development resources over the next decades. The *GFDL White Paper* resulted after considerable debate and consideration. This document identified the following two central goals or themes for GFDL:

1. We must be a world leader in climate modeling and in the simulation, analysis, and assessment of climate change.

2. To contribute to the development of new tools that improve NOAA's operational forecasting.

These two goals are mutually synergistic and their success is closely linked. Most notably for the present document, one central aim of the "tools" goal should be to develop the means to address the "climate" goal. Conversely, the development of coupled climate models should actively support, foster, and assist in the development of general and flexible tools.

To reduce the lab's efforts to just *two* goals or themes is key. The alternative, articulated by both the White Paper and Millennium Panel Report, is for groups at GFDL to maintain predominantly separate research agendas. The end result is a lack of overall vision typical of many academic departments. In previous decades, GFDL flourished with such an approach. However, we support the White Paper's assertion that GFDL will not survive in today's much more competitive research world without a strong and committed focus on just a few grand themes.

The White Paper provided an overall vision for how to implement the above two goals. Notably, it stated that

> We must prioritize our research efforts on fundamental atmospheric and ocean problems according to the promise they hold of impacting in important ways on either the modeling, analysis, and assessment of climate change, or the development of tools of potential operational significance for NOAA.

A focus on climate change represents a significant statement regarding the lab's interests in the science of the problem, its complex and rich nature, and its vital importance to NOAA and the nation. This focus forms the basis for the following discussions.

Acting in a synergistic relation with GFDL, an initiative for a *Princeton Climate Prediction Center* has been lead by Vallis (June 2000). The goals of this initiative are to "create a pre-eminent center for climate prediction, fully integrated with NOAA's emerging Climate Services." The activities of the center will complement many of GFDL's research and development efforts in seasonal to multi-decadal prediction. The success of this center is closely tied to GFDL's ability to reach a new level of expertise and commitment to coupled model development. Therefore, the proposal provides added motivation to realize the climate modeling goals articulated here and in the White Paper.

2.2 GFDL coupled model development

Coupled models are necessary to achieve the climate goal of the White Paper, while both goals are facilitated by the FMS software engineering framework. Hence, we propose that

> The central goal of model development at GFDL is to use FMS to develop state-of-the-art coupled climate models.

Using CVS parlance, the coupled model effort should focus on the development of a main *trunk* coupled model for use in addressing the climate goal. The climate trunk is the focus of this document. Nonetheless, it is essential to note that a climate trunk must foster selected and crucial *branch* research agendas focused on seasonal-to-interannual prediction and fundamental atmospheric, oceanic, land, ice, chemical, and biological processes. Consistent with the desire for a focused agenda, the success of the climate goal depends on an intimate and coherent connection between the trunk and the branches. *The climate problem and its needs should form the central link between all these efforts in order to define a healthy climate tree.*

2.3 How much focus?

It is worth asking here whether all GFDL scientists are in agreement with the climate focus proposed in the White Paper? How much focus should occur around this theme? Are folks willing to restructure in order to realize a strong and committed climate effort? These are fundamental questions which set the tone and strategy for how organizational issues are addressed.

As highlighted in the White Paper, we emphasize our belief that without just a few central themes, the lab's efforts will not succeed at a world-class level for any of its current sub-critical agendas. *We assume this point to be the case in the following as we focus on climate as one such theme.*

3 General modeling goals

This section highlights some broad goals of the coupled model development. More precise issues are discussed in the Appendix.

3.1 Reduce and ultimately remove flux adjustments

A primary aim is to pursue research into physically sound and effective methods that reduce, and ultimately eliminate, the need for artificial flux adjustments. It is inconsistent with all world climate research goals to maintain the use of flux adjustments in the next generation models. The Hadley Centre has provided a relatively stable coupled model simulation without flux adjustments. Their efforts provide a case in point for the feasibility of running climate models without adjustments prior to resolving many of the outstanding problems. Nonetheless, their success was neither easy nor reproducible thus far.

The goal of eliminating flux adjustments is daunting. Yet doing so is crucial to the success of this effort and for climate modeling in general. What are the elements of a model that removes the need for adjustments? How important are ocean eddies, either resolved or parameterized? How accurate do we need to simulate clouds, radiation, convection, and other crucial atmospheric processes? How should the finer resolution models be initialized to reduce climate drift? Our ability to answer these and other critical questions will largely determine the success of GFDL's future climate research.

3.2 Transcend traditional GFDL group boundaries

Coupled model development at GFDL is currently sub-critical for purposes of reaching state-of-the-art status. To remedy this situation, the coupled model effort must result from enhanced coherence between many scientific projects in the lab. We consider such coherence natural for two main reasons. (A) FMS provides a powerful software environment that promotes the interchange of modules. Consequently, FMS fosters a scientifically open and accessible investigation of various alternative modeling approaches. (B) Computational resources have evolved to the point that scientifically interesting and important research can be conducted by many scientists using similar, if not identical, models. Quite simply, there are less boundaries today between the goals of the various groups.

Consider the following examples that motivate an inter-disciplinary effort and illustrate the loosening of group boundaries. First, coupled climate models aimed at providing scenarios for global warming have traditionally produced a poor ENSO representation. Reasons have been proposed, such as insufficient resolution and poor parameterization schemes. Since ENSO is the largest interannual climate signal, a climate change simulation in a model without a sound ENSO representation is unacceptable for the next generation climate model. Second, ENSO forecast models have traditionally ignored high latitude processes and have been integrated for only a short period at GFDL. However, there are strong indications that decadal fluctuations of ENSO can induce changes in predictability, and greenhouse forcing may affect such regimes. Hence, decadal ENSO fluctuations, either natural or anthropogenic, should be considered if we are to produce new understandings and advances in seasonal-to-interannual forecasts. At these longer time scales (order decades), high latitude processes (e.g., ice dynamics and deep water formation) become much more important. Third, GFDL studies of fundamental atmospheric processes, such as convection, radiation, boundary layers, and clouds have traditionally employed a prescribed SST lower boundary condition. However, such processes ultimately must be understood within a coupled climate context. Hence, an interactive ocean boundary condition will broaden the scientific capabilities and importance of these studies. Fourth, similar reasoning argues that ocean processes such as deep water formation and mesoscale eddies should ideally be considered in the context of how they interact with a dynamic atmosphere and ice.

These examples could have been written down many years ago and provided just as much scientific motivation as today. However, with the advent of FMS, new computational facilities, and increased scientific understanding, it is within our capabilities to realize an inter-disciplinary effort that straddles traditional space-time boundaries. The extension of various research efforts into the coupled context is feasible and warranted. Hence, the research agendas of many scientific projects should evolve towards a common numerical representation of key components.

Notably, this evolution should not proceed by fiat. Rather, it is hoped that progress will occur via an open scientific assessment of various alternative approaches and algorithms. Furthermore, it should not produce a monolithic model which is inaccessible to isolating individual processes. Rather, a synergy must be fostered and facilitated between process oriented and large-scale oriented studies.

3.3 Resource requirements

FMS currently consists of a set of *flexible modules*. A central goal of GFDL's research and development should be to evolve a structure which utilizes and refines these modules for the purpose of developing state-of-the art *coupled models*. These models must maintain a high level of physical integrity as well as the ability to run efficiently. These two goals are often in conflict. However, we contend that if the lab focuses its efforts, the need to make compromises on physical and numerical integrity can be greatly reduced.

Given the difficulty of projecting how much computer power we will have, it is nonetheless possible and useful to hypothesize that the next generation trunk climate model will consist of the following main components:

- Atmospheric model with roughly R30/T42/N45 horizontal resolution and 30-50 vertical levels
- MOM 4 ocean with roughly 1-degree horizontal resolution and 40-50 vertical levels
- Dynamic sea ice (SIS)
- Modern land model (LaD)

Based on the success of other centers (e.g., Hadley, MPI, NCAR) with models of the general complexity envisaged here, state-of-the-art coupled-model research is attainable at GFDL with a model of this type.

The Appendix details a number of key metrics and capabilities which we consider to be essential elements of the next generation coupled model. Prioritizing these items is a difficult process that will require scientific debate. Such debate will be central to the development effort.

4 Some key questions

Many difficult issues must be addressed when considering how to manifest a healthy *climate tree*. This team did not come to a consensus on all issues, and we imagine that such will also be the case amongst a larger gathering of scientists. The key questions which we discussed, and some tentative and less than unanimous proposals, are presented in this section. Some of the questions clearly overlap, yet their presentation is given in order to provide various perspectives.

We believe these issues *must* be addressed and resolved amongst an open forum comprised of *all* parties, including non-group leaders, who have an interest in their outcome. Our hope is that the presentation here will motivate such debate.

4.1 Should we wait until the new full-time lab director?

GFDL is in an uncertain period of transition between Mahlman and another full-time director. It may be some months, or upwards of a year, before a new director is in-house. At the time of the White Paper meetings early 2000, it was decided that this transition period allows us to define our visions without the "heavy hand" of a lab director influencing these discussions. The White Paper succeeded in that goal. If the new director does not agree with the White Paper, the lab may eventually embrace other visions. Yet given the positive response from the Millennium Panel to the White Paper, it seems more likely that the new director's visions will parallel the White Paper.

The question then arises whether we should take the next step towards implementing the White Paper prior to a new full-time director taking office. *We strongly believe that to wait is not prudent.* Instead, the issues raised here can and should be addressed now. Granted, the new director's input will be crucial in the long run. But the needs and opportunities are imminent. We must empower ourselves to address the problems at hand. Communication and movement is important. Otherwise, efforts will remain scattered, inefficient, and morales will suffer.

4.2 What about growth in support of our goals?

The White Paper considered the possibility of growth in support of its goals. There is a potential that such growth may arise from the NOAA Climate Prediction Initiative. More resources would ideally enable us to realize the central goals stated here, and such should be sought.

However, we believe it unlikely that significant added resources will be garnered without a concomitant re-focusing of efforts and goals as articulated here and in the White Paper. That is, unless NOAA determines that GFDL is serious in its aspirations for climate, we see little reason for them to support a substantially increased climate effort. Furthermore, *we contend that with a focused and committed effort using present resources, we can and should begin to address the White Paper's goals.*

4.3 How to define the *climate tree*?

One proposal is to define an effort to be part of the climate tree so long as it can conceivably be integrated into the main climate trunk within a 5-7 year cycle. This time scale arises from experience given the time scale for developing, running, and analyzing a particular coupled climate model class. There is disagreement in the lab as to the appropriateness of this time scale, with some arguing for a far shorter turnaround cycle. But for the purposes of this document, we assume 5-7 years is appropriate.

Specific examples are useful. The proposed efforts at non-hydrostatic atmospheric modeling and hurricane forecasting will not be a climate branch. The reason is that it is inconceivable, assuming reasonable computational increases, that such models will form the core of a GFDL coupled climate model until sometime after 2010. Nonetheless, these are important and valuable research efforts which fall under the second goal of the White Paper.

However, should research into, say, ocean eddy parameterization or gravity wave drag be included as a climate branch? Such efforts will likely branch from other non-climate trees at GFDL. Arguably these efforts should also fall under the climate tree since one of the aims of these fundamental studies is to advance the fidelity of coarse climate models through parameterizations.

It therefore remains difficult to precisely define those topics which fall onto the climate tree and those which do not. We suggest that a method which will enable research to be naturally cohesive is for each project to be conceived within an overall vision. If that vision is articulated precisely, as we feel was done in the White Paper, and if it is committed to and acted upon by the lab's scientists, then research efforts should focus on problems relevant for this vision. Pushing the tree analogy further, *focusing on a common climate vision will prompt many different GFDL trees to be members of the same species.*

4.4 How much resources should be focused on the climate trunk?

There are two main perspectives here.

4.4.1 Definitive allocation committed

One proposal is that *the trunk climate change model be constructed so that four integrations of approximately 100 years duration can be completed within one calendar month using one-half of the lab's computational resources.* This timing is necessary to achieve an acceptable cycle time of experimental design, execution, and analysis. In addition, the need to run ensembles places a heavy burden on climate change studies much as it does on seasonal-to-interannual predictions. The precise number of ensemble members is a topic of debate; we chose four as a nominal number for purposes of concreteness based on past experience.

To facilitate the realization of this turnaround with a state-of-the-art climate change model, it is proposed that at least *one-half of the lab's computational and intellectual resources be directly devoted to research and development within the climate tree.* Additionally, during selected periods, the lab must make available *roughly one-half of the lab's computational resources to the climate change trunk.* Otherwise, we contend that the climate change effort will remain constrained to use an overly coarse resolution with low-fidelity parameterizations. In this situation, the lab-wide cohesion desired from this effort will remain sub-critical, and the world-class science that we aspire to will be elusive.

By proposing one-half of the resources for climate, and in particular for running the main trunk model during selected periods, we hasten to re-emphasize the core nature of this effort which *must* transcend group boundaries. That is, the aim is for more than one group or project to utilize this model and its branches for their research. The aim *is not* to funnel resources to the current G group efforts at the sacrifice of other groups. It is therefore arguably not too radical to propose such a large allocation. Indeed, note that the proposal maintains that a full one-half of the lab's resources will support the growth and maturation of other trees.

4.4.2 Less than definitive allocation committed at this time

Another proposal is to avoid specific allocations at this time. The main reason is that computational requirements have not been detailed on the new system for models of the type recommended in this report. Allocating half the lab's resources to the climate tree, while it may be possible after merging previously parallel efforts in different groups, is difficult to promote. Such a decision is warranted only after a thorough computing inventory is obtained, and information on what, if any, activities would need to cease in order to accommodate our goals. At that point, the consensus may be one half is sufficient, or perhaps more than half will be required and desired.

4.5 Should development occur incrementally or via a clean slate?

The development of MOM has traditionally occurred in sequential, incremental steps from older code. Frequent tests are made at each level of development to ensure that previous answers remain unchanged if desired, or are altered if the source of the change is understood from a numerical and/or physical perspective. This is a slow process that takes years. However, it has resulted in a model whose core features are well known and *trusted*. Trust is crucial for the use of this model in a larger context where non-experts make use of it to pursue their respective scientific goals.

The MOM experience is contrasted with that of the current status of an FMS-based atmospheric model. That effort so far has not been incremental. Instead, many have concluded that the older atmospheric models were simply unworkable and hence should be jettisoned in favor of a *clean slate.* This approach is satisfying since it allows for new ideas and algorithms to be rapidly incorporated into the framework. From this perspective, the present state of FMS is powerful. However, FMS has yet to produce a new atmospheric model that has been demonstrated to be useful for scientific investigations of global circulations and coupled climate phenomena. Until a new FMS-based atmospheric model is developed, the ideal of having an FMS-based model used for coupled model research along with a new model being developed in parallel will remain elusive.

Given the extreme complexity of constructing a "trusted" atmospheric model (and ultimately a coupled climate model), the clean slate approach is arguably quite risky. Interestingly, extreme complexity can also be used to argue that a radical paradigm shift is required in order to "break the mold" in hopes of reaching a new level of physical and numerical integrity. From this alternative perspective, the clean slate approach is the only one that will lead us to the next generation of atmospheric models.

These two perspectives have been the root of often heated debates regarding atmospheric model development. How valuable are the simulations with the older non-FMS models? How important is it to maintain linkage with their solutions, given that they formed the basis for numerous scientific studies and assessments yet possess many shortcomings? Is it more optimal to incrementally build models or to start from scratch?

Many inside and outside this team have strong feelings concerning these questions. Perhaps a middle ground can be achieved. Difficult questions must be addressed to decide how resources are devoted to the various avenues. Constant re-evaluation of the success of the approaches should be maintained. No one person or group has the answer, yet many have coherent and logical reasons for their approach and their representation in the process is vital. *Therefore, participation of all interested scientists should be allowed, encouraged, and expected.*

4.6 Are we ready to combine bottom-up and top-down approaches?

There is a hierarchy of metrics which gauge the degree to which an algorithm, process, or model is "understood," "trusted," or "successful." Whereas a scheme may be suitable for process studies, it may prove difficult to incorporate into a coupled model until various other schemes are re-tuned or abandoned in favor of alternatives. Conversely, a well tuned scheme may perform suitably in a coupled model, yet lack fundamental physical foundations and so be questioned as a process.

Related difficult questions arise concerning how much we can compromise on various metrics. What if the representation of a process or phenomena is not as sound as some would desire yet is good enough for others? For example, should the development of a new coupled model await the development of a physically based and complete cloud parameterization scheme? What if the next generation model requires sizable flux adjustments for stability? How exact do we need to compute radiation? Should ocean mesoscale eddies be explicitly resolved? More generally, when are processes, algorithms, component models, and the coupled model "good enough" or "reasonable"?

There are two overall research approaches which often lead to different perspectives on these questions. The first one focuses on fundamental processes. Here, the aim is a basic understanding of the process in relative isolation. This is termed here the "bottom-up" approach. Although addressing basic questions, it often suffers from not articulating how the process interacts with other aspects of the climate system. The second approach focuses on a reasonably complete description of the climate system in which many interacting processes are combined into a coupled model. The overall effects of various processes are viewed in a holistic manner. This is a "top-down" approach. Although providing a "big-picture" presentation of the climate system, it often suffers since many of the processes have so far been either under-resolved due to computational limitations, or the physical processes are overly simple.

Are we ready to combine the two approaches? Can process studies be conducted in a coupled model framework, and can coupled model studies employ sufficient resolution and sound parameterizations that assist in further development and understanding of fundamental processes? Are we ready to commit to achieving an overall consensus on model metrics, or will efforts splinter when factions feel their goals are met yet others require more effort?

We contend that GFDL is ready to develop a strong and committed synergistic relationship between the two approaches. Process researchers must become entrained in the next generation coupled model development and consider how various processes interact within the climate system. Conversely, those interested in long-term climate simulations must foster a framework and willingness to incorporate well tested parameterizations into their simulations. By doing so, there will evolve a hierarchy of coupled models all linked to the main climate trunk. As understanding improves, there should be a systematic passage of developed algorithms to the main trunk. Conversely, information and experience concerning the performance of the processes in the trunk simulations should feedback to further advance process research.

4.7 Should we always maintain a coupled climate model?

Presently, GFDL has *no* scientifically credible coupled climate model which can be run efficiently on the new computer. The next generation model, which is the main focus of this document, will likely not be used routinely for some years for climate studies. Some argue that we may not have this model on the new computer; i.e., we need more than five years. Others feel two or three years may be sufficient. Clearly the ideal is to develop a process where a mature model is running large-scale climate experiments while a future/immature model is being developed. At a natural time, a clean hand-off can be made thus starting a new cycle. Unfortunately, we are presently far from this ideal.

Given the present situation, the question arises whether we should devote all development efforts towards realizing an FMS-based coupled model, or should some of the efforts be focused on maintaining a non-FMS model for use on the new computer? This is a difficult and contentious question. Its answer fundamentally depends on the value given to the current non-FMS model versus the hopes for an FMS-based model. It also depends on the value given the ability to run prediction/scenario experiments with the older model versus our taking a "developmental leave of absence" from this process. Some argue that to continue producing research with the non-FMS based model is to jeopardize the scientific reputation of the lab since that model is severely flawed. Others argue that a leave of absence will sacrifice a core and highly visible aspect of the lab which may compromise GFDL's ability to acquire a new computer in five or six years, or to garner full NOAA and Congressional support for the Climate Prediction Initiative.

Either path alone seems risky. An optimal middle ground must be articulated, with cohesion and synergy maintained between the two sides. That is, neither approach should be considered independent of the other. There must be significant overlap with feedbacks that lead to a strong and healthy support mechanism for both approaches. We hasten to add that the older non-FMS code should be abandoned in favor of the FMS-based models *as soon as feasible*, so long as we maintain the ability to link to the old solutions. In the long-run, FMS *is the tool-box* for constructing our models–there is no contention on this point.

4.8 How to organize coupled model development?

A coupled model development effort represents in part a systematic process aiming to piece various FMS *modules* into a coherent coupled *model*. There will be continual need to make important and difficult decisions, and these decisions must be made with the best available scientific information. By the nature of the associated problems, we anticipate that the organizational framework *must transcend traditional group boundaries at GFDL*. We assert that no structure exists within the lab to facilitate this important process. Two possible structures are articulated below.

4.8.1 Perhaps a coordination team?

The OP team governs priorities for the FMS software framework. It works within the traditional group structure. Correspondingly, one can envision a Coupled Model Coordination Team (CMCT) whose primary goal is *To actively and vigorously coordinate and foster development of coupled models.* The CMCT will potentially overlap in membership with the OP team, and the OP and CMCT must develop a synergistic relationship. However, *the mandates and governance of the two teams should be independent.*

A proposal for the composition of the CMCT is to have it minimally consist of leaders, or their representatives, of the groups most actively involved or interested in coupled model development (e.g., E,G,M,O). At least the same number of non-group leaders will also be selected by the lab director for membership. Membership should be designed to provide a thorough cross-section of the key developmental *and* usage perspectives within the lab.

The CMCT will be chaired by one of its members. The chair is appointed by and reports directly to the lab director. This person is responsible for leading the coupled model development effort.

4.8.2 Perhaps a distinct coupled model development group?

How relevant is the present group arrangement for the new scientific and resource problems at hand? Arguably, it is not optimum and thus a reorganization is necessary. That is, as the space-time boundaries which have largely defined the different lab groups become blurred, the traditional group structures that have respected these boundaries should be reconsidered. This reconsideration is a reflection of the need to allow structures to evolve as the laboratory's scientific goals evolve. Notably, other labs (e.g., BMRC, NCAR, Hadley) have within the past decade organized or reorganized for the purpose of meeting the needs of their new scientific challenges.

A viable alternative to a coordination team is to directly place its decisions into the hands of a *new* group whose central purpose is to achieve the coupled model development goals stated in the previous section. Notably, a coupled model development group could evolve naturally from the CMCT mentioned above.

4.8.3 Perhaps an open structure?

If a minimal restructuring is desired, one may view the promotion of a new group in the context of allowing scientists to *straddle more than one group*. In particular, rotation in and out of the new coupled model group when appropriate seems a viable and useful possibility. Such a *flexible organizational structure*, which is implicitly in effect for certain laboratory scientists today, would be compatible with the flexible modeling paradigm that is aimed for with FMS.

4.9 How to empower the coupled model development?

Whether the CMCT or separate group is conceived, the fundamental problem remains how to empower the effort. The current group structure in the lab promotes the partitioning of computational and human resources. However, the coupled model effort conceived here and in the White Paper necessitates a coordinated, collegial, committed, and focused effort between groups. What happens when the desires of a particular group conflict with the needs of the overall coupled model effort?

Clearly there should be debate in an open forum based on science and vision. Given the broad nature of this effort which transcends the group boundaries, the participants in this debate should routinely include more than the traditional group leaders. Indeed, we contend that much of the current problems can largely be overcome if frequent candid and open discussions take place amongst the group leaders and selected representatives of the various efforts. The present "Lab Council" seems a useful start. However, its current composition lacks certain representatives whose voice in coupled modeling matters is essential.

We recognize that debates over resources often lead to the drawing of hard-lines. If in these circumstances the allocation of resources ultimately remains in the hands of an individual group leader, as is the current situation, then the *status quo* will remain. Arguably, the needs of the coupled model development may then be jeopardized. This is not an easy subject to address. Should the group leaders give up power in this situation to the CMCT or to a coupled model group? Should the lab director be burdened with mediating all conflicts? For trans-group coordination to be facilitated, these difficult issues must be debated *and resolved*. We contend that the *status quo* is not the best outcome of such debates.

5 Summary and concluding remarks

5.1 Climate focus

We agree with the White Paper's desire to focus on only two grand themes. We have focused on the climate theme here. In particular, we believe that the focus of coupled model development should be to use FMS to build models aimed at addressing questions of climate change. The result should be a central trunk model from which closely linked branches can grow that consider issues of predictability, fundamental processes, parameterizations, and algorithm development. Other healthy trees, such as high resolution ocean and atmospheric modeling, hurricane forecasting, should also be grown and maintain a synergistic relation with the climate goal. Without such a focus, the current separate efforts of the groups will remain sub-critical.

5.2 Key questions must be discussed and resolved

Key questions were highlighted in Section 4. They need to be addressed and resolved if substantive progress is to be made to empower coupled climate modeling. We strongly feel that the way to articulate answers to these questions is to incorporate voices from central participants in the coupled model process. Notably, these voices include leaders of the traditional groups *as well as selected non-group leaders.*

Given our difficulties reaching consensus on some issues, we are nonetheless optimistic that if a focus remains on the goals of the White Paper, and participants agree and act on these goals, then the organizational and resource issues will naturally follow. At the least, we hope that this document provides a vehicle for further discussions, and provokes a candid and honest debate which covers philosophical, scientific, and resource issues. *The outcome of this debate should be the development of a sound and detailed action plan for coupled model development to which all participants are fully committed and empowered.*

5.3 What is next?

This document represents the outcome of meetings amongst the team members over the course of early Autumn, 2000. We will present it to a selection of group and non-group leaders on October 31 for their input and suggestions. Much of how we proceed in the future depends on the ensuing discussions. Given the importance of these discussions to the lab as a whole, we propose to present the salient points during a lunchtime seminar/discussion sometime near the end of 2000. Over the course of discussions and debates, we aim to foster the means to resolve the various issues presented here, and others which may arise. With help from others outside this team, we hope to develop an *action plan for coupled model development* which will coalesce various GFDL model development efforts.

A Some model metrics and capabilities

This extended appendix presents basic phenomenology and capabilities which are aimed for the main trunk of the coupled model and its components. It represents a start in a long process towards realizing our model aims. The items here comprise many of the essential metrics which determine the suitability of the model as a tool for studies at GFDL over the life-time of the next generation coupled model. Although it is difficult to be comprehensive both in listing items and providing motivation, and priorities remain to be debated, articulating these goals is a useful and necessary exercise if only to provoke a scientific debate.

B Atmospheric model

Atmospheric model metrics may be separated into "AMIP metrics" and "coupled metrics." The AMIP metrics are well established and documented. They comprise the primary metrics which should be considered when tuning the new atmospheric model. After realizing a model that lives in the upper 25% of the traditional AMIP metrics relative to other models, the model's performance under coupling should then be assessed. Experience indicates that good AMIP performance is necessary, but not sufficient, for good coupled performance. In general, realizing a model that is respectable in a coupled context is far more difficult than in an AMIP context. Indeed, this "Coupled Model Rule of Thumb" has proven true for all component models.

Piecing the various FMS modules together into a coherent atmospheric model remains a highly nontrivial task. It is anticipated that this effort will require some 2-3 years (i.e., completion between Fall 2002 and Fall 2003). Achieving this time table will require a concerted and focused effort by numerous lab scientists.

B.1 Resolution and cost

Given the projected computational resources to be made available over the next 2-3 years, it is feasible to assume that the atmospheric trunk will have resolution close to T42/R30/N45 horizontal resolution with 30-50 vertical levels. This resolution is considered respectable for purposes of the centennial length climate integrations (O and G groups), for many process oriented studies (M-group), and for baseline ENSO prediction (E-group). Although of use for many purposes, branches are certainly envisioned which will test the resolution choices and perform process studies aimed at focusing on a particular aspect of the main trunk simulations. Nonetheless, this resolution, combined with a suitable suite of physically based parameterizations with good numerical representations, should be capable of maintaining a high level of integrity based on the metrics described below.

B.2 AMIP metrics

AMIP metrics are well documented and there is experience at GFDL in assessing a model's AMIP performance. Particular attention should be focused on phenomena important for seasonal to decadal fluctuations, such as the structure of the storm tracks, PNA, NAO, MJO, monsoons, tropical storms, Arctic sea level pressure, large-scale precipitation, temperature, clouds, and circulation patterns.

B.3 Coupled metrics

The following lists some of the key metrics which are required of the atmospheric model when coupled to a dynamic ocean, sea ice, and land surface model.

- Upper atmosphere radiation fluxes: The top of the atmosphere long and short wave fluxes must compare favorably with observations (ERBE and CERES). In particular, a global top of the atmosphere radiative balance is crucial for climate change simulations.
- Surface atmospheric fluxes: Fluxes from the atmosphere's lower boundary should compare favorably to observations. These fluxes include long wave, short wave, latent heat, sensible heat, moisture, and momentum.
- Large-scale precipitation, temperature, clouds, and circulation patterns should compare well with observations. The following items in particular are crucial:
  - Poleward heat and moisture transport in each ocean basin should agree with observations and be compatible with the implied fluxes needed by the oceans. This metric has been identified by the Hadley Centre as essential for maintaining a relatively drift-free centennial-scale climate simulation.
  - The sea level pressure in the Arctic should be improved relative to super-source as this is important when running with the new dynamical ice model (see Section D).
  - An improvement in the simulation of surface climatology over North America is essential for the US climate assessment process.
- Tropical circulations:
  - The MJO is thought to be important for decadal fluctuations in tropical storm intensity, ENSO variability, storm-tracks, and large-scale precipitation.
  - Representation of respectable tropical storm climatology and variability. Note that tropical storms and MJO are quite sensitive to the tuning of convective schemes. Typically there is a tradeoff between climatology and variability.
  - Proper winds stress patterns in the Tropical Pacific are crucial for representing a realistic ENSO cycle.
  - Monsoon circulations

B.4 Capabilities

In addition to the previously listed phenomenological metrics, the following represent desired computational and numerical capabilities of the model.

- Tracer transport: The representation of tracer transport must remain quasi-positive definite in order to allow for studies of chemistry, moisture, and other such processes as have been of central interest to the atmospheric processes group.
- Conservation: heat, water, and tracers should be conserved within an amount suitable for climate simulations.
- Clouds: The model should possess a prognostic bulk cloud microphysics scheme.
- Convection: The model should employ a mass flux based convection parameterization.

- Planetary boundary layer:
  - Improved inversions
  - Output of SAT from the vertical diffusion code
- Radiation code:
  - The model will possess a diurnal cycle.
  - Input of trace-gas and aerosol time series should be routinely handled.
  - Clear-sky fluxes should always be computed and archived.
  - Overall cost of the radiation scheme should be no more than 15% of the total atmospheric model component when running with a diurnal cycle.
- Orography which can change in time will afford use of the model for paleo-studies.
- Maintaining backward compatibility of the code for some 15 years will afford for continued studies with the model and allow comparisons with the most recent model generation.

B.5 Spectral and B-grid cores

At this time, there has been no decision made regarding the suitability of a spectral versus a B-grid core. Fleshing out the merits of either should be a high priority over the next year. It appears essential that for the current coupled model effort to succeed as set out in the White Paper, *only a single core should be in use for the trunk.*

C Ocean model

Over the past one-two years, there has been an effort to develop the configuration of the next generation ocean model of use for *both* the E and G groups. This effort has yet to conclude, and will likely require at least another year or two. Nonetheless, there is some consensus regarding the basic metrics and model configuration to be used for the main trunk. It is notable that by combining efforts, the E group will incorporate the Arctic ocean along with dynamic sea ice, whereas the G group will employ enhanced horizontal and vertical resolution compatible with the needs of resolving a respectable ENSO. Use of the same ocean model by these two groups, and hopefully by others as well, is a primary aim of the next generation coupled model effort.

C.1 Metrics

The following basic metrics have been identified as important for this effort.

- Realistic ACC flow
- Poleward heat and moisture transport in each ocean basin compatible with observations and with that required by the atmospheric model
- Water mass and passive tracer structure compatible with observations.
- Respectable representation of the equatorial current structure in order to allow for a high fidelity simulation of ENSO
- Respectable Gulf Stream and Kuroshio structures.

C.2 Configuration

The ocean model will be a version of MOM 4. Consistent with the above goals, the following items are considered essential numerical aspects.

- Spherical grid of 1-degree zonal resolution between $81^\circ S$ to $60^\circ N$ using roughly Mercator resolution with enhanced meridional resolution within 15° of the tropics. Poleward of $60^\circ N$, the grid will become bi-polar with the coordinate singularities located over land regions. This model will use no high latitude filtering.
- 40-50 vertical levels, with enhanced resolution in the upper 200m as used in the IRI/ARCs ENSO model. This resolution is needed to allow for a mixed layer scheme, keep the vertical tracer gradients resolved, represent the interaction between currents and topography, and reduce the overall amount of spurious diapycnal mixing associated with numerical truncation errors.
- Partial bottom cells
- Explicit free surface
- Explicit fresh water fluxes (not virtual salt fluxes)
- Quick or 4th order tracer advection
- Isoneutral tracer diffusion, Gent-McWilliams skew-diffusion, and a flow dependent diffusivity.
- Vertical background diffusion as used in the IRI/ARC model, which uses Bryan-Lewis going from around $0.05 cm^2/sec$ in the upper ocean to $1.0 cm^2/sec$ in the intermediate to deep ocean.
- KPP mixed layer scheme
- Smagorinsky Laplacian friction with added background outside of the tropics to ensure full resolution of the boundary currents.

Preliminary versions of this model have been found to be roughly 2-6 times more expensive than the ocean component of the R30 coupled model.

D Sea Ice Model

Over the past few years, Winton has developed a new dynamic sea ice model SIS (Sea Ice Simulator). This model has matured physically, numerically and computationally so that it is compatible with FMS. Important aspects of this model which will be key to coupled modeling are

- Realistic dynamics (e.g., moves with winds and ocean currents)
- Snow cover available on sea ice
- Multi-level thicknesses
- Ice salinity
- Heat and water conservation
- Generalized curvilinear coordinates for use with the spherical and bi-polar grid of the ocean

E Land Model

Milly has developed the LaD model within the FMS framework. Important aspects of the land model for use in the coupled model are the following

- Transpiration
- Rivers, with time lag between precipitation and when it enters ocean
- Multilevel river model
- Soil freezing

F Key coupled metrics and capabilities

Some of the following have been mentioned previously, but it is useful to summarize them again.

- It should run for 100s years stably under un-forced greenhouse gas situations *without* the use of flux adjustments. This is a substantial goal. The Hadley Centre has proven themselves capable of achieving this goal, although their efforts have not been reproduced when moving to higher resolution (e.g., 1/3 ocean drifts when coupled). The feasibility of realizing this goal in the next generation GFDL coupled model will need to be frequently assessed. At the least, the magnitude of the adjustments *must* be largely reduced relative to the current generation of coupled models.
- The traditional GFDL leg 1, leg 2 approach to initializing coupled models is very time consuming and expensive. Ideally, "cold" or "lukewarm" starts will need to be developed in order to reduce the spin-up time. Again, the Hadley Centre has proven that such an approach can work, though many factors are involved which make it difficult to reproduce under new model configurations.
- The model's representation of ENSO should be of very high quality. ENSO is a substantial climate signal which has traditionally been severely under-represented in the climate change models. This must not continue with the next generation models.
- Diagnostics are essential for understanding the multiple dynamical regimes in this model. Hence, all components of the model equations in all component models should be output for budget analysis.
- To better allow process studies and to isolate important sub-components, the trunk coupled model should have ready switches which allow for turning off components. For example, there should be available a mixed layer ocean to replace the fully dynamical ocean. Conversely, an energy balance atmosphere should readily replace the dynamical atmosphere.
- All fluxes, tracers, etc should be conserved to within the necessary numerical accuracy.

G Miscellaneous models

The atmosphere, ocean, ice, and land models are largely under development by folks at GFDL. They are clearly needed for the next generation coupled model. Other models which should be considered for the *next* next generation coupled model include

- Glacier model. If the Greenland and Antarctica ice shelves potentially may melt over the course of the next century, they should be simulated.
- Vegetation model. Vegetative processes provide a potentially large feedback on the climate system under enhanced greenhouse gas scenarios.
- Carbon model. Sarmiento's group should be entrained in this effort soon, with their use of a possibly lower resolution version of the next generation coupled model.
- Inland seas and lakes may best be handled by a one-dimensional model rather than the ocean model. Lake models may need to be designed for this purpose.