A Strategic Plan for the Whole Atmosphere Community Climate Model (WACCM)

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Science Plan

Executive Summary: Scientific Objectives of the Whole Atmosphere Community Climate Model (WACCM)

The goals of the WACCM project are to:

- **a)** Develop a state of the art numerical model that will serve the needs of the scientific community at large in a unified software engineering framework.
- **b)** Use the WACCM model to understand the couplings between atmospheric layers, the role of chemical and physical processes in defining these couplings and the interaction between the Earth's atmosphere and our Sun.
- **c)** Predict the evolution of ozone and other forcing agents in the middle atmosphere.
- **d)** Support observational campaigns to help interpret those data.

The WACCM is a project of the Earth and Sun Systems Laboratory (ESSL) at the National Center for Atmospheric Research (NCAR). It unifies the modeling efforts of three NCAR divisions: the Atmospheric Chemistry Division (ACD), the Climate and Global Dynamics (CGD), and the High Altitude Observatory (HAO). Using the framework designed for the NCAR Community Climate Model (CAM), WACCM provides a unified modeling effort that combines climate, chemistry and physics of the upper atmosphere.

The major tasks facing WACCM in the next 5 years are:

- **a)** Improved understanding and description of past and future chemical and physical variability: water vapor, ozone, polar mesospheric clouds.
- **b)** Improved understanding of key dynamical variability: Tropical oscillations, tides, stratospheric warmings.
- **c)** Raise the model upper boundary to represent completely the thermosphere
- **d)** Support an ever increasing community of users.

These goals and plans are discussed in detail on pp. 3-12. Resources required to implement the Science Plan are given on p. 17.

1. Introduction

At the beginning of the 1970's knowledge of the middle (the layer between 10 and 100 km) and upper atmosphere (thermosphere and ionosphere) was derived mainly from relatively sparse ground-based observations; theoretical treatments of middle/upper atmosphere dynamics and chemistry were incomplete at best; and computer modeling was rudimentary. The advent of satellite-borne instrumentation in the 1970s provided the first truly global views of the middle/upper atmosphere and stimulated the development of comprehensive theories to explain the observations. At the same time, rapid increases in computing power and advances in computational fluid dynamics led to the development of more detailed theories and realistic numerical models. The discovery of the ozone hole in 1985 stimulated the study of middle atmosphere chemistry, which led to a successful explanation of the basic mechanisms of ozone loss in the lower stratosphere.

In spite of these rapid advances, much remains unknown about the middle/upper atmosphere. During the 1990s, observations made by the various instruments onboard the UARS and TIMED satellites, together with increasingly sophisticated ground-based radar and lidar stations, revealed a range of new phenomena such as mesospheric thermal inversions (Sassi et al, 2002), a tertiary ozone maximum (Marsh et al., 2001), and a rich spectrum of tides (both migrating and non-migrating) and atmospheric normal modes that interact with chemical trace species (Oberheide and Gusev, 2002, Garcia et al, 2005). In the stratosphere proper, the behavior of water vapor and its secular trend has attracted renewed attention (Randel et al., 2004), as has new evidence of the apparent link between the state of the winter stratosphere and the tropospheric Arctic oscillation (Baldwin et al, 1994). In the mesosphere and lower thermosphere, evidence of its feedback interactions with the stratosphere and the troposphere are also found in numerical simulations (Liu and Roble, 2005). The response of the middle atmosphere to solar variability, although not a new problem, remains incompletely understood, as does the role of coupling in communicating such response to the troposphere (Labitzke, 1987; van Loon et al., 2004).

Recent studies have also revealed that the lower atmosphere variability is critical to the understanding of upper atmospheric variability and space weather. Apart from driving the mesospheric circulation away from radiative equilibrium, the atmospheric gravity waves can significantly affect the amplitude, phase, and vertical propagation of tides and planetary waves in the mesosphere and lower thermosphere (Meyer 1999; Liu and Hagan, 1998; Sassi et al., 2002; Ortland and Alexander, 2006). Observations have shown that non-migrating tides can be as strong as the migrating components in the mesosphere and lower thermosphere (Oberheide et al., 2006). The excitation of these non-migrating tides is thought to be related to tropospheric latent heat release and interactions between migrating tides and planetary waves (Hagan and Roble, 2001, Oberheide and Gusev, 2002, Oberheide et al., 2003), but these processes are not well represented in current models. Rapid growth of planetary waves and stratospheric sudden warming can have profound impacts on the temperature and composition of the mesosphere and lower thermosphere (Liu and Roble, 2002), but there is still large discrepancy between numerical simulations and observations (Siskind et al., 2005), probably due to poor representation of gravity waves in models. Planetary waves are observed in the ionospheric F region, which may be an indication of coupling of the ionosphere and the middle atmosphere through the dynamo region (Mendillo et al., 2002). Plasma irregularities in the ionosphere, which have important space weather implications, are also believed to be connected to perturbations from the lower atmosphere, but are still poorly understood and poorly represented in current models.

The middle/upper atmosphere today presents exciting research challenges and opportunities for innovative ideas. Just recently it has been shown that the interpretation of tropospheric temperature trends (warming) is improved when the stratospheric trend (cooling) is accounted for in satellite retrievals (Fu et al, 2004). It has been argued that changes in radiatively active gases in the middle atmosphere (e.g., carbon dioxide and ozone) can impact natural modes of variability that couple the surface with atmospheric levels in the stratosphere (e.g., Thompson and Solomon, 2002). The seasonal and sub-seasonal coupling between the troposphere and the stratosphere is still highly debated (Perlwitz and Graf, 1995; Baldwin and Dunkerton, 2001). Mesospheric, thermospheric and ionospheric responses to increased greenhouse gases are expected to be large compared with those in the troposphere and stratosphere (Rishbeth and Roble, 1992; Qian et al., 2006; Marsh et al., 2006), and they will affect the drag on low-Earth-orbit spacecraft, lifetimes of space debris, and changes to ionospheric radio propagation conditions. Quantification of these effects requires detailed knowledge of the lower and upper atmospheric coupling.

NCAR has been committed to the development of numerical models to study specific aspects of the atmospheric general circulation, transport of constituents, and radiative and chemical processes in various atmospheric regions for many decades: the Community Atmosphere Model (CAM) has been developed in CGD, the Model of Ozone and Related Tracers (MOZART) in ACD, and the Thermosphere-ionosphere-mesosphere-electrodynamics general circulation model (TIME-GCM) in HAO. However, the aforementioned challenges in middle/upper atmospheric research demand an integrated model to treat the whole atmosphere consistently in order to understand the complex interactions. The integration of these model components allows the study of solar influences in the stratosphere that can be mediated by chemical changes and downward transport from the lower thermosphere (Schmidt et al, 2006; Marsh et al, 2006; Matthes et al, 2006). Higher model tops, moreover, pose new questions regarding the role of the mesosphere in controlling the structure of the stratosphere (Garcia and Boville, 1994), or even of the troposphere (Norton, 2003), particularly when some of the most important physical processes of the middle atmosphere are not resolved but are instead represented by *ad hoc* parameterization schemes (Sassi et al, 2007).

2. The Whole Atmosphere Community Climate Model

The Whole Atmosphere Community Climate Model (WACCM) is an inter-disciplinary project that brings together physical components or models from three ESSL divisions: the physics and dynamics of the lower atmosphere (CAM, from CGD); the chemistry of the middle and upper atmosphere (MOZART, from ACD); and the physical processes of the upper atmosphere (TIME-GCM, from HAO). The scientific goal of WACCM is to study the couplings (chemical, dynamical, and radiative) among atmospheric layers (Roble, 2000). From the first version of WACCM, which did not include interactive chemistry (Sassi et al., 2002), through an intermediate version with limited interactive chemistry (Sassi et al., 2005), to the current, fully interactive model (Garcia et al., 2006), the project has grown from an in-house effort to a small community of users and developers both inside NCAR and from universities, government laboratories, and non-profit research groups. The project is also hosting a number of post-docs and graduate students from the US and abroad.

Since the inception of the project, ~20 papers have been published using WACCM results (see http://waccm.acd.ucar.edu/Pubs/index.shtml). WACCM has also figured prominently in international activities, such as the Climate-Chemistry Model evaluation (CCMVal) exercise, sponsored by SPARC; and WACCM scientists have contributed to the 2006 WMO Ozone Assessment. A high level of engagement of WACCM in the community is beneficial to the project, because it promotes the development of WACCM and fosters the exchange of new ideas and concepts.

3. Near-Term Research Questions

We highlight below the most relevant questions now under study, or to be studied in the near future:

a) ***How important are stratospheric chemistry and sea surface temperature to explain the temperature changes in Antarctica?*** Recent surface warming over Antarctica has the potential to produce marked climate effects because of the impact of continental ice sheet loss on sea level. Some aspects of the Antarctic warming have been linked to ozone depletion in the lower stratosphere (Thompson and Solomon, 2002). Another hypothesis, however, suggests that the warming of tropical oceans could play a significant role in Antarctic warming (Hurrell and van Loon, 1994; Grassi et al, 2006). WACCM will be used with fully interactive ozone chemistry and observed SST to investigate the combined roles of stratospheric ozone loss and tropical SST increases. We will use diagnostics of the Southern Annular Mode (SAM) to relate these forcing terms to the observed Antarctic temperature changes.

b) ***Is there a connection between the stratosphere and the troposphere on seasonal time scales?*** Recent studies show an apparent connection between the state of the winter stratosphere and the behavior of the tropospheric Arctic Oscillation (Baldwin and Dunkerton, 2001). Although plausible mechanisms linking the two regions have been proposed, the existence of the link remains speculative. Early work with WACCM suggests that extreme winter stratospheric states do influence the subsequent behavior of the Arctic Oscillation. The fully interactive WACCM will be used to evaluate this connection in different climate states, allowing for changes in forcing agents and boundary conditions.

c) ***Does the middle atmosphere matter to tropospheric climate sensitivity?*** While there is circumstantial evidence that the stratosphere matters to seasonal predictability in the troposphere, we do not know what role, if any, the stratosphere plays on climate time scales. A typical quantity used in tropospheric climate modeling is the climate sensitivity (Gregory et al., 2004), which measures the equilibrium surface temperature change in a double-CO2 scenario. WACCM will be run coupled to a mixed-layer ocean model and WACCM simulations with current level of CO2 and double that value will be compared to equivalent CAM simulations.

d) ***How is middle/upper atmospheric predictability affected by the lower atmosphere?*** WACCM is used to explore predictability in the context of the whole atmosphere (from the ground to the thermosphere) (Liu et al., 2007). From ensemble WACCM simulations, it is found that the growth of differences in initial conditions becomes apparent first in the upper atmosphere and progresses downward. The growth rates of the differences change in various atmospheric regions and with seasons, and correspond closely with the strength of planetary waves. The growth rates, on the other hand, are not sensitive to the altitudes where the small differences are introduced in the initial conditions or the physical nature of the differences. Furthermore, the growth rates are significantly reduced if the lower atmosphere is regularly reinitialized, and the reduction depends on the frequency and the altitude range of the re-initialization. The implications for the feedback interactions between the lower and upper atmosphere and for the data assimilation of the middle and upper atmosphere are being investigated.

e) ***How can we better understand the observed trends of minor species in the stratosphere?*** Water vapor exhibited trends in the last 25 years that are not consistent with methane and temperature changes; at this point, there is no theoretical understanding for these observations (see Garcia et al., 2006). The implications of a poor description of water vapor in the stratosphere are serious, since water vapor is central to HO_X chemistry and to heterogeneous chemistry on aerosols. A speculation is that the entry of water vapor into the stratosphere through the tropopause is not well represented in numerical models. WACCM will be used to investigate processes related the transport and dehydration of water vapor near the tropical tropopause, and ozone transport in middle and high latitudes.

f) ***Evaluation of chemistry and support for satellite missions.*** The goals of TIMED and HIRDLS programs are to elucidate the circulation, photochemistry and energy budget of the middle atmosphere. Through participation in these programs, access to data and numerical simulations, WACCM scientists not only support these satellite missions, but also are using them to evaluate and validate WACCM chemistry and dynamics. An "off-line" version of WACCM has been developed for this purpose that constrains the troposphere and lower stratosphere to analyzed meteorological fields. This permits campaign-style model/data intercomparisons.

g) ***Can we improve the definition of tropospheric sources of gravity waves?*** It is well known that a spectrum of unresolved gravity waves is necessary to close the momentum budget above the stratopause. Several studies (e.g., Garcia and Boville, 1994) have shown that the importance of gravity waves can extend down to the lower stratosphere, and potentially influence climate aspects of the troposphere. The largest uncertainty regarding gravity waves is their tropospheric sources. WACCM is already implementing a scheme that links the spectrum of gravity wave to the model convection (Beres et al., 2005) and it has been shown that this scheme improves the simulation of the stratopause semiannual oscillation. However, other tropospheric sources, such as shear instability and frontogenesis, are not taken into account in WACCM. Moreover, improvements of orographically forced gravity waves are possible with the inclusion of a mountain drag scheme. These scheme improvements will allow WACCM to represent realistically the influence in the middle atmosphere of climate changes occurring in the troposphere.

h) ***Is there a connection between climate change and the occurrence of polar mesospheric clouds?*** The summer mesopause is the coldest place in the atmosphere and is the location where water vapor can freeze resulting in ice particles and clouds. Observations have shown a change in the occurrence and properties of polar mesospheric clouds, but this is not reflected in changes of temperature, which do not show a detectable trend. Another possibility is that increases in mesospheric water vapor (e.g., from methane oxidation) enhance the occurrence of clouds (Thomas, 2003; Shettle et al., 2002). While it has been suggested that climate change may impact the formation of clouds in the mesosphere, it is still debated whether changes in forcing agents from the lower atmosphere, or variability in solar inputs, or other unexplored mechanisms are responsible for the observed climatology. WACCM will be modified to calculate the formation of polar mesospheric clouds, and numerical simulations will be run to evaluate secular changes in the occurrence frequency of mesospheric clouds.

i) ***Tropical oscillations.*** The lack of a Quasi-Biennial Oscillation is a well-known deficiency of most middle atmosphere models. Recent studies have suggested that some parameterizations of convection that have more temporal variability along with increased vertical resolution (Giorgetta et al., 2002) produce a realistic tropical oscillations in some models. A realistic representation of the Quasi-Biennial Oscillation is also thought to be a critical ingredient to improve the model variability at high latitudes (Gray et al., 2004). In close collaboration with the developers of CAM, WACCM scientists will explore the implementations of different convection schemes. Once a viable candidate is found, the vertical resolution in the middle and lower stratosphere will need to be increased (to about 500 m) in order to resolve the tropical waves generated by convection.

j) ***Mesospheric/thermospheric tides and tropospheric forcing.*** The convection scheme used in the model and the model resolution are also believed to be critical in correctly resolving the tides in the middle/upper atmosphere. The mesospheric/thermospheric tides in current WACCM simulations are found to be weak compared with observations (Chang et al., 2006), and may be due to the relatively small variability of the Zhang/McFarlane convective scheme. The sensitivity of the tidal amplitude to model resolution is being examined by the TIME-GCM with regular and high resolution (5^o x 5^o, 2-gridpoints/scale height and 2.5^o x 2.5^o, 4-gridpoints/scale height, respectively). Evidence of tidal modulation by the tropical oscillations (QBO and SAO) is also found from observations, and the mechanism of such modulation is being investigated using WACCM.

4. Longer-term Studies

The WACCM group is also active in defining scientific priorities on longer time scales (~5 years). These are projects that require longer times to come to fruition, either because of the time required for model development, or because the science is not yet fully developed.

a) ***Model resolution.*** It has been shown that the simulation of tropospheric eddies is improved at horizontal resolutions near 1 degree or finer (Jablonowski and Williamson, 2006). We may ask, then, how an improved horizontal resolution will affect the climatology of the middle atmosphere, particularly in the lower stratosphere, which is critical for chemical and climate problems. Moreover, decreasing the grid size to few tens of kilometers would allow the resolution of a larger part of the gravity wave spectrum. Although it is unlikely that we will be able to abandon gravity wave parameterizations in the near future, and climate simulations are currently not feasible at resolutions finer than 1 degree, a comparison of short numerical integrations with observations will illustrate how well we are able to reproduce the part of the spectrum that we are currently parameterizing.

b) ***Gravity wave effects in the thermosphere/ionosphere.*** The very fast components of gravity waves generated from the troposphere can propagate into the thermosphere. These waves are thought to play an important role in inducing thermosphere/ionosphere variability and ionospheric irregularities. With the inclusion of physics-based gravity wave parameterization schemes in WACCM, and the increasing resolution of the model to directly resolve gravity waves, it is desirable to use WACCM to study the global distribution of these gravity waves and their variation over various temporal scales. The effects of these waves on the thermospheric tides, circulation, and heating, can be explored using WACCM. Recent theoretical studies also show that secondary generation of gravity waves due to wave breaking could be an important source of thermospheric gravity waves. The impact of these waves should be properly represented in WACCM, in conjunction with theoretical and mesoscale simulations.

c) ***Variability of tides and planetary waves and their influence on the thermosphere/ionosphere.*** WACCM simulations of tides account for day-to-day variability associated with variable tidal sources in the troposphere and interactions between planetary waves and tides along with planetary waves and gravity waves in the middle atmosphere. As the tides and planetary waves propagate into the thermosphere, or modulate the propagation of gravity waves into the thermosphere, they affect thermospheric/ionospheric dynamics and electrodynamics, and are an important source of upper atmospheric day-to-day variability. Understanding the relative role of this source of variability to the role of geomagnetic activity is an important problem in ionospheric physics. WACCM can be used to evaluate in great physical detail the sources, propagation properties, and ionospheric influences of tides. Understanding of these processes is essential for being able to interpret upper-atmospheric behavior and to contribute to the eventual development of forecast models. Furthermore, extensive observations of daily variations of the ionosphere and of geomagnetic variations associated with ionospheric electric currents, when compared with WACCM predictions, can be used to test whether WACCM contains the appropriate physics and parameterizations to simulate tides accurately. This information may ultimately be used in the data-assimilation version of WACCM.

d) ***Data assimilation of the mesosphere and lower thermosphere.*** A recent study explored the feasibility of mesosphere/lower thermosphere data assimilation using the ensemble Kalman filter (EnKF) method (Matsuo et al., 2007). It demonstrated that error growth in the assimilative model and its interaction with EnKF are crucial in controlling the quality of the assimilation. Because middle/upper models with forced lower boundary show little error growth (Liu et al., 2007), there is insufficient variance in the filter assimilation prior estimates. WACCM, on the other hand, displays robust error growth, and can be used to develop a data assimilation system for the mesosphere and lower thermosphere.

e) ***Climate interactions.*** The impact on tropospheric climate of a fully interactive chemistry-climate model extending into the middle atmosphere is already a short-term goal of the WACCM project, (see item **1*c*** above). However, those experiments do not take into account the role of the fully resolved ocean circulation combined with the effect of solar variability. Simulations with a full-depth ocean and solar variability represent a significant investment in time and resources, and a real challenge for a "whole atmosphere" model. However, such simulations will be needed to illustrate aspects of climate prediction that depend on the much slower response of the ocean circulation. For example: Are decadal changes in the SAM the result of slowly varying ocean circulation? Can climate change during the solar Maunder minimum be explained in terms of changes in solar irradiance? (see also **2*e*** below).

f) ***Simulations of the recent past: Maunder minimum.*** The Maunder minimum is the period between 1645 and 1715 when sunspots became very rare compared to other periods in the historical record. That period corresponds also to the so-called Little Ice Age, when some of the globe is believed to have suffered from anomalously cold winters (refs). WACCM, with its interactive chemistry and the ability to include the effects of solar variation, will be a useful tool to study the role of solar variability in determining the climate during those times.

g) ***Simulation of climate change in the thermosphere.*** As anthropogenic greenhouse gasses (primarily CO_2) warm the lower atmosphere, the upper mesosphere and thermosphere has been predicted to cool due to non-LTE emission from increased CO_2 levels [Roble and Dickinson, 1989]. This causes a contraction of the atmosphere and general reduction in density which has now been observed in drag effects on Earth-orbiting satellites (Emmert et al., 2004). The magnitude of this change over long periods, in combination with solar cycle modulation, has been estimated with global mean and TIME-GCM simulations (Qian et al.). WACCM will be used to address the full atmospheric response to anthropogenic global change in a consistent fashion extending from the ground to the exobase.

h) ***Simulations of the remote past: Major asteroid impacts.*** WACCM is currently being used by a group at the Planetary Science Institute in Tucson (AZ) to carry out a pilot study that will illustrate the thermodynamic and chemical consequences of re-entry material due to a collision between the Earth and a major asteroid (Melosh et al., 1990). It is believed, in fact, that ballistic re-entry material under those circumstances may have caused major changes to the temperature, radiation and composition of the atmosphere of about 60 MYA. Ultimately these effects resulted in the extinction of dinosaurs and worldwide changes to the fauna and flora of that time (Robertson et al., 2004). The pilot study needs to prove that the WACCM can handle numerically large heating rates and energy imbalances occurring in the mesosphere and lower thermosphere just a few hours after the impact.

i) ***Geo-engineering solutions to global warming.*** Recently, the somewhat 'old' idea of injecting sulfur-containing gases into the lower tropical stratosphere to produce an enhanced aerosol loading equivalent to half the loading of a large volcanic eruption (e.g., Mt. Pinatubo) has been proposed (Crutzen, 2006). This injection of sulfur-containing gases would be on the order of 1 MT of sulfur per year, and would be expected to reduce the solar heating of the troposphere, thus counteracting the effect of anthropogenic increases in greenhouse gases. The addition of sulfur would also increase the surface area densities (SAD) on which heterogeneous chemical processes occur that cause stratospheric ozone depletion. This increase in sulfate SAD would have the largest impact in the Arctic, where ozone depletion is not yet saturated. The heating of the lower topical stratosphere would also change the stratospheric circulation. Modeling these effects is necessary to better understand the consequences of such a large geo-engineering solution to global warming.

j) ***How deep into the Earth's atmosphere do the effects of geomagnetic and auroral variability penetrate?*** Auroral particle precipitation and electric currents flowing between the magnetosphere and ionosphere strongly impact thermospheric dynamics and composition. There is evidence that aurorally produced nitric oxide may be able to circulate down into the upper stratosphere near the winter poles and affect ozone chemistry (Garcia et al, 1984). Changes in thermospheric winds and temperature structure can influence the propagation and reflection conditions of atmospheric tides, gravity waves, and planetary waves, and could conceivably affect the structure of the waves at lower altitudes as well as in the thermosphere itself. Such impacts could, in principle, play some role in affecting the Earth's climate on time scales characterizing the solar activity cycles of eleven years and longer.

j) ***Coupling between the magnetosphere-ionosphere-thermosphere systems.*** The coupling between WACCM and the magnetosphere-ionosphere model will enable the consistent simulation of the magnetosphere-ionosphere-thermosphere system. Using the coupling model, we will investigate 1) the impacts of solar energetic particles on middle and lower atmosphere, 2) possible effects of geomagnetic storms on the mesosphere and middle atmosphere, 3) lower atmospheric effect (tides, planetary waves and gravity waves) on ionospheric conductivity and the coupling between the magnetosphere and ionosphere, and 4) energy and momentum dissipation during and after geomagnetic storms. As described in greater detail in the Appendix (p. 21) the project is engaging an effort to extend the model vertical domain to the limits of applicability of the equations of continuous fluids (approx. 500 km). This involves major updates to the physical components of the model, as well as a redesign of the equations of dynamics and thermodynamics to account for the spatial variation of physical constant (e.g., specific heat). It will provide the continuity of modeling across scales that was one of the stated goals to develop WACCM.

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Implementation of the Science Plan

WACCM was initially developed as an in-house effort with startup money provided through an opportunity fund grant by the NCAR Director in 1999. At that time (see Table 1) 1.3 FTE (Project Scientists) were supported and working on the development of WACCM; two-part time software engineers dedicated half of their time to WACCM development (1 FTE); and three senior scientists supervised the project at about 1/2 time commitment each, with occasional support from a couple of Scientist 3s (~ 1.7 FTE total). At the beginning, the project could not count on students and post-doctoral fellows to help develop the model from the ground up. More importantly, the project had no junior or mid-level scientists (Scientists 1 and 2).

Table 1: WACMM Personnel Resources (estimated FTE, except for postdocs and graduate students, for which the actual number is indicated)

	1999	**2006**
Senior Scientist, **Scientist 3**	1.7 FTE Boville (0.5), Garcia (0.5), Roble (0.5), Liu (0.1), Solomon (0.1)	1.0 FTE Garcia (0.5), Roble (0.2), Liu (0.2), Solomon (0.1)
Scientist 1, 2	none	1.0 FTE Gettelman (0.2), Richter (0.5), Marsh (0.3)
Project Scientist	1.3 FTE Kinnison (0.5), Sassi(0.8)	1.5 FTE Kinnison (0.5), Sassi(1.0)
Software Engineer 4	1.0 FTE Walters (0.5), Foster (0.5)	1.0 FTE Walters (0.5), Foster (0.5)
Postdocs and graduate students	none	2 postdocs; 2-3 graduate students (on average)

In 2006, the total FTE Senior Scientists and Scientist 3s is considerably smaller (~1 FTE total; this figure includes the loss of one key Senior Scientist and the partial retirement of a second one). The slight increase in Project Scientist FTE results from an increased commitment of just one person (Sassi, from 80 to 100%). The contribution from Scientists 1-2 reflects the part-time commitment of three persons in two Divisions (estimated at ~1 FTE total). Programming support (Software Engineers) is unchanged. The increased involvement of post-doctoral fellows and graduate students is the one major increase in personnnel between 1999 and 2006; however, it must be kept in mind that postdocs and graduate students contribute mainly to research and relatively little to model development or maintenance.

The science plan for WACCM described above includes the release of the model to the community, the participation in international activities and the support of a broadening outside community. For the release of the model, we will work closely with NCAR's Community Climate System Model (CCSM) group. As regards model development and maintenance, WACCM has part-time support, but we need this support to be explicitly recognized by NCAR/ESSL as a long-term project need. In addition, we believe that the participation of WACCM in international efforts, such as CCMval, the WMO Ozone Assessment, has been very fruitful and should be continued. The same applies to the participation of WACCM in the IPCC Assessment, and in other activities, such as the new SPARC project on dynamical variability, which is likely to start in 2007 (during the SPARC Scientific Steering Group in October 2006 this effort was officially sanctioned).

In view of these ongoing needs, and consistent with the Strategic Plan outlined above, we are requesting of ESSL the following:

1) Recognition of WACCM as a multi-disciplinary, inter-divisional ESSL project, or center;

2) Support of 1 FTE Software Engineer (at the 3 or 4 level) for WACCM development and maintenance;

3) Continuing support of the current number of FTE devoted to WACCM research in CGD and ACD (Scientists 1-2 and Project Scientists; a total of 1.7 FTE in CGD and 0.8 FTE in ACD);

4) Assignment of 1 FTE Associate Scientist or Project Scientist (level 1 or 2) to assist with model operation and analysis, maintenance of the WACCM website, and liaison with the outside user community;

5) Finally, because of the need for close collaboration with CGD scientists in model development, a set of secondary offices at the Mesa Lab, to be shared among the members of the WACCM group who are located on other campuses.

Note that items 2) – 3) do not constitute an increase of resources for WACCM; what we seek instead is official recognition by NCAR/ESSL that this level of support is the minimum required to maintain a viable program. Only item 4) represents a new personnel resource, one that we believe is essential as the model becomes widely used as a community tool. We note also that the WACCM project lacks strong scientist-track representation at CGD after the loss of Byron Boville. Ideally, Byron's position should be filled by an established scientist with an interest in the middle atmosphere and the coupling of chemistry and climate, who would dedicate a significant fraction of his/her time to WACCM research and development.

Appendix

A goal of the original WACCM proposal was to provide a unified modeling framework for simulations of the thermosphere and ionosphere, to the altitude where the equations of continuous fluid dynamics cease to be valid (~500 km). This effort represents a grand challenge for the project, not solely from the point of view of the implementation of new physical schemes, but also from a software engineering aspect. The equations controlling the dynamics, thermodynamics and transport need to include the changes of mass occurring as a result of changes in composition, and dynamical coupling with ionospheric processes must be included. HAO has some limited internal and external resources to initiate this development, but it is expected that the overall effort will extend over several years.

a) ***Major species diffusion and transport.*** In the atmosphere the minor constituents can be assumed to diffuse separately through the background gas. For major thermospheric constituents (N_2, O_2, and O) this assumption does not hold, and previous studies indicate that the effect of major constituent diffusion becomes important above ~110 km. WACCM v. 3 does consider the molecular diffusion of minor constituents, but not the major ones. When extending the upper boundary of WACCM, the major constituent diffusion will be implemented.

b) ***Thermodynamic parameters.*** Above the homopause (~100 km), it is necessary to consider the change of thermodynamic parameters (specific heats and gas constants) as well as the mean molecular mass as functions of composition, so these parameters become 3D arrays instead of fixed constants and should be updated at each time step. The routines where these parameters are used in physics and dynamics modules have been identified; in the finite volume dynamic core (currently used by WACCM) the conservative mapping scheme must be modified as a result of the variation of these parameters.

c) ***Improvements to auroral precipitation, convection, and ion-neutral chemistry.*** Ionization parameters and ion-neutral chemical reactions have been incorporated into the WACCM time-dependent chemistry in a simplified manner that should be updated for extension into the upper thermosphere. The auroral precipitation module needs to be re-written and updated, the correspondence to the convection pattern verified, and the result for heating rates, odd-nitrogen chemistry, and related auroral phenomena validated. These improvements will provide the robust high-latitude forcing in WACCM that is necessary for realistic studies of the penetration of solar geomagnetic storm effects. Ultimately it will be desirable to have an interface from Assimilative Mapping of Ionospheric Electrodynamics (AMIE) specification fields into WACCM.

d) ***Inclusion of ambipolar diffusion.*** Ambipolar diffusion along the geomagnetic field and electrodynamic drifts perpendicular to the field can transport O^+ over significant distances during the lifetime of the ion. Initially, the formulation of O^+ transport used in the TIME-GCM will be adapted to WACCM. As a future project, O^+ transport in a coordinate system aligned with the geomagnetic field will be tested for use with WACCM. This would have the advantage of calculating transport more accurately, especially in the equatorial region, and of creating a more realistic upper boundary condition on O^+ by facilitating the calculation of interhemispheric ion transport along field lines and the storage of ions in the plasmasphere.

e) ***Ion and electron energetic.*** Ions and electrons in WACCM currently have the same temperature as the neutrals. In reality, the temperatures diverge in the upper ionosphere. Addition of the ion energy equation is relatively straightforward, but the electron energy equation requires careful treatment of the sources and sinks of photoelectrons and their ability to transport energy over long distances parallel to the geomagnetic field.

f) ***Calculation of electric fields and currents associated with the ionospheric dynamo.*** Electric fields, now included in WACCM in the form of an empirical model, respond to changes in thermospheric winds and ionospheric electron densities. The electric field affects both the transport of ions and the exertion of the ion-drag force on the neutral dynamics. A fully physical simulation model should be able to calculate electric fields self-consistently, as is done in the TIME-GCM. This capability is essential for studies of the impact of upward propagating gravity waves and tides on the ionosphere-thermosphere system. The implementation of the self-consistent electric field calculation in WACCM will entail developing efficient means of transferring information between separate geographic and geomagnetic grids, which is non-trivial in a parallel-computing environment.

g) ***Coupling to magnetospheric models.*** The Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model under development at HAO currently uses the TIE-GCM for its atmospheric component. Our ultimate goal is to extend this model to the TIME-GCM and to WACCM using a consistent coupling framework.