



# **HIGH ALTITUDE OBSERVATORY**

**National Center for Atmospheric Research**

## **STRATEGIC PLAN 2011-2015**

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# 1. Introduction

This is the High Altitude Observatory (HAO) Strategic Plan for 2011–15. It results from substantial input from HAO staff, at an all-staff retreat and then through detailed work in working groups and via further consultation, and from broad consultation with the wider community (including members of our External Advisory Committee and our affiliate scientists), the National Science Foundation (NSF), and with the directorate of the National Center for Atmospheric Research (NCAR). It is meant to be an *actionable* plan, in that it will direct the investment of efforts and resources in the Observatory in the next several years, and we will judge our progress and success against the elements of this plan. It is also a living plan, so that although it looks forward on a five-year timescale, it is intended that it will be revisited and renewed halfway through that period.

The scientific program of HAO is solar-terrestrial physics, broadly interpreted. By this we include solar physics, physics of the heliosphere, the study of geospace and space weather, and the physics of the Earth's magnetosphere and upper atmosphere. Linked to the program of the rest of NCAR, and that of the NCAR Earth System Laboratory (NESL) in particular, this provides coverage of the Sun-Earth system from the solar interior right down to the surface of the Earth. The scope of our science includes the study of other stars and other planets insofar as these further the understanding of the Sun-Earth system.

The ends towards which we conduct this scientific program are expressed in our mission and vision which are set out below. The manner in which HAO will realize its mission and vision over the next five years is then articulated in the rest of this strategic plan. We believe that this plan recognizes the legitimate interests of our varied stakeholders: our primary sponsor, the NSF; other government agencies, particularly NASA; the world-wide solar-terrestrial physics community; the universities; the rest of NCAR and UCAR; our own staff, visitors and students; and the wider public.

## Mission and Vision

It is the **mission** of HAO to understand the behavior of the Sun and its impact on the Earth, to support, enhance, and extend the capabilities of the university community and the broader scientific community, nationally and internationally, and to foster the transfer of knowledge and technology.

This mission is given fuller expression in the following statement of HAO's vision.

It is HAO's **vision** to:

- Perform world-leading science to understand fundamentally and with predictive capability the sources and nature of solar and geospace variability;
- Provide scientific leadership and facilities to serve the wider community in common pursuit of these science objectives, and both support and benefit from the NCAR community;
- Support the education and training of early-career researchers in solar-terrestrial physics and instrumentation;
- Provide advocacy for solar-terrestrial physics, promoting its results, and articulating its societal importance, to the rest of NCAR, the NSF, the university community, and the public.

## HAO within NCAR

HAO is part of NCAR, and its constitutional position in NCAR is analogous to that of the other NCAR laboratories. HAO's role as the "solar-terrestrial laboratory" of NCAR is to look outwards from the Earth, studying the Sun-Earth system from the Earth's upper atmosphere through the heliosphere and solar corona all the way to the Sun's interior. The Observatory's mission and vision are well aligned with those of NCAR as a whole. Indeed there is a very close match between the strategic imperatives that we identify below and the imperatives articulated in the NCAR Strategic Plan: promoting innovation and creativity within the organization and in the larger community; providing capabilities for more accurate prediction and attribution of changes; advancing world-leading models and theory development; providing observational facilities; developing and transferring scientific applications, technologies and information; and contributing to the education of students and training of early-career scientists. HAO's strategic imperatives, as those of NCAR, are also well aligned to support the NSF's mission, including conducting and supporting basic scientific research, strengthening scientific research potential, supporting education and training, and informing policy formulation.

Interactions between HAO and other parts of NCAR take place on various levels. Amongst the most important of these interactions, members of HAO and NESL work together on scientific projects and on developing community models, notably the Whole Atmosphere Community Climate Model (WACCM). In its development of instrumentation projects, HAO frequently benefits from the workshop facilities and expertise of the Earth Observing Laboratory (EOL). HAO scientists also make substantial use of the computational facilities provided by the Computational Information Systems Laboratory (CISL), as well as having scientific interactions with scientists in CISL's Institute for Mathematics Applied to Geosciences (IMAGE). Naturally, HAO staff members serve on numerous NCAR committees. We also work

in partnership with the Education & Outreach section of the University Corporation for Atmospheric Research (UCAR) in furtherance of our aim to support education and to inform the wider public. Notwithstanding these existing links, the Observatory is committed to finding further opportunities to communicate its science and vision to the rest of NCAR and to foster further collaborations and interactions that advance NCAR's mission and vision and benefit the wider community. Many opportunities are identified in the program frontiers presented in this strategic plan.

## **HAO and the Broader Community**

To carry out its mission and follow its vision, HAO interacts closely with the broad solar-terrestrial community. Because the scientific problems are so complex, it is imperative that collaborative, community-based approaches are employed. HAO works closely with researchers in the solar-terrestrial physics community throughout the world on basic research, observing programs, and instrumentation efforts, helping to develop and augment the capabilities of a broad array of scientific disciplines. HAO supports the solar, space, and upper atmospheric research communities by developing and maintaining community observing facilities, instruments, databases, and models. HAO's long-standing visitor program fosters scientific interaction, collaboration, and exchange. HAO's scope and breadth of activities enables the Observatory to effectively bridge gaps between diverse scientific disciplines in the USA and in many countries active in solar-terrestrial research. Collaborations are maintained with an extensive community of researchers through the NSF programs for Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR), Geospace Environment Modeling (GEM), Solar, Heliospheric and INterplanetary Environment (SHINE), and Space Weather, and through other national and international projects such as NASA's Living With a Star (LWS) program. HAO also works with researchers in the planetary and astrophysics communities to better understand the Earth and Sun through comparative studies of other planets and stars.

Observations obtained with the instruments of HAO's Mauna Loa Solar Observatory (MLSO) and distributed via the web provide researchers with a daily picture of the physical condition of the solar atmosphere. HAO builds community instruments, such as the Advanced Stokes Polarimeter which is now upgraded to the Spectro-Polarimeter for the Infrared and Optical Regions (SPINOR), available to any qualified user to make solar vector magnetic field measurements. These users receive technical and data-processing support from HAO staff, including support of the Community Spectro-Polarimetric Analysis Center (CSAC). HAO is collaborating with the Universities of Hawaii and Michigan to develop the COronal Solar Magnetism Observatory (COSMO). A major solar facility development for this decade is the NSF-funded Advanced Technology Solar Telescope (ATST) led by the National Solar Observatory (NSO). HAO is co-Principal Investigator on ATST and is

designing the Visible Spectro-Polarimeter (ViSP) instrument, which is planned to be deployed at the time of ATST first light. It is also envisaged that HAO and CSAC will play a major role in interpreting the polarization data from ATST. HAO also operates optical instruments at the NSF Polar Cap Observatory in Resolute, Canada, develops instrumentation and hardware for scientific balloon observations, and develops other instruments for groups worldwide. In addition, HAO manages archival databases, including the CEDAR database, which collects and stores data from diverse providers and instruments, and provides access to outside users.

HAO develops large-scale, computational community models that support community research in upper atmospheric, ionospheric, and magnetospheric physics. These include the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM), the upward extension of WACCM (part of the Community Earth System Model [CESM] effort), and the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model developed as part of the Center for Integrated Space Weather Modeling (CISM), an NSF Science and Technology Center led by Boston University.

## Shared Values and Traits & Behaviors

Through a deliberate and collaborative process, HAO has identified the organizational values that are commonly shared by our staff and has identified a set of traits and behaviors expected of our staff in the execution of their roles and responsibilities.

We believe this establishes the framework of our operational culture, recognizing that our core strength lies in the quality of our people. By developing and communicating this framework, both internally and externally, it reinforces an essential foundation necessary to the execution of our mission, supporting our future vision and the successful pursuit of our strategic imperatives and frontiers.

HAO embodies the following shared values:

- We value the diversity of our staff, in perspective, gender, ethnicity and background, recognizing that this diversity is important to our organizational strength and excellence;
- We value a working environment that supports excellence, transparency, flexibility, academic freedom, and the virtues of a healthy work-life balance;
- We value open and honest communication among our staff, respecting the diversity of perspectives that exist, and we strive to make organizational decisions that are consensus-driven and inclusive;

- We value teamwork, and the demonstration of mutual respect within an atmosphere of collegiality;
- We value creativity that broadens our opportunities for success and humor that enlivens our workplace.

HAO expects the following traits and behaviors of its staff:

- To conduct themselves in a manner that is supportive of each other, respectful, tolerant of differences, and responsive to both individual and collective needs;
- To carry out the responsibilities of their roles with a commitment to excellence and dedication to organizational goals and commitments;
- To maintain honesty, integrity, and openness in workplace interactions.

## 2. HAO and the Changing Context of Solar Terrestrial Physics Research

Since 1940, HAO scientists have investigated many of the fundamental problems of solar-terrestrial science and, to this day, we pursue a fuller understanding of the complex Sun-Earth system. The primary goal of HAO's ongoing science research program lies in identifying the origins and function of the Sun's ubiquitous magnetism, the radiative and particulate variability that it drives, and the impact of that variability on the geospace environment and on the Earth's atmosphere.

The significance of this research to the broader community, and to society at large, continues to grow. Unprecedented observational, theoretical and computational breakthroughs compel new insights and a deepened physical intuition. Moreover, the societal relevance of space weather and climate change necessitates a thorough and accurate picture of the Sun's influence on the Earth.

Understanding solar physics — from the generation of energy and magnetism deep in the Sun's interior to the production of coronal mass ejections (CMEs) and solar wind — is essential to understanding the origins of the processes that ultimately impact terrestrial systems. Over the past decade, solar telescopes have probed the structure and dynamics of the Sun as never before. Models, both analytic and numerical, have raced to keep up with the three-dimensional complexity being observed. HAO continues to support and lead innovation and the long-term development of solar observations, theory and models.

HAO's primary observing facility is the Mauna Loa Solar Observatory. Exciting developments at MLSO include the installation of the Coronal Multi-channel Polarimeter (CoMP), which for the first time will provide daily observations of coronal magnetism. Moreover, the white-light coronagraph at MLSO, which remains the only telescope observing the K-corona below 1.5 solar radii, will be upgraded to enable observations a full scale-height closer to the surface of the Sun and with significantly improved signal-to-noise ratio. These improvements of the MLSO facility provide the foundation for the ultimate vision of COSMO, proposed by HAO and university partners.

HAO designs, constructs, and maintains solar research instrumentation for community use, and it supplies diagnostic tools and collaborative help to analyze the observations. For example, HAO, in collaboration with the Lockheed Martin Solar and Astrophysics Laboratory, built an instrument for the groundbreaking JAXA/NASA Hinode satellite: the Stokes Polarimeter (SP) instrument of the Solar Optical Telescope (SOT). The SOT/SP measures both transverse and line-of-sight magnetic fields at resolutions never before seen. The data from the SP are routinely calibrated, processed, inverted, and made available through CSAC to serve the community with extremely high-resolution vector magnetograph data.

Magnetism throughout the Sun is a focus for HAO models and theory development ranging from detailed analyses of fundamental physical processes to massively-parallel numerical models of global magnetohydrodynamics. These efforts are critical components for a future community Sun-system model. The origins of solar magnetism lie in the solar dynamo, which produces a complex, time-dependent magnetic field. Models of the dynamo strive to understand the generation and transport of magnetic flux to the solar surface. Magnetic flux pierces the photosphere and emerges into the solar atmosphere, where it remains in a stressed state, building up magnetic energy. Models of the storage and release of magnetic energy on multiple temporal-spatial scales address the fundamental questions of solar atmospheric heating, solar wind acceleration, and the triggering mechanism for solar eruptions.

Solar eruptions – and the space weather they create – have gained significance commensurate with the ever-increasing dependence of our society on advanced technologies. Space weather is a topic that links the solar and geospace aspects of HAO research. The occurrence of solar flares and CMEs can lead to disturbed conditions and geomagnetic activity in the Earth's magnetosphere and upper atmosphere. HAO solar observations and models provide clues to CME origins and their connections to space weather at the Earth. CMEs propagate through the heliosphere, and the goal of CISM is to create a physics-based numerical simulation model that describes the space environment from the Sun to the Earth. The role of HAO within CISM has been to develop coupled models of the magnetosphere, thermosphere and ionosphere.

The structure and dynamics of the Earth's upper atmosphere and space environment, their response to variable solar radiative and particulate emissions, and their coupling with the lower atmosphere, are major areas of activity at HAO. As with solar science, ongoing technological developments in observational and computational resources drive this dynamic field. Moreover, the societal relevance of this field of research continues to grow, owing to humankind's vulnerability to severe space weather and relentless climate change. HAO carries out its mission in this area by developing and utilizing simulation models of physical and chemical processes, by carrying out observational programs, by interpreting model results and observations jointly, and by providing information and data services to the scientific community.

HAO has developed a variety of geospace and upper-atmosphere observational resources. The NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) Doppler Interferometer (TIDI), operated by HAO and university partners, performs ultra-high-spectral-resolution measurements of airglow layers in the mesosphere and lower thermosphere in order to measure winds and temperatures using the Doppler shifts and line shapes of spectral features. HAO provides instrument and operational information, project documentation, and preliminary wind data as a web resource to the community. Through the CEDAR database, HAO provides ground-based upper-atmosphere observations and empirical model outputs, as well as geophysical indices and tools required for data interpretation.

HAO models explore the processes affecting the physical states of the Earth's mesosphere, thermosphere, ionosphere, and magnetosphere. This work includes efforts to identify the coupling of these regions to both the Earth's lower atmosphere and the interplanetary medium. It also tracks their responses to variable solar outputs. HAO has developed large-scale, computational models that are mainstays of community research efforts in upper atmospheric, ionospheric, and magnetospheric physics. For example, the Thermospheric General Circulation Models (TGCMs) are three-dimensional, time-dependent models of the Earth's neutral upper atmosphere. The models use a finite-difference technique to obtain a self-consistent solution for the coupled, nonlinear equations of hydrodynamics, thermodynamics, continuity of the neutral gas, and for the coupling between the dynamics and composition. Furthermore, the dynamics and chemistry of the upper atmosphere is addressed by WACCM, which spans the range of altitude from the Earth's surface to the thermosphere. The development of WACCM is an NCAR inter-divisional collaboration that unifies certain aspects of the upper atmospheric modeling of HAO, the middle atmosphere modeling of NESL's Atmospheric Chemistry Division (ACD), and the tropospheric modeling of NESL's Climate & Global Dynamics division (CGD), using the NCAR Community Climate System Model (CCSM) as a common numerical framework.

HAO is a multidisciplinary institution, enabling both deep and broad analysis. Each component of the Sun-Earth system has compelling scientific puzzles to be solved by

specialized research. Such investigations of the different regimes may proceed in parallel. However, the connections and commonalities between these studies allow a system view to develop. As a service institution, HAO provides resources to build a strong and interconnected community. As a national center for basic research, HAO studies fundamental physical processes. The duality of focused and synergistic research is key to effectively navigating the constantly changing context of solar-terrestrial physics research.

Finally, HAO benefits greatly from the guidance of members of the wider community, though formal as well as informal channels. HAO has two formal external advisory bodies: the External Advisory Committee, which advises the director on all aspects of the HAO program, and the Mauna Loa Users Committee, which gives feedback and advice to HAO on the status, desired enhancements, and future new developments of the MLSO facility and operations. Our cadre of affiliate scientists also provide informal but valuable advice on strategic directions in the changing landscape of solar-terrestrial physics.

### 3. HAO Strategic Imperatives

HAO Strategic Imperatives address our fundamental activities that are to be protected and nurtured as the highest priority. All have the same priority. Each Imperative is followed by a prioritized set of supporting actions that HAO will undertake. Our Imperatives are:

- Promote innovation and creativity within HAO and across the solar-terrestrial physics community;
- Provide capabilities for more accurate prediction and attribution of changes in solar output and the impacts of such changes;
- Advance world-leading numerical models of the atmosphere and Sun-Earth system, make them widely available, and support their use by the scientific community;
- Develop and provide state-of-the-art observational facilities that meet the needs of NSF, NCAR, and the solar-terrestrial physics community;
- Develop and transfer scientific applications, technology, and information products that address societal needs;
- Attract a diverse group of university students and early-career scientists and engineers to solar-terrestrial physics and provide them with exciting opportunities for educational and professional development.

Our approach to sustaining and growing each of these strategic imperatives follows.

## **Promote innovation and creativity within HAO and across the solar-terrestrial physics community**

As a constituent part of a national center that provides service and leadership for the scientific community, HAO must be a venue where new ideas, methods, tools, and practices are developed, gathered, evaluated, and shared. HAO should serve as a hub for community interactions, collective definition of grand challenges, and development and implementation of collaborative research activities to address such challenges. To fulfill this role, HAO must maintain a world-class scientific workforce, a high standard of excellence, strong collaborations, and a broad spectrum of fundamental research that leads to new understanding. To support this imperative, HAO will:

- Conduct discovery-oriented research in solar-terrestrial physics to identify evolving fundamental research questions, develop new approaches, and guide the direction or redirection of ongoing research programs;
- Maintain a strong scientific visitor program to attract and support a broad community of researchers, and encourage HAO staff to spend time in other research organizations, to foster and facilitate the circulation of scientific information and the development of new research perspectives;
- Work with universities, the broader science community, and policy and decision makers, to identify grand-challenge problems in solar-terrestrial physics of societal and scientific interest, in order to define new approaches and methods for research;
- Enhance observational and modeling facilities by evaluating new technologies, and developing prototype instruments, models, and model components;
- Further the above activities by establishing, supporting, and hosting an externally-proposed program of small-group workshops covering focused science and instrumentation topics in solar-terrestrial physics;
- Provide regular opportunities and infrastructure for staff to pursue high-risk, potentially path-breaking research projects.

## **Provide capabilities for more accurate prediction and attribution of changes in solar output, and the impacts of such changes**

Climate change and space weather have significant environmental and economic costs. Understanding the variability intrinsic to the coupled Sun-Earth system is thus not only an intellectually intriguing challenge, but a societally relevant one. Solar radiation drives climate; it supplies nearly all of the energy entering the Earth's atmosphere. Moreover, the variable solar wind in which the Earth is

embedded, and energetic transient solar activity, can severely impact our space environment. It is an HAO imperative to advance understanding of the origins and nature of solar variability and its impacts at the Earth, from short-term space weather to long-term solar cycle modulation. To support this imperative, over the next five years, HAO will:

- Collect critical measurements and develop the appropriate diagnostic tools needed to improve our understanding of physical processes and to test and improve models and their predictions of the Earth's atmosphere and the Sun;
- Study the magnetic nature and dynamics of CMEs and their precursors, integrating observations and models;
- Develop a comprehensive model of interactive processes throughout the Earth's atmosphere-ionosphere-magnetosphere systems, and analyze how these are affected by solar variability;
- Model the internal (magneto-)hydrodynamical processes involved in the generation of the Sun's cyclically varying magnetic field, the formation of flux tubes, and the transport of magnetic flux through the convection zone to the photosphere;
- Use models and observations to more accurately identify the natural and anthropogenic processes driving upper-atmospheric changes as well as related societal and environmental vulnerabilities, impacts, and feedbacks;
- Work with collaborators to obtain and interpret observations of solar-like stars that test theories and models of the solar dynamo.

### **Advance world-leading numerical models of the atmosphere and Sun-Earth system, make them widely available, and support their use by the scientific community**

HAO has considerable expertise in modeling many aspects of the solar-terrestrial system, and has a major role to play in leading and supporting the community in development of state-of-the-art models. CISL and in particular the new supercomputing facility in Wyoming provide the infrastructure support for researchers in the community and HAO scientists to run these models. Over the next five years, HAO will work with its partners within NCAR, universities, and the wider research community to:

- Lead and support the development of space weather community models, including development and support of WACCM, TIE-GCM, and the CMIT model;

- Develop and release new community modeling systems that incorporate new components and offer state-of-the-art representation of a greater number of solar-terrestrial system processes;
- Lead and support the development of models of the solar dynamo and magnetic flux emergence from the solar interior through the photosphere;
- Lead and support the development of models of the initiation and dynamic evolution of CMEs, providing quantitative determination of the 3D magnetic field evolution and the dynamic properties of the CME ejecta originating from the lower solar corona;
- Adopt and follow a set of best practices for developing and modifying model software, including requirement specifications, design reviews, version control, and procedures for software testing, validation, and release;
- Develop and test procedures for assimilating data into the models.

## **Develop and provide state-of-the-art observational facilities that meet the needs of NSF, NCAR, and the solar-terrestrial physics community**

Observational science is central to the vision and mission of HAO. To fulfill this imperative, HAO must maintain its observing facilities and seek opportunities to develop and upgrade existing observational technology and instruments. At present HAO maintains and operates permanent observing facilities such as those at Mauna Loa and Resolute Bay, providing access to the current and extensive archives of observational data directly to the community. MLSO, in particular, has been operated by NCAR for over 40 years. HAO participates in the definition, design, and development of satellite, balloon, and ground-based observing platforms. Success in meeting this imperative depends critically on HAO's ability to attract and retain an experienced cadre of engineers, technicians, and scientists, who provide world-class support for planning, developing, and implementing these facilities. Over the next five years, HAO will:

- Enhance MLSO through the upgrade of existing instrumentation and addition of complementary instrumentation to meet the observational demands of the community and in support of HAO's scientific strategic goals;
- Complete the design and fabrication of the ViSP instrument for the ATST which will provide a major observational facility for solar physics;
- Develop, progress, and work towards a full implementation of COSMO;
- Meet the challenge posed by the increasing volume and complexity of observational data sets by developing and implementing the systems and procedures required to access, manage, and distribute the data to the community in a timely manner;

- Continue to participate in the design and development of ground and space-borne instrumentation for observations of the Sun-Earth system;
- Develop life-cycle plans for our facilities and instruments considering the anticipated changes in technology and scientific understanding needed to formulate a long-range strategy for replacement and upgrade;
- Continue improving project management and engineering best practices across the organization for planning, bidding, designing, developing and sustaining HAO's instrumentation projects and facilities;
- Conduct exploratory development projects in partnership with other institutes/universities that are selected for their potential to provide novel observational capabilities that address emerging scientific challenges.

In order that the observing systems that HAO operates for the community remain vital, HAO must pursue the innovative refurbishment and instrument replacement projects outlined above. These major efforts, along with continued development of smaller component instruments for community use, represent a critical component of our long-term vision for observational capabilities. COSMO is such a project. Through the synoptic observations of the coronal magnetic field, COSMO will provide unprecedented insight into structure, heating, and dynamics of the outer solar atmosphere as well as the activity responsible for space weather. The centerpiece of COSMO will be a meter-class coronagraph with instrumentation to measure the coronal magnetic field using the polarization of forbidden infrared emission lines, based on the heritage of the groundbreaking CoMP instrument. Supporting instruments will provide essential contextual measurements of the chromospheric and prominence magnetic fields (ChroMag) and white-light corona (K-coronagraph). Pursuing the development of COSMO is an imperative for the Observatory, but its construction and deployment cannot be realized without additional funding, hence it also has the characteristic of a program frontier.

## **Develop and transfer scientific applications, technology, and information products that address societal needs**

It is part of HAO's mission to foster the transfer of knowledge and technology from its origins in fundamental research for the benefit of society. HAO recognizes its responsibility to conduct and support research that is relevant to societal needs, to provide scientific information to support policy making and decision making in the public and private sectors, and to contribute to national and international scientific assessments. We will collaborate with university partners, other research organizations, and the private sector to carry out these activities. Over the next five years, HAO will:

- Develop and test, and transfer to operational agencies state-of-the-art numerical models and techniques for solar-terrestrial physics and space weather modeling;
- Support the research community by providing repositories of tested code, documentation, and tutorials;
- Develop and transfer advanced observational systems to the research and operational communities nationally and internationally, in collaboration with our university partners.

Examples of these activities include transfer of models to the Community Coordinated Modeling Center (CCMC), and development of a CoMP-like instrument and Fabry-Perot Interferometers for a variety of end users.

## **Attract a diverse group of university students and early career scientists and engineers to solar-terrestrial physics and provide them with exciting opportunities for educational and professional development**

A steady flow of talented new participants into solar-terrestrial physics is essential for scientific progress in this field. HAO is committed to fostering graduate and postgraduate research and education, providing opportunities for undergraduate participation in research, and promoting students' interest in solar-terrestrial physics. As a constituent element of a national center active in research, modeling, and observational activities, we can provide unique hands-on educational experiences and many opportunities for students, advisors, and early career scientists to collaborate with a wide variety of scientists and engineers. Over the next five years, HAO will:

- Promote a variety of early-career employment options that provide entry points and pathways to different aspects of solar-terrestrial research at HAO and in the broader community;
- Maintain a strong program for postdoctoral scientists at HAO;
- Increase the size of HAO's graduate program in support of the university community, and further encourage joint work among graduate students, their university advisors, and HAO researchers;
- Conduct educational activities/programs that integrate research and education in HAO, including work-study and summer programs for undergraduates as well as underrepresented groups that supplement their educational experiences;
- Continue aggressive outreach to qualified candidates for educational programs, with particular attention to attracting candidates from diverse backgrounds and disciplines;

- Increase the involvement of HAO scientists and engineers in teaching and supervising students, and other educational activities in the university community, and engage this community in increasing diversity;
- Cooperate with the NSF Faculty Development in Space Sciences (FDSS) program through hosting scientific visits and promoting close collaborations of FDSS-supported university faculty members.

HAO staff will continue to participate in and contribute to the NCAR and UCAR education and outreach programs such as Significant Opportunities in Atmospheric Research and Science (SOARS) and Advanced Study Program (ASP), and collaborate through other external programs, for example, the Research Experiences for Undergraduates (REU) summer program led by the University of Colorado, the Boulder Solar Alliance colloquium series, and the CISM summer school.

## 4. Program Frontiers for HAO

Building on our commitment to delivering on the strategic Imperatives, described above, we have identified four program Frontiers. These Frontiers embody a set of grand challenges that we would wish to make progress in addressing in the next five years if resources permit. The Frontiers are ordered by priority such that, if resources beyond what is required to deliver on our Imperatives become available, we would prioritize undertaking Frontier 1, then Frontier 2, and so on. Should adequate external resources be obtained by staff and external collaborators to make progress on a specific frontier, those would enable work to be undertaken on that frontier irrespective of its prioritization: that is entirely appropriate, since all these program frontiers are important priorities for HAO.

### **Frontier 1: Investigate the Onset and Development of Magnetic Flux Transport through the Chromosphere, and the Impact of its Short-term Variability on the Sun-Earth System**

The magnetic, thermal, and radiative phenomena of the mid-solar atmosphere can directly impact the Sun-Earth system on timescales of days or shorter. Driven by the convective flows and the continuous emergence of magnetic flux from the solar interior, the magnetic and thermodynamic environment of this region, the chromosphere, is relentlessly forced. The chromosphere is a highly structured, partially ionized plasma that forms the boundary layer between the solar photosphere and corona. Not only is it the conduit through which all of the energy that drives the Sun-Earth system must pass, the chromosphere is the region closest to the photosphere where that energy transport can be directly observed and the

ubiquitous magnetic field is force-free. In this context the chromosphere forms the magnetic and thermodynamic base of the Sun-Earth system. The chromosphere offers a unique opportunity to understand, and quantify, the response of the outer solar atmosphere to this forcing, and through its study we will develop a deeper physical understanding of the persistent radiative and particulate input to the Sun-Earth system. By necessity, observation, theory, and modeling efforts must work in concert to unlock the fundamental mysteries of the complex boundary. In confronting this frontier, HAO will form partnerships with the broader community on all aspects of the initiative with the expectation that the mutual scientific return will benefit all, thus filling a crucial void in our current observational knowledge of processes driving the short-term forcing of Earth's atmosphere.

The envisioned effort will engage HAO staff with those from other divisions of NCAR (specifically CGD, ACD, and CISL), the University of Colorado Laboratory for Astrophysics and Space Physics (CU/LASP) and the broader university community in a cross-disciplinary program to investigate the impact of short-term solar variability on the Sun-Earth system. We will interact with the community through a series of focused workshops to develop the comprehensive observing and modeling systems needed to monitor and understand the influence of the radiative and particulate input to the Earth's dynamic atmosphere as forced by the Sun's ever-evolving magnetism. Specific tasks are:

- Develop and deploy wavelength-diverse spectro-polarimetric instruments to monitor the four-dimensional (space and time) evolution of the magnetic field at the inner boundary of the Sun-Earth system, and to provide essential observational context for the modeling and theoretical efforts;
- Research diagnostics for the remote sensing of magnetic field vectors in highly dynamic plasmas, develop the associated inversion tools, and make them available to the community through the CSAC;
- Advance models of magnetic flux emergence through the entire solar atmosphere with increased realism in the physical description of magnetized plasmas and their interaction with radiation;
- Based on the observed rate and magnitude of mass transport through the chromosphere, develop a physical model of the ultraviolet (UV) and extreme-UV (EUV) radiation formed at the interface for ingestion into the WACCM and TIME-GCM models.

A "gap" exists in our observational understanding of the solar atmosphere. That gap is widely recognized as the magnetic and thermodynamic environment of the chromosphere. Instrumentation and numerical simulation are advancing at a rapid pace such that an effort to pursue this frontier activity is both timely and practical. Resources exist within NASA, NSF, and Department of Defense research programs to perform the effort outlined above.

## **Frontier 2: Investigate Impacts on Terrestrial and Space Climate of Solar Variability on Decadal Time Scales**

Understanding climate change is recognized as a critically important problem for our time. As our society becomes ever more dependent on advanced technologies, space climate is also becoming an important topic. This program will enable better understanding and attribution of the solar cycle impacts on the terrestrial/space climate, with important implications for the global and regional climate variability and predictability on decadal time scales. It also helps distinguish the effects of variability of radiative and non-radiative solar outputs on the habitability of the terrestrial environment. The further development of the community model CESM/WACCM for this study will involve close collaborations with the community and will also serve the community. Tasks to achieve the frontier are:

- Incorporate solar spectral observations (Solar Radiation and Climate Experiment [SORCE], augmented with model calculations for pre-SORCE epochs), solar wind and magnetospheric forcing, improved ocean initialization, and the newly developed module for self-generation of quasi-biennial oscillation in NCAR CESM/WACCM;
- Develop D-region chemistry and global electric circuit and prescription of solar-modulated galactic cosmic rays on cloud physics and the global electric circuit for CESM/WACCM;
- Use CESM/WACCM to study global and regional climate variability and predictability on decadal time scales; Determine significance of radiative vs. non-radiative impacts, and the mechanisms of these impacts; Distinguish and quantify the impact of solar decadal variability from terrestrial system variability;
- Use CESM/WACCM and TIME-GCM and long-term datasets of geomagnetic activity, greenhouse gas concentrations, satellite drag data, and global ionosonde data to investigate space climate response to lower atmospheric variability (including anthropogenic forcing) under different solar cycle conditions, with consideration of relative roles of solar wind and interplanetary magnetic field, as well as solar and magnetospheric energetic particles.

Our ultimate goal is to understand the linked processes from the Sun to the Earth that drive decadal variation. The system is at its simplest configuration during solar minima, when solar activity is low and transient events, like CMEs, are infrequent. This, coupled with the significant variations known to occur among and within minima, makes minima both tractable and interesting periods for studies of space-climate variability. We propose to:

- Characterize the three-dimensional heliosphere at solar minimum, using a range of possible photospheric magnetic field distributions as boundary conditions on empirical/MHD models; Obtain further information about solar minimum heliospheric structure from coronal observations (e.g., MLSO white-light coronal

morphology and CME activity), and about the lower boundary condition from photospheric/chromospheric observations (e.g., chromospheric network spatial scales observed with the Precision Solar Photometric Telescope [PSPT]);

- Use resulting solar wind properties at the Earth (both thermodynamic and velocity, with attention to amplitude, duration, and periodicities of solar wind streams) to examine how the Earth's space environment responds to these different solar minimum configurations (e.g., aurora, radiation belt, cosmic rays);
- Study the range of potential solar cycle variation that might be expected from the Sun, by placing the Sun in an ensemble of solar-analog stars, identified primarily using seismic measurements from the Kepler mission. Augment broad-band radiative variability from Kepler with new measurements of Ca II lines, a proxy for magnetic activity, and with vacuum UV measurements using the Hubble Space Telescope.

This work will involve national/international and interdisciplinary collaboration, and the participation of graduate students and postdoctoral visitors. Specific collaborations include: ACD and CGD for CESM/WACCM developments and ocean modeling; CU/LASP for implementation in WACCM and TIME-GCM of the solar spectral irradiance derived from space observations and/or irradiance models; ACD and the National Oceanic and Atmospheric Administration (NOAA) for the development and implementation of D-region chemistry and global electric circuit/cloud physics; and the Air Force Office of Scientific Research (AFOSR) for the heliospheric modeling.

### **Frontier 3: Determine How Small-scale Structures are Produced in the Earth's Upper Atmosphere, and Their Effects on Global Dynamics**

The solution to critical problems of upper-atmospheric physics and space weather depends on understanding the generation and development of small-scale structures in the ionosphere and thermosphere and their influence on large-scale structure and dynamics. This project will develop the community modeling and observational capabilities, in collaboration with other NCAR divisions and with the external scientific community, to significantly advance our understanding of the multi-scale interactive processes affecting the upper atmosphere and the generation of ionospheric irregularities. Models that can simulate these processes self-consistently over a wide range of spatial and temporal scales do not currently exist, nor do observational capabilities that measure all of the important parameters.

HAO, in collaboration with the broader scientific community, has the expertise to develop a combined modeling, experimental, and data-interpretation program that can transform our ability to observe, simulate, and understand these processes, leading to major improvements in predictive capabilities of societal benefit. Tasks for the achievement of this Frontier are:

- Develop a high-resolution thermosphere-ionosphere community model to study interactions among scales;
- Deploy instruments to measure thermospheric winds and airglow signatures of equatorial plasma bubbles at HAO's Mauna Loa facility as part of a coordinated observing campaign;
- Ascertain how breaking gravity waves influence thermospheric turbulence, composition, temperature, and large-scale dynamics, using theoretical, modeling, and data-analysis studies;
- Determine the geophysical conditions under which ionospheric instabilities are triggered to produce equatorial plasma bubbles, using theoretical, modeling, and data-analysis studies;
- Enumerate the effect of mesoscale structures at middle and high latitudes on energy and momentum transfer and redistribution during geomagnetically active periods;
- Quantify the influence of ionospheric waves and irregularities on the calculation of electric currents, fields, and Joule heating through theoretical and data-analysis studies.

The envisaged program of work will involve collaborations within NCAR – interactions with ACD and CGD scientists for model developments, and connections with CISL to achieve good performance on petascale computers. It will also involve relations with scientists in the CEDAR community to coordinate observations and analysis, and collaboration with scientists outside NCAR in the use of the new community models. Coordination and interaction with scientists making space-based observations of ionospheric bubbles (e.g., with the proposed NASA GOLD mission) will also be required.

#### **Frontier 4: Link Dynamo Models to Simulations of Flux Emergence**

It is timely and important to build on HAO's expertise and heritage of developing models of the solar dynamo, convection and rotation, and flux emergence, to achieve a new modeling capability that addresses in a unified way the problem of magnetic flux emergence from the Sun. The magnetic fields that are ultimately the source of the activity that takes place in the solar atmosphere have their origin inside the Sun, where convective, rotational, and other flows of highly electrically conducting plasma contribute to the operation of the dynamo. After emerging from the interior into the solar surface layers, these fields contribute to the structure, heating, and dynamics of the overlying atmosphere, producing energetic, eruptive events like flares and CMEs that can significantly affect the Earth's upper atmosphere and environment in space. Much progress has been made in recent years in modeling solar convection, the solar dynamo, the formation of buoyant magnetic structures and flux emergence. However, due to the vast range of length and time-scales as

well as different physical regimes encountered from the base of the solar convection zone to the solar corona, a unified picture of magnetic field generation, flux transport and emergence, and active region formation does not yet exist. By expanding and coupling models currently in use at HAO we propose to:

- Develop a large-scale 3D dynamo model focusing on evolution of large scale non-axisymmetric flow and magnetic fields, and use this to compute progenitors of buoyant structures at base of convection zone;
- Expand the Finite-difference Spherical Anelastic MHD (FSAM) code, adding convection, rotation, and a tachocline;
- Use FSAM to investigate non-linear buoyancy instabilities in 3D and the rise of buoyant structures through convection zone toward surface;
- Extract from the FSAM 3D simulations parameterizations of turbulent transport and induction effects to improve non-convective dynamo models;
- Develop FSAM into self-consistent convective dynamo code (long term goal);
- Build upon the recent improvements implemented into the Max-Planck University of Chicago Radiative MHD (MURaM) code at HAO and expand its capabilities further, by moving the top boundary condition several Mm upward to be less restrictive on emerging flux, expand overall domain size horizontally and in depth to capture the scale of a typical active region; Investigate the last stages of flux emergence and active region/sunspot formation in the uppermost 20–30 Mm of the convection zone, which is not covered by previous code;
- Develop or adapt existing code-coupling frameworks to allow coupled runs of the dynamo model, FSAM, and MURaM.

Achieving this frontier will involve collaborations with, amongst others, CISL and the Geophysical Turbulence Program (GTP), the University of Colorado's Joint Institute for Laboratory Astrophysics (JILA), the Lockheed Martin Solar and Astrophysics Laboratory (LMSAL), UC Berkeley, UCLA, and the Max-Planck-Institute for Solar System Research (Germany).

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## 6. Acronym List

ACD	Atmospheric Chemistry Division
ATST	Advanced Technology Solar Telescope
CCMC	Community Coordinated Modeling Center
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
CESM	Community Earth System Model
CGD	Climate & Global Dynamics Division
CISL	Computational Information Systems Laboratory
CISM	Center for Integrated Space Weather Modeling
CME	Coronal mass ejection
CMIT	Coupled Magnetosphere-Ionosphere-Thermosphere
CoMP	Coronal Multi-channel Polarimeter
COSMO	Coronal Solar Magnetism Observatory
CSAC	Community Spectro-Polarimetric Analysis Center
EOL	Earth Observing Laboratory
FSAM	Finite-difference Spherical Anelastic MHD
GEM	Geospace Environment Modeling
GOLD	Global-scale Observations of the Limb and Disk
GTP	Geophysical Turbulence Program
HAO	High Altitude Observatory
IMAGe	Institute for Mathematics Applied to Geosciences
MHD	magnetohydrodynamics
MLSO	Mauna Loa Solar Observatory
MURaM	Max-Planck University of Chicago Radiative MHD
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NESL	NCAR Earth System Laboratory
NSF	National Science Foundation
PSPT	Precision Solar Photometric Telescope
SHINE	Solar, Heliospheric and INterplanetary Environment
SORCE	Solar Radiation and Climate Experiment

SOT	Solar Optical Telescope
SP	Stokes Polarimeter
TIDI	TIMED Doppler Imager
TIE-GCM	Thermosphere-Ionosphere-Electrodynamics General Circulation Model
TIME-GCM	Thermosphere-Ionosphere-Mesospheric-Electrodynamics General Circulation Model
TIMED	Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics
UCAR	University Corporation for Atmospheric Research
ViSP	Visible-Light Spectro-Polarimeter
WACCM	Whole Atmosphere Community Climate Model