IGBP Report 58



Science Plan and Implementation Strategy





Citation

This report should be cited as follows: AIMES (2010) Science Plan and Implementation Strategy. IGBP Report No.58. IGBP Secretariat, Stockholm. 30pp.

Financial support

This work was financially supported by the International Geosphere-Biosphere Programme (IGBP), the U.S. National Science Foundation (NSF) Grant No. 0442079 and The National Center for Atmospheric Research (NCAR). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funders.

Front cover image

Cover image created by Hilarie Cutler, IGBP. Original photos from iStockphoto.

Publication details

Published by: IGBP Secretariat Box 50005 SE-104 05 Stockholm SWEDEN Tel: +46 8 166448 www.igbp.net

Editors: Susanne Nash, Owen Gaffney and Jennie Rice

Graphic Design: Hilarie Cutler

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Science Plan and Implementation Strategy

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Acknowledgements

The authors would like to acknowledge the original members of the AIMES Scientific Steering Committee for their contributions:

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Scientists and policymakers agree that global environmental change needs to be studied in a more integrated way. This is because the workings of the Earth system involve strong interactions among the atmosphere, ocean and land (including the major role of ecosystems), and because human activities are impinging on these workings to a degree that implies major human consequences.

The Analysis, Integration and Modelling of the Earth System project, or AIMES, is a core project of the International Geosphere-Biosphere Programme (IGBP). AIMES develops innovative, interdisciplinary ways to understand the complexity of the natural world and its interactions with human activities. Key foci are to understand and quantify the consequences and feedbacks of human activities and ecosystems with biogeochemical cycles and the climate system. AIMES' objectives include scenario analyses informed by climate science collaborations with palaeo-environmental scientists, archaeologists and historians to develop a better understanding of Earth-system changes and human-environment interactions.

AIMES' participatory steering committee includes representatives of diverse natural and social science communities that interact and collaborate across **four integrative themes**:

- Process and parameterisation studies (translating specific aspects of Earth-system processes and function to global models);
- Regional-global integration (understanding global Earth-system context to regionally-based analyses);
- Applied Earth-system science (end-to-end research to meet decision makers' needs for integrated information);
- Earth-system dynamics (fundamental Earth-system research, involving global observations and models).

AIMES' work entails collaboration on a broad front with other IGBP projects and the other programmes and projects of the International Council for Science's (ICSU) Earth System Science Partnership. This partnership of global environmental change programmes is made up of IGBP, the International Human Dimensions programme (IHDP), the World Climate Research Programme (WCRP) and DIVERSITAS.

Process and parameterisation studies include the Global Emissions Inventory Activity, GEIA (moving from prescription to prognostic modelling of reactive trace-gas emissions), and a new collaboration with the WCRP's Climate in the Cryosphere (CLiC) project on carbon and permafrost dynamics in the northern high latitudes. Regional-global integration activities are planned in monsoon Asia (where human activities could influence climate in a populous region) and the northern high latitudes (where climate change, remotely forced, could trigger global-scale consequences).

Activities under the theme on applied Earth-system science include a new approach to scenario development for the Intergovernmental Panel on Climate Change (IPCC); the International Nitrogen Initiative (exploring how to redress the imbalance between too little nitrogen in poor countries and too much in rich ones); and the integration of economic and Earth system models for policy and energy assessment.

Under Earth-system dynamics, the Coupled Carbon Cycle-Climate Model Intercomparison Project (C⁴MIP) aims to improve the quantification of carbon cycle feedbacks to climate and, ultimately, a broader range of biogeochemical feedbacks and their interactions with ecosystem services. Integrated History and Future of People on Earth (IHOPE) is taking a new look at human history, considering environmental impacts on people as well as human impacts (for example, socio-political, -ecological and -economics) on the environment.

Finally, AIMES builds capacity through a Young Scholars' Network (YSN) and training workshops.



There is a growing recognition within the research community that global change must be studied in a more holistic, interdisciplinary and integrated way than before. Crucial to the emergence of this perspective is the increasing awareness of two aspects of Earth-system functioning. First, that surface layers of the Earth – atmosphere, ocean and land – operate as a coupled system, within which the biosphere is a highly influential component. Second, that human activities are pervasive and profound in their consequences; they modify the physics, chemistry and biology of the Earth at the global scale, in ways that have the potential to feed back on human society. Thus humans can be considered not only as external forcings but also, more realistically, as fully embedded players in a coupled, dynamical system (Figure 1). This emerging perception is challenging the way in which research on the analysis and modelling of the Earth system is organised, from the level of individual research groups and institutions to the international global-change research programmes.



Figure 1. Conceptual diagram of Earth-system interactions. Understanding the Earth's system requires an unprecedented degree of integration between the biological, physical and social sciences and the humanities. Blue arrows represent AIMES' role, red arrows for other global environmental-change activities.

The integration challenge – to understand human and environmental interactions – is the driving force for AIMES. The role of AIMES is represented by the linkages depicted in Figure 1, especially the blue arrows indicating effects that have not been a major focus for other projects or programmes. Figure 1 implies a need for close collaboration and communication with other projects and programmes in the international science community – in particular, with the members of other global environmental-change programmes – with a shared goal to develop transdisciplinary approaches to understand our life-support system and our role within it (Figure 2).



Figure 2. AIMES' relationship as an integrative project with IGBP, the World Climate Research Programme, the International Human Dimensions Programme and DIVERSITAS, the International Council for Science's global environmental change programmes (GECs). AIMES is a core project of IGBP (denoted by connecting line) and collaborates with other projects within the GEC community of international programmes.



Theories, models and observations contribute to an understanding of both the natural Earth-system dynamics on which anthropogenic perturbations are superimposed, and of the complex response of the system to drivers of change. AIMES aspires to achieve a deeper and more quantitative scientific understanding of the role of human perturbations on the biogeochemical cycles and their role in altering the coupled physical climate system in the past, present and future. The project seeks to describe better and quantify the interactions and feedbacks between the biogeochemical and climate systems, the consequences of human activities and decisions for these systems, and the implications of global environmental changes for humanity. AIMES is guided by a Scientific Steering Committee (SSC) that functions in a participatory role. Integration across scientific disciplines is key to the AIMES philosophy and the composition of the AIMES SSC necessarily includes both natural and social scientists. An International Project Office (IPO) manages AIMES' research activities. The IPO is led by the Executive Officer who collaborates with AIMES co-chairs, AIMES project leaders and Earth-system scientists and scholars. The chairs and the SSC are responsible for strategy and planning; the IPO is responsible for logistics, fund-raising, and liaison with the institutes involved in the network (Figure 3). The SSC meets annually. Since 2005, the AIMES IPO has been hosted at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, USA.



Figure 3. AIMES structure



The AIMES core project succeeds IGBP's Global Analysis, Integration and Modelling (GAIM) Task Force.

Under the chairmanship of Bert Bolin, the GAIM Task Force held its initial meeting at the 1989 Third International Conference on Analysis and Evaluation of Atmospheric CO2 Data Past and Present held at Hinterzarten, Germany. The goal was to advance the study of the coupled dynamics of the Earth system using both data and numerical models. Regular (annual) meetings began in 1992 under the chairmanship of Berrien Moore, who passed the reins to John Schellnhuber from 2000-2004. Colin Prentice joined John Schellnhuber as co-chair during 2003-2004. At the time, it was clear that the global carbon cycle was a major gap in IGBP's portfolio. GAIM undertook a series of activities to fill that gap. The goal of GAIM was to quantify the links between the global biogeochemical and climate systems. The key means to this end was to accelerate the development of global biogeochemical model components suitable for coupling with physical models of climate. GAIM also addressed land-atmosphere biophysical interactions in the contemporary and palaeo (Late Quaternary) domains, and played a key role in setting priorities for dataset development by the IGBP Data and Information System (IGBP-DIS).

GAIM and AIMES evolved in three phases. First, a strong initial focus of GAIM was on quantifying subsystems of the biogeochemical cycles and physical interactions between climate and ecosystems including the water cycle. Activities included the Regional Interactions of Climate and Ecosystems (RICE), the GAIM 6000 Years Before Present experiment, and model development and intercomparisons. These included the Potsdam Net Primary Productivity (PIK-NPP), the Ecosystem Model-Data Intercomparison (EMDI), the Carbon Cycle Model Linkage Project (CCMLP), the Ocean Carbon Model Intercomparison Project (OCMIP) and the Atmospheric Tracer Transport Model Intercomparison (TRANSCOM). The GAIM 6000 Before Present experiment spawned a major global data synthesis activity – the Global Palaeo Vegetation Project (*aka* BIOME 6000) – in co-operation with IGBP-DIS and the Past Global ChangES (PAGES) and Global Change and Terrestrial Ecosystems (GCTE) projects.

Second, a transition period from around 2000 to 2003 revisited GAIM's goals and initiated a push to define broader Earth system questions. Towards the end of GAIM, under the leadership of John Schellnhuber, there was an increased focus on the interaction between human society and the biogeophysical Earth system (Schellnhuber 2000). This led to explicitly defining the role of an integrative Earth-system project in the IGBP framework, including a strong social-science and/or policy dimension highlighting overarching issues for Earth-system science for years to come. The early 2000s also saw the proliferation of fully coupled carbon-climate models and the development of the Coupled Carbon Cycle-Climate Model Intercomparison Project (C⁴MIP) as a joint venture with the World Climate Research Programme's Working Group on Coupled Models (WGCM).

Third, the name change from GAIM to AIMES reflects current priorities to integrate human interactions with biogeophysical Earth-system analyses to address the emerging intellectual challenges, while maintaining strong activities on biogeochemistry-climate linkages in so far as these are not addressed by other IGBP or GEC programmes.





The challenge facing AIMES demands a distinctive operational approach involving a high degree of interaction with other IGBP core projects and ICSU's three other GEC programmes.

This document defines the working methods adopted by AIMES and further illustrates these with examples of active projects. Descriptions of projects are not intended to represent a comprehensive plan of activities, but rather, to provide insight into an implementation strategy. A prescriptive approach towards a strict implementation policy would be counter to AIMES' unique mission. Rather, it is expected that AIMES will continue to evolve in response to developments in the many related areas of Earthsystem science on which it depends, and in the nature and priorities of the other projects and programmes with which AIMES must necessarily collaborate.

The integrative remit of AIMES is to develop a quantitative understanding of Earth-system processes,

Figure 4. AIMES Integrative Themes.

their forcings and impacts. This requires close interaction and collaboration with IGBP core projects researching local and regional aspects of the atmosphere, ocean and land, and projects investigating their interfaces, for example atmosphere-ocean, land-atmosphere, land-ocean interactions. AIMES research integrates with research on palaeo systems and the Earth System Science Partnership (ESSP) projects.

As an integrative project, AIMES does not have one central biospheric challenge or remit. AIMES has developed four themes that do not specify an explicit Earth-system component, or domain, but rather endeavour to capture integrative and synthetic challenges for Earthsystem science. The four integrating AIMES themes are not mutually exclusive with regard to any individual activity, but rather, can be considered as 'building blocks' towards an holistic understanding and quantification of Earth-system dynamics (e.g., see Figure 4). The four integrating AIMES themes are:

Theme 1: Process and parameterisation studies

AIMES continues to facilitate Earth-system modelling initially established by the GAIM Task Force. It does this by: identifying gaps in current model structures, improving global representations of critical processes, better translation of field observations and detailed process understanding to the global scale of analysis. Such activities can be led by AIMES or by another core project, or, they can involve several core projects with AIMES serving as a coordinating body. It is expected this theme will generate datasets and and/or modelling components required for implementing other themes as well as evaluating and initialising datasets for Earth-system models.

Theme 2: Regional-global interactions

AIMES promotes an Earth-system perspective on regionally based analyses. This is done through AIMES' contribution to quantifying the impacts and feedbacks in regions where rapid development could trigger large-scale changes in the atmosphere or biosphere, and/or where rapid regional changes may have global consequences. This theme calls for interaction between AIMES activities and Integrated Regional Studies (IRS), which are important cross-cutting activities of ESSP as well as other regional activities in national and international programmes.

Theme 3: Applied Earth-system science

Decision-makers increasingly request integrative assessments of global change to evaluate risks, compare policy options to manage and/or mitigate those risks, and to evaluate consequences of global environmental change for development goals. Such requests require an increasingly close engagement between natural and social scientists, including economists. AIMES will lead IGBP's emerging strategy for end-to-end applied Earth-system science. This includes engaging with stakeholders to incorporate scientific understanding into information for assessment, policy, resource management and decision making communities.

Theme 4: Earth-system dynamics

This theme encompasses fundamental research to understand past, present and future interactions and feedbacks in the Earth system. Work under this theme may be quantitative and model-based (e.g. estimating the strength of global-warming feedbacks using state-of-theart coupled models) or exploratory and observationally based (e.g. using historical evidence to assess social resilience to environmental shocks). Implementation of theme four will call for strong links with IGBP and GEC projects. AIMES will lead the development of a conceptual framework for Earth-system modelling that integrates human activities and environmental processes.

AIMES consults and collaborates extensively with the other GEC projects and programmes. PAGES has a special status as the other explicitly integrative programme-wide IGBP project. For instance, under AIMES leadership, PAGES co-sponsors the Integrated History and Future of People on Earth (IHOPE) activity alongside the International Human Dimensions Programme (IHDP). Aside from PAGES, the remaining IGBP core projects represent specific or integrative domains of the Earth system and AIMES anticipates collaboration with IGBP Core Projects on relevant activities across the four AIMES themes.

As the successor to the GAIM Task Force, AIMES is historically partnered with WCRP, particularly the Working Group on Coupled Models (WGCM), to link biogeochemical and biophysical climate modelling communities for research and assessment activities. The AIMES SSC meets jointly with WGCM approximately every other year to discuss and plan research and assessment activities (e.g., Hibbard et al. 2007 and Meehl and Hibbard 2007). The AIMES scientific collaboration with WCRP also includes WCRP's modelling strategy, Coordinated Observation and Prediction of the Earth System (COPES). This collaboration is enabled by direct communication and joint participation in the WCRP Modelling Panel (WMP) which facilitates "analysis and prediction of the Earth-system variability and change for use in an increasing range of practical applications of direct relevance, benefit and value to society." Joint activities between AIMES, the COPES Strategic Framework and other WCRP projects provide the basis for fully integrated biogeochemical and coupled physical Earthsystem modelling.

Other avenues of scientific outreach include a dynamic land-surface model evaluation, Land Use and Climate, Identification of Impacts (LUCID) with IGBP's Integrated Land Ecosystem-Atmosphere Process Study (iLEAPS) and the WCRP Global Energy and Water Cycle Experiment's (GEWEX) Global Land/Atmosphere System Study (GLASS); collaboration with iLEAPS on an IGBP fire activity including AIMES and PAGES; linking marine ecosystems (Global Ocean Ecosystem Dynamics, GLOBEC) and climate variability (Climate Variability and Predictability, CLIVAR) (see section 7.1.2 below); and a joint experimental design to evaluate biogeochemical (primarily carbon cycle) feedbacks in Earth-system modelling for the the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report with the WCRP Stratospheric Processes and their Role in Climate (SPARC) project, the WGCM, IGBP's Integrated Global Atmospheric Chemistry (IGAC) project and the IPCC's Task Group on New Emission Scenarios (TGNES) (Hibbard et al. 2007, Taylor et al., 2008).

Implementation Strategy and Research Activities

AIMES' research activities are in part derived from historic GAIM activities and in part represent new initiatives, incorporating human and environmental interactions. With AIMES' broad remit as an integrative modelling project, there is a danger of attempting to initiate or lead multiple projects or activities with diffuse results. To ensure productive and successful implementation of the AIMES themes, AIMES SSC leadership is required. This ensures activities within the AIMES themes represent more successfully the components of Earth-system model development and it ensures the evaluation necessary to represent human activities and decision-making in Earth-system modelling. A representative suite of AIMES activities leading to Earth-system modelling and their current status is summarised below.

Theme 1: Process and parameterisation

Observations and process understanding are required to support model development. In particular creating coherent global-scale models often requires integrating observations from different sources, regions and disciplines.

The Global Emissions Inventory Activity (GEIA)

The need of Earth-system global models for accurate data on sources of human and natural emissions from the Earth's surface (for example, fossil fuel and the terrestrial biosphere) and its atmosphere (e.g. aircraft and lightning) motivated the creation of GEIA. Initially this was a data synthesis activity, but more recently it has become a process and parameterisation project under AIMES. The shift reflects the need to progress from simply prescribing emissions in atmospheric chemistry models to predicting emissions within a coupled modelling framework (Figure 5). Accordingly, GEIA will facilitate model development, evaluation and intercomparison and continues its strong focus on data synthesis.

GEIA collaborates with three IGBP core projects: Integrated Global Atmospheric Chemistry (IGAC), Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS) and the Surface Ocean–Lower Atmosphere Study (SOLAS), as well as the WCRP Stratospheric Processes and Their Role in Climate (SPARC) project.



Figure 5. Representative atmospheric chemistry models that use emissions inventory data. Note that with increasing levels of process information, the time for model calculations also increases (from the final report of the GEIA summer school on surface emissions and prediction of atmospheric composition changes.)

AIMES will establish links with the other international projects involved in ocean and human studies. New information developed as part of GEIA continues to be organised, communicated and solicited through the GEIA website (www.geiacenter.org), supported by the National Science Foundation and NASA, and the GEIA e-network (over 500 scientists worldwide). This work is performed in collaboration with the ACCENT European Network (Atmospheric Composition Change: A European Network). Its website, www.accent-network.org, currently hosts the most recent GEIA inventories and databases. (Table 1) In collaboration with SOLAS, iLEAPS and others, GEIA also promotes capacity and outreach activities including summer schools, which provide training and important next steps in emissions and Earth-system modelling. GEIA is a self-governing activity, co-sponsored by AIMES and ACCENT. It is expected that GEIA will continue to collaborate with AIMES on future emissions inventory activities through to 2015.

Climate and Marine Ecosystems

Changes in the frequency and amplitude of modes of climate variability profoundly influence a variety of ecological processes and, consequently, temporal and spatial patterns of population and species abundance (e.g., Stenseth et al. 2002, 2003; Wang and Schimel 2003). These changing spatial patterns can have significant societal impacts, for example, by benefiting or harming different nations or groups of resource users, and by disrupting international agreements regarding the division of fishery benefits (Miller and Munro, 2004). Indices of large-scale climate modes, in contrast, provide an integrated measure of weather, and therefore can be linked to the overall physical variability of the system (Stenseth and Mysterud 2005). For instance, indices for the North Atlantic Oscillation (NAO) imply information about temperature, storms and precipitation, cloudiness, hydrographic characteristics, mixed layer depths, and circulation patterns in the ocean and explains more of

Global Inventories				
Inventory	Categories	Spatial resolution	Temporal resolution	Period
POET	Anthropogenic biomass burning natural	1" x 1"	annual (anthro) monthly (biom. burn.) monthly (nat.)	1990-2000
RETRO	Anthropogenic biomass burning	0.5" x 0.5"	monthly	1960-2000
EDGAR 32FT200	Anthropogenic biomass burning	1" x 1"	annual	2000
GFED v2	biomass burning	1" x 1" GFED home site)		1997-2005
GICC-bb	biomass burning	1" x 1"	monthly	1997-2005
CO ₂ Andres <i>et al.</i>	Anthropogenic	1" x 1"	annual	1997-2003
GEIA v.1	Anthropogenic biomass burning natural	1" x 1"	annual + monthly for NOx,SO ₂ , & nat VOC	depending on the compound
AMAP-Mercury	Anthropogenic	0.5" x 0.5"	annual	1995 & 2000

Table 1. Example of emissions inventories from the Global Emissions Inventory Activity (GEIA).

Regional Inventories

Inventory	Categories	Spatial resolution	Temporal resolution	Period
REAS - Asia	Anthropogenic	0.5" x 0.5"	1 year	1980-2020
EMEP - Europe	Anthropogenic	0.5" x 0.5"	1 year	1970-2020
ABBI - Asia	biomass burning	1" x 1"	1 year	March to May 2000 - March to May 2001

Remark:

- anthropogenic: fossil fuel use + biofuel use + industry + agriculture waste burning
- biomass burning: fires from wild lands (forest fires + savannah fires)
- natural: vegetation and oceans emissions





the observed variability of a species than just, say, water temperature (Figure 6). Moreover, since oscillatory mode variations produce coherent variations in climate over large regions, they produce impacts on ecosystems at spatial scales that have major effects on society in many ways, including substantial control over Atlantic and Pacific fisheries, wildfire and other disturbances. Modal variability thus forms a natural subject in which investigators of climate, ecosystem and climate impact science can collaborate. AIMES will collaborate with other IGBP projects for model-data inter-comparisons as well as evaluation and benchmarking global ocean ecosystem models.

Theme 2: Regional-global interactions

AIMES is developing a regional-global coupling strategy to link human and natural processes of the Earth system. Regional-global interactions of the Earth system and human development are considered through two pathways:

- (1) When rapid change in the human system in a particular region has the potential to trigger a global response, either directly through transport of materials or indirectly through teleconnections in climate. To appreciate the significance of the regional information, it has to be embedded in a global context. For example, intense land-use change and industrial/urban emissions in Asia could affect the climate and hydrological cycle across the entire Asian monsoon region, with major consequences for its large human population; and
- (2) When global changes trigger rapid changes in a region with the potential for global feedbacks. The emphasis here is not so much direct human causation within the high latitudes, but the consequences of human actions external to high latitudes. This regional-global interaction is strongly represented by the effect of global climate change on northern high latitude (NHL) hydrology, land-surface properties and carbon storage, which could produce global amplifying effects on lower latitude climates. Such feedbacks are not well quantified at present, despite their potential importance for human activities.

The global perspective from AIMES unravels such interactions at a distance through collaboration with integrated regional studies including the Large-scale Biosphere-Atmosphere Experiment in Amazonia (LBA) and ESSP activities, exemplified by the Monsoon Asia Integrated Regional Study (MAIRS). The LBA project was a pioneering international research initiative led by Brazil, which was designed to quantify the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia, the impact of land-use change on these functions, and the interactions between Amazonia and the Earth system. AIMES will collaborate with MAIRS and LBA scientists, providing a global dimension to the regional-global interaction pathway described above.

Northern high latitudes regional-global interactions: quantifying and understanding connectivity between global change and the state of the boreal and Arctic regions

The Arctic and high latitudes are known to have responded strongly to external forcing in the past, and

the role of internal feedbacks (vegetation, sea ice) is well established. As described above, in the second regionalglobal interaction pathway, the northern high latitudes (NHL) are now changing rapidly under both direct human pressures and the impacts of global warming. Because of biogeochemical, hydrological and energy feedbacks between the Earth system and the NHL, the future state of the entire Earth system is strongly dependent on the response of the NHL to warming (e.g., Figure 7). Current research focuses on many issues central to IGBP, such as:

1. The vulnerability of vast NHL soil carbon stocks to warming-induced mineralisation, and vegetation changes which could accelerate CO_2 accumulation in the atmosphere and thus act as a positive feedback on climate change.



- 2. Changes in albedo, e.g., the interactions between reduced sea ice and snow-cover, changing vegetation, and energy balance. Reductions in albedo associated with reduced snow and ice and increased forest cover will increase the absorption of radiation and raise temperatures, another positive feedback. (Aerosols and their effect on haze and interactions with clouds are more uncertain.)
- 3. Changes in terrestrial hydrology, e.g., the implications of altered precipitation and evaporation ratios on terrestrial runoff with regard to permafrost dynamics and ocean salinity gradients. Freshwater loading on the Arctic Ocean from river discharge is important as a control on the thermohaline circulation, so changes in discharge could affect North Atlantic deep-water formation with far-reaching climatic consequences.
- 4. Changes in ocean circulation, e.g. potential changes in thermohaline circulation through surface warming (see 2, above), changes to the salinity gradient (see 3, above) and altered CO_2 uptake (see 1, above), and changes to ocean solubility and uptake rates, all of which could feed back on global climate.
- 5. Changes in human behaviours, e.g., in the lifestyle of indigenous communities, and the potential opening of new shipping routes.

An initial survey of representative NHL activities (past, present and planned) includes, but is not limited to: International Polar Year 2007-8; Ecosystem Studies of Sub-Arctic Seas (ESSAS), through GLOBEC; Global Terrestrial Network on Permafrost (GTN-P); Northern Eurasian Earth Science Partnership Initiative (NEESPI); Boreal Ecosystem-Atmosphere Study (BOREAS); EuroSiberian Carbon Flux; NSF Arctic System Science (ARCSS); The International Tundra Experiment (ITEX); The Circumarctic Environmental Observatories Network (CEON); The Arctic Regional Climate Model Intercomparison Project (ARCMIP); Global implications of Arctic climate processes and feedbacks – (GLIMPSE); Arctic Ocean Model Intercomparison Project (AOMIP). These numerous activities provide insight into local or regional processes and indicate a high degree of international interest in Arctic environments. Yet we still lack a coherent strategy to integrate the various process, observation and modelling studies in a global context.

In a NHL activity, AIMES will therefore focus on *integrating across process studies and scales*. AIMES will help coordinate the various northern high-latitude studies, and relevant global environmental change programmes. A global modelling framework will facilitate analysis of potential feedbacks between humans, biogeochemistry and climate. A NHL-focused activity will aim to improve how key NHL processes in Earth-system models are represented by drawing on a range of observational, experimental and regional modelling studies. It will also apply to global models in an attempt to quantify key vulnerabilities and thresholds arising out of the coupling between NHL and the Earth system. It is expected that AIMES will develop the necessary collaborations with WCRP and other international projects to implement an NHL activity by 2010.

Theme 3: Applied Earth-system science

Decision-makers increasingly request insight into the interactions and feedbacks between human activities and the climate system. It is clear we need applied Earth-system science (AESS) to bridge understanding between the scientific community and the public and policy communities. The AIMES AESS science theme therefore embraces two challenges that will provide 'usable science' to the public, policy and assessment communities: (1) providing linkages between increasingly complex coupled Earth system models into assessment activities, and (2) translating research results into useable science for resource managers and decision makers. Two AIMES-led AESS activities are discussed below.

Applications of Earth-system models in climate change assessment

A workshop in 2006, co-sponsored by AIMES, the WCRP WGCM and the Aspen Global Change Institute (AGCI) began a dialogue for scenario development and an experimental design for the climate modelling community for the IPCC Fifth Assessment Report (AR5) (Figure 8). The aim of this collaboration is to develop a more transparent alternative to 'emissions scenarios', or the historic Special Report on Emissions Scenarios (SRES) (Nakićenović and Swart 2000), focusing on mitigation pathways to greenhouse gas stabilization that would (a) allow a broader participation of modelling groups, including stand-alone terrestrial and marine biogeochemistry models, the fully-coupled carbon cycleclimate models as well as the atmosphere-ocean general circulation models, and (b) provide a more coherent



Figure 8. Participants from Aspen Global Change Institute (AGCI) in 2006 representing AIMES, the WCRP's Working Group on Coupled Models (WGCM), IGAC, SPARC, GEIA, and the integrated assessment and impacts communities.

suite of model results for policy and decision-makers to use (Figure 9). Outcomes from this workshop and others describe the carbon cycle diagnostics long-term experimental design (Hibbard *et al.*, 2007), an in-depth joint IGBP and WCRP report (Meehl *et al.* 2007) and a report to the IPCC on new scenarios (Moss *et al.* 2008). AIMES and the WGCM will continue a productive collaboration through to 2015 with products including peer-reviewed papers, co-sponsored (IGBP/WCRP) reports and new joint activities.

The International Nitrogen Initiative (INI)

The growing human population means demand for food and energy is rising. This has more than doubled the production rate of reactive nitrogen on the land surface and altered the nitrogen cycle globally more than that of any other element (Vitousek *et al.* 1997). Consequently, in many parts of the world the conversion of N_2 to reactive forms (nitrogen oxides plus other oxidised nitrogen species, NH_3 , NH_4 , and organic N) is now controlled



Figure 9. Approaches to developing of global scenarios: (A) previous sequential approach; (B) proposed parallel approach. Numbers indicate analytical steps (2a and 2b proceed concurrently). Solid arrows indicate transfers of information. Dotted arrows indicate integration of information. Figure adapted from Moss *et al.*, 2008, 2009.

mainly by fertiliser production, combustion of fossil fuel, and biological fixation in agriculture, which have come to dominate over the natural processes of biological nitrogen fixation (BNF) and lightning. But the production of reactive nitrogen is far from uniform. A persistent lack of nitrogen to grow food has maintained food insecurity and continuing land degradation in many developing countries, while the developed countries have experienced pollution by excessive nitrogen in the biosphere, leading to aquatic eutrophication and loss of terrestrial biodiversity.

The challenge is how to optimise nitrogen use to sustain life, and to minimise the negative impacts of nitrogen on the environment and human health. INI was established in 2003 to address this challenge. INI focuses on (1) the assessment of basic knowledge on the production and distribution of reactive N, (2) finding solutions for regions with an under- or over-abundance of N and (3) scientific, engineering and policy tools to implement such solutions. It is expected that INI will function as a self-governing body, in collaboration with AIMES and its co-sponsor, the Scientific Committee on Problems of the Environment (SCOPE).

Integrating socio-economics and Earth-system modelling

Quantitative predictions tend to be both inherently uncertain and potentially misleading because human actions are imperfectly predictable and the structure of the societies and economies that drive those actions evolve continuously. Using economic components in a complex global prediction model is therefore a conceivable use, but not the only use (and probably not the most important use) of economics in applied Earth-system science. An alternative approach is to build integrated models strategically to respond to specific policy questions. This approach can explore for example the relative effects of different policies, unexpected effects of policies, the effects of different levels of policy stringency, and the distribution of the costs of policies among nations and sectors.

Potential approaches to embed economic theory in integrated Earth-system modelling can be divided into four areas. (1) National or sub-national models of supply and demand could contribute to understanding the drivers of greenhouse gas emissions, predicting adaptation responses, and estimating the economic costs and benefits of such actions. (2) Global economic models of trade and migration could allow exploration of how behaviour in one country affects other countries and imposes consistency at a global scale, so that global resources are fully but not over-used. (3) Economic theory could help to design policies that create appropriate incentives within and between countries; this approach could motivate model simulations and contribute to their interpretation. (4) Policy evaluations could be carried out, using a combination of qualitative assessment and econometric models. The results of policy evaluations should feed back into (3) but also into the basic modelling of (1) and (2) and the science components needed to create better policies, and more useful policy-evaluation models in the next round.

Considerable work has already been done with socioeconomics on approaches (1), (2) and (3) above, but much less on (4). There are successful models of integration of economics and natural science especially with regard to energy, but there could usefully be more. AIMES will contribute to integrating socio-economic and climate modelling communities through collaboration and cooperation with the integrated assessment communities. It is expected that AIMES will examine approaches to promote modelling activities for policy evaluation, drawing on the various approaches outlined above and promoting linkages between key socio-economic communities and the global environmental-change community.

Theme 4: Earth system dynamics

Two groundbreaking AIMES activities have begun to address the fundamental challenges of Earth System Dynamics: one principally from a biogeophysical-biogeochemical perspective on the consequences of industrial CO_2 emissions, the other from the perspective of human affairs.

The coupled carbon cycle-climate model intercomparison project (C⁴MIP)

C⁴MIP was proposed in 1998 as a GAIM-WGCM collaboration to analyse the interactions between the carbon cycle and climate in the presence of anthropogenic forcing. The first results of C⁴MIP (Friedlingstein *et al.* 2006), also reported in IPCC Fourth Assessment Report (Denman *et al.* 2007), have shown that the climate-carbon cycle feedback is positive (i.e. carbon cycle processes tend to amplify global warming), but that there is a large uncertainty concerning its magnitude (Figure 10).



AIMES will pursue several avenues of research that follow naturally from these findings. On the one hand, narrowing the spread of model simulations is a priority; this will require new diagnostics that can identify potential errors in the carbon cycle simulation, in the climate models and in their interaction. On the other hand, several new directions for coupled modelling will address further Earth-system processes and feedbacks, especially those involving biogenic emissions, aerosols and atmospheric chemistry, and those involving ecosystem services.

Ice-core records, now extending to eight glacial-interglacial cycles, show remarkable covariation of climate and biogeochemical indicators including CO₂, CH₄ and dust (Petit et al. 1999, EPICA members 2004), while extensive marine and continental palaeodata document widespread changes in ecosystems and climate. Models have not yet attempted to simulate the evolution of the biogeochemical cycles over these time scales, and the observed 80 ppmv change in CO₂ and 350 ppbv change in CH₄ between glacial maxima and interglacial states are still not unequivocally explained. One next step for the Earth-system modelling community will be to address this "ice core challenge" for CO₂ using coupled carbon-climate models. This activity is called the PalaeoCarbon Model Intercomparison Project (PCMIP). The principle of PCMIP will be first to simulate the Last Glacial Maximum (LGM) marine and continental carbon cycles, then to attempt to simulate the transient evolution of the Earth system from glacial to interglacial states. This will take into account the full range of

mechanisms capable of modifying CO_2 on this time scale including changes in ocean circulation, marine ecosystems, sea-level and continental shelves, and terrestrial dust export.

Later, using carbon cycle-climate-chemistry models now being developed, C⁴MIP will spin off a project to address glacial-interglacial changes in atmospheric oxidising capacity, methane concentrations, and the global N cycle. One goal of the Palaeoclimate Modelling Intercomparison Project (PMIP, supported jointly by PAGES and the WCRP project Climate Variability and Predictability (CLIVAR)) is to foster the creation of well-documented, spatially explicit marine and terrestrial palaeodatasets for comparison with climate model outputs. C⁵MIP will build on PMIP data and modelling efforts and will be pursued in co-operation with e.g., GEIA, IGAC, ILEAPS and PAGES.

The current C⁴MIP models represent managed ecosystems simplistically, or not at all. However, in the modern world, land use and land-cover changes have a significant impact on the climate system through biophysical changes and biogeochemical cycles. They too should be included in global models for simulating the climate of the 20th and 21st centuries. Further, ecosystem services such as crop yield, food and fibre production and fisheries are likely to be affected in the future by climate change and by changes in atmospheric CO₂ and other aspects of atmospheric chemistry such as NOx deposition and surface O₃ concentration. Ecosystem services are those functions of ecosystems that directly or indirectly support human welfare (Costanza *et al.* 1997). The Millennium Ecosystem Assessment (2005) drew attention to the extent to which human activities depend on ecosystem services, and the associated risks of nonsustainable biosphere management (Figure 11). AIMES will promote the development of terrestrial and marine ecosystem-services modelling, including the consequences of environmental and management changes, as a component of Earth-system modelling and in partnership with other relevant IGBP projects including for instance, GLP, IMBER and LOICZ.

The Integrated History and Future of People on Earth (IHOPE)

The recent history of the Earth has traditionally been cast in terms of the rise and fall of great civilisations, wars, and specific human achievements. This narrative omits ecological and climatic contexts and leaves open vital questions about how society and environment interact.

IHOPE's goal is to integrate human history with a detailed, spatially explicit environmental history. Three major questions – one substantive, one operational and one strategic – have emerged as central to IHOPE: (1) What factors govern the emergence and sustainability (or collapse) of socio-ecological systems? (2) How can we evaluate alternative explanatory frameworks and models against observations of highly variable nature, quality and coverage? (3) How can we use knowledge of human-environment interactions in the past to better envision the future? In attempting to answer these questions, IHOPE should provide a richer picture of how and why the Earth has changed in the recent and more distant past, with possible lessons for the future.



Figure 11. The strength of linkages between groups of ecosystem services and human well-being including extent to which socio-economic factors can mediate those linkages (From Millennium Ecosystem Assessment (2005)). One of the challenges for AIMES will be to develop a framework for the linked human-environmental and climate systems.

CONSTITUENTS OF WELL-BEING

The IHOPE Research Information System, or IRIS, will be used to test integrated models and shed light on the processes by which human societies have adapted (or failed to adapt) to a changing physical environment. Through a collaboratory IRIS, IHOPE will (1) map the record of natural and human-system change on the Earth over the last several millennia, with increasing temporal and spatial resolution towards the present; (2) assess the impacts of historical human activity on biogeochemical cycles and climate; (3) develop and test hypotheses about the responses of human societies to environmental change; and (4) using innovative modelling approaches, try to project with more confidence and skill the options for the future of humanity (Figure 12).

The IHOPE community includes archaeologists, who study and interpret what has happened to human societies; anthropologists, who investigate how the structure of societies change; Quaternary scientists (including palaeoecologists) who study what happened to the physical and biological environment; geographers, who manage and analyse data over multiple temporal and spatial scales; and Earth-system scientists who are interested in the interaction of human activities, e.g. with hydrologic processes and the biogeochemical cycles. It is recognised that many of the disciplines that could contribute to IHOPE employ models that represent very



Figure 12. The IHOPE Research Information System (IRIS) will consist of web-based collaboratory tools where colleagues and projects can discover, access and provide data systems and portals and use or provide analytic or modelling tools. IRIS will facilitate integration of data access, discovery and inference. (Figure courtesy of S. Aulenbach from Hibbard *et al.*, 2008).

different views of historical information and operate on different temporal and spatial scales. Conflicting goals across disciplines must be addressed to develop creative solutions to the appropriate interpretation and analyses of disparate observations and modelling approaches.

IHOPE is starting with regional case studies where dense data are available. This is the result of research in a wide range of disciplines, and representative of the many categories of data to be collected ultimately at the global scale. Regional case studies are being framed through the coupled process and transitions of the humanenvironment system: for example, the colonisation of pristine landscapes by hunter-gatherers in Australia; the colonisation and abandonment of landscapes by huntergatherers in the Sahara during and since the Holocene; recolonisation by humans in northern Europe after the deglaciation; the transition to settled agriculture in the Middle East; and the Viking Landnam colonisation of inhabited regions. The regional case studies will quantify population numbers and density through time, quantify and map areas affected by specific settlements and/or populations, apply objective schemes to assess human impact on natural vegetation from palaeoecological records, quantify and map timings of population expansion and migration events, and synthesise environmental reconstructions.

Expected outcomes from the IHOPE project include a new, trans-disciplinary community of archaeologists, anthropologists, palaeoclimatologists, historians, ecologists, data system specialists and modellers. IRIS will provide the platform for interdisciplinary query and interaction. Products from IHOPE will include peerreviewed papers, books and new, coupled human-natural system collaborations towards understanding human/ environmental interactions from human settlement to present through to future. An end-time for IHOPE is not anticipated within the span of the AIMES project of ten years (to 2015), but well beyond. It is expected that IHOPE will develop its own central coordinator by 2010.

Capacity Building and Networking

The Young Scholars Network (YSN)

YSN fosters international collaborations among earlycareer scientists and scholars on integrative research to understand the interaction of humans, biogeochemistry and climate better. Topics for YSN workshops are generated through discussion and election by YSN participants. Thematic criteria include relevant topics in Earth system science that embrace social, humanities and biogeochemical interactions and feedbacks with the climate system. Criteria for participant selection includes: (1) integrative research orientation, (2) geographic and disciplinary breadth (with participation from developing countries strongly encouraged), and (3) sufficient representation from the human and social sciences. For each workshop, two young scholars work with leading senior participants to develop the agenda and outcomes. In addition to young scholar support, two to four senior scholars are supported by AIMES to interact with the YSN participants. Expected outcomes of annual YSN meetings include workshop reports or peer-reviewed white papers. Long-term outcomes are a cohort of young scientists and scholars with the resources to develop inter- and trans-disciplinary research activities in Earth system science.

Other capacity-building activities

In addition to YSN, AIMES will promote capacity building in global environmental-change research through other IGBP projects, the ICSU's global environmental change programmes, coordinated by the Earth System Science Partnership, the SysTem for Analysis Research and Training (START, also coordinated by ESSP), the Inter-American Institute (IAI) and the Asia-Pacific Network (APN). Training workshops for early-career scientists, to be held in developing regions, will be coordinated with relevant projects and programmes. Funding will be sought from multiple international sources, to maximise global participation. Project Organisation and Management



The SSC is responsible for providing scientific guidance to and overseeing the development, planning and implementation of the AIMES core project, including communication of ongoing AIMES activities and fostering the publication and dissemination of AIMES results. The SSC will encourage national governments and regional and international funding agencies to support the implementation of core research and the achievements of AIMES goals through the provision of adequate support at national, regional and international levels. The SSC will also encourage collaboration between AIMES research and relevant activities of the sponsors and others, including liaison with other IGBP projects and ESSP programmes and projects.

The International Project Office (IPO) serves as the secretariat for AIMES, and administers the project on a day-to-day basis. The IPO is responsible for assisting the SSC in all aspects of its work, and collates and communicates information related to national and international AIMES research. The IPO works with IGBP to secure resources for AIMES. It also ensures effective coordination with other IGBP activities and supports a data management and archiving system for AIMES. The IPO keeps a record of AIMES products, including syntheses and review papers, workshop reports, books and book chapters, journal special issues of features, and data and model output. Wherever possible, these are made freely available on the AIMES website (http://www.aimes.ucar. edu), which will also publish general information about AIMES activities.

The AIMES SSC meets annually, and about every other year AIMES meets jointly with the WGCM to ensure collaborative global climate model communication on activities and progress in Earth system model development. Additionally, AIMES will meet with other IGBP and global environmental change projects (including ESSP) at least every five years to discuss ongoing and future visionary and collaborative activities.

Recognition of research projects

AIMES provides a flexible framework to encourage the fullest participation and collaboration of multinational, regional and national efforts. A recognition ("endorsement") system is required so that (1) the AIMES SSC knows what research is being conducted under the AIMES banner, (2) research under the AIMES banner is within the science areas defined in the science plan, and (3) such research conforms to the scientific principles and ideals outlined in the science plan.

Principal investigators and national/regional groups can submit projects, through the IPO, for recognition by the AIMES SSC. The following benefits and responsibilities flow from recognition as an AIMES project.

Benefits of recognition

Recognition as an AIMES project:

- Provides an opportunity for participation in the development, planning and implementation of a collaborative international research programme.
- Adds to the scientific value of planned work by providing complementary information; for example, by widening the range of studies and extending their spatial and temporal coverage.
- Promotes rapid communication of ideas and results through meetings and publications.
- Makes available modelled and measured/observed datasets and develops a common data policy.
- Enables close working links with other relevant international programmes and activities.
- Gives opportunities for participation in model and model-data fusion, development and intercomparison activities.

Responsibilities of recognition

Recognised projects are expected to:

- Accept the general principles and goals outlined in the AIMES science plan.
- Carry out research broadly in accordance with the relevant aspects of the science plan.
- Participate in AIMES activities and assist in AIMES planning and development.
- Acknowledge AIMES and IGBP contributions in research products and activities, for example, acknowledgement of AIMES and IGBP in scientific papers and reports.
- Make data collected and model outputs generated within the project available to the wider community through the AIMES IPO.

The AIMES IPO was established in 2005. It is anticipated that AIMES will continue to 2015. The success of AIMES will depend not only on practical advances in Earth system model development and application but also on visionary approaches to integrative science. Many of AIMES' goals to understand and quantify the coupled human-environment systems will require 'out-of-the-box' thinking and foresight. As such, a balanced portfolio of activities ranging from low-to-high risk of success is necessary.

AIMES Vision

As the Earth-system modelling community and AIMES mature, coupled biogeochemistry and climate modelling activities will increasingly be used for impacts, adaptation and vulnerability studies of human and ecological systems. AIMES will work towards this goal in collaboration with the WCRP (e.g., WGCM) and other international communities (e.g., IPCC) with initial analyses of model skill, evaluation and benchmarking terrestrial and marine biogeochemical components during the first five years, or to 2010. During this period, steady and incremental progress on implementation of biogeochemical cycles for terrestrial and ocean components into atmosphere-ocean general circulation models will be promoted as well as an AIMES contribution to high resolution 'seamless prediction' activities with WCRP, but also, utilising new Earth system model formulations to coordinate with impacts, adaptation and vulnerability communities towards an evaluation of possible thresholds, tipping points and extreme events on human and ecological systems.

AIMES is also charged with introducing human activities into Earth-system models. AIMES will contribute to this need through interdisciplinary workshops and promote the coordination of socio-economic and Earth-system modelling activities. The goal of such cooperative activities will be to gain a basic understanding of how humans interact with environmental systems, and also to create a framework for Earth-system science to be applied in the analysis and solutions of environmental problems. To further promote this discussion, AIMES will promote activities that engage social scientists, historians and other scholars of the human enterprise. Including humanenvironment interactions into discussions of integrative Earth system science will accelerate both basic human dimensions science and the development of applied Earth-system science, leading to new and innovative approaches for the global environmental change programmes and projects beyond 2015.

To broaden the scope and participation of AIMES, an Open Science Conference (OSC) will be held on Earth systems analyses in 2010 with themes ranging from forecasting, assimilation and human-environmental interactions. This OSC will provide a venue for the evolution of future integrative and applied Earth-system science activities through 2015, when a final OSC will be held as a synthesis meeting. It is anticipated that both OSC meetings will produce special issues in a peer-reviewed journal or contracted for a book, to be determined by the AIMES SSC.



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Acronyms

ACCENT	Atmospheric Composition Change: a European Network	EMDI	Ecosystem Model-Data Intercomparison
AESS	Applied Earth System Science	EPICA	European Project for Ice Coring
AIMES	Analysis, Integration and Modelling of the Earth System	ESSAS	Ecosystem Studies of the Sub-
AOMIP	Ocean Model Intercomparison Project	ESSP	Earth System Science Partnership
AR4	Fourth Assessment Report of the Intergovernmental Panel on	GAIM	Global Analysis, Integration and Modelling Task Force
ARCMIP	Climate Change The Arctic Regional Climate	GCTE	Global Change and Terrestrial Ecosystems
	Model Intercomparison Project	GEC	Global Environmental Change
ARCSS	Arctic System Science	GECs	Global Environmental Change Programmes
AGCI	Aspen Global Change Institute		
BIOME 6000	Global Palaeo Vegetation Project	GEIA	Global Emissions Inventory Activity
BNG Boreas	biological nitrogen fixation Boreal Ecosystem-Atmosphere	GEWEX	Global Energy and Water Cycle Experiment
BP	Study Before Present	GLASS	Global Land/Atmosphere System Study
C ⁴ MIP	Coupled Carbon Cycle-Climate Model Intercomparison Project	GLIMPSE	Global Implications of Arctic Climate Processes and Feedbacks
CCMLP	Carbon Cycle Model Linkage Project	GLOBEC	Global Ocean Ecosystem Dynamics
CEON	Circumarctic Environmental	GLP	Global Land Project
CLIVAR	Climate Variability and	GTN-P	Global Terrestrial Network on Permafrost
COPES	Coordinated Observation and Prediction of the Earth System	ICSU	International Council for Science
		IGAC	International Global
DIVERSITAS	DIVERSITAS: an international programme of biodiversity science	IGBP	Atmospheric Chemistry project International Geosphere- Biosphere Programme

IGBP-DIS	IGBP Data and Information System	NERC	Natural Environment Research Council
IHDP	International Human Dimensions	NHL	Northern High Latitudes
	Programme on Global Environmental Change	NSF	National Science Foundation
IHOPE	Integrated History and Future of People on Earth	OCMIP	Ocean Carbon Model Intercomparison Project
iLEAPS	Integrated Land Ecosystem- Atmosphere Process Study	OSC	Open Science Conference
		PAGES	Past Global Changes
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research	PIK-NPP	Potsdam Net Primary Productivity activity
INI	International Nitrogen Initiative	RCPs	Representative Concentration Pathways
IPCC	Intergovernmental Panel on Climate Change	RICE	Regional Interactions of Climate and Ecosystems
IPO	International Project Office	SCOPE	Scientific Committee on
IPY	International Polar Year		Problems of the Environment
IRIS	IHOPE Research Information System	SOLAS	Surface Ocean-Lower Atmosphere Study
IRS	Integrated Regional Studies	SPARC	Stratospheric Processes and their Role in Climate
ITEX LBA	International Tundra Experiment Large-scale Biosphere-	SRES	Special Report on Emissions Scenarios
	Atmosphere Experiment in Amazonia	SSC	Scientific Steering Committee
LOICZ	Land-Ocean Interactions in the Coastal zone	TGNES	Task Group on New Emission Scenarios
LUCID	Land Use and Climate, Identification of Impacts	TRANSCOM	Atmospheric Tracer Transport Model Intercomparison
MAIRS	Monsoon Asia Integrated Regional Study	WCRP	World Climate Research Programme
NAO	North Atlantic Oscillation	WGCM	Working Group on Coupled Models
NASA	National Aeronautics and Space Administration	WMP	WCRP Modelling Panel
NCAR	National Center for Atmospheric Research	YSN	Young Scholars' Network
NEEPSI	Northern Eurasian Earth Science Partnership Initiative		

AIMES

Analysis, Integration and Modelling of the Earth System, AIMES Science Plan and Implementation Strategy

AIMES is part of the International Geosphere-Biosphere Programme. IGBP is one of the International Council for Science's four global environmental change research programmes coordinated by the Earth System Science Partnership.

AIMES: www.aimes.ucar.edu

IGBP: www.igbp.net

ICSU: www.icsu.org

