Max-Planck-Institut
für Meteorologie

2020 VISION

THE STRATEGIC PLAN BY THE
MAX PLANCK INSTITUTE FOR METEOROLOGY

Content

Foreword

Since its inception, the Max Planck Institute for Meteorology has sought to understand Earth's climate system, using as its principal tool comprehensive Earth system modeling. It was here, in 1996, that a group led by Klaus Hasselmann identified clearly and for the first time the human fingerprint on global warming. And now, looking out across the decade to come, we are keenly aware of the urgency to expand our understanding of the climate system and the multiple forces acting to change it.

This 2020 Vision formulates our scientific goals, the intellectual challenges inherent in them, and the conceptual questions that will guide our future research – and further shape our scientific identity.

Hamburg, in 2011

Martin Claussen
Jochem Marotzke
Bjorn Stevens

OUR MISSION: TO UNDERSTAND EARTH'S CHANGING CLIMATE

Our mission presents a profound intellectual challenge due to the complexity, multiplicity, and interconnectedness of the climate system itself. What is the present state of our climate, and what causes it to change? Does the system reverberate chaotically and recombine into a new, different state? Or do external forcings such as alterations in the incidence of solar radiation and increased carbon dioxide levels prevail as agents for change? What is the combined effect of forces both internal and external acting simultaneously?

And then there is the problem of timescales. We know from proxy measurements that the climate has lurched many times between glacial and interglacial states, but how do we separate long-term trends from short-term variations? Then, contributing to the complexity and blurring the difference between causality and coincidence, there are numerous, quasi-predictable cycles in the atmosphere and ocean, such as El Niño and the North Atlantic Oscillation, capable of changing weather conditions worldwide.

Industrialization and its demand for natural resources, continental-scale agriculture and its demand for land, and the swelling global population with its demand for everything continue to reshape the Earth. Since the dawn of the Industrial Revolution, our exhausts and effluviums have increased atmospheric carbon-dioxide levels by more than one third. These products of human activity have begun to leave their mark, and are changing our climate. What separates anthropogenic climate change from natural climate variations is its unprecedented rate of change. Not only by changing Earth's climate but by doing so at fast-forward speed, humankind has become a true geophysical force.

It is of course insufficient for a scientist simply to say that humanity — or humanity in conjunction with other forces — has changed the world's climate. As scientists, we need to identify the causes of change and, if possible, need to predict change. But to do so requires a degree of understanding of the climate system as a whole far greater than we possess at present. And that brings us back to our mission and the pressing intellectual challenge before us.

To fulfill our mission by confronting the challenge, we will approach the problem in the light of two guiding questions:
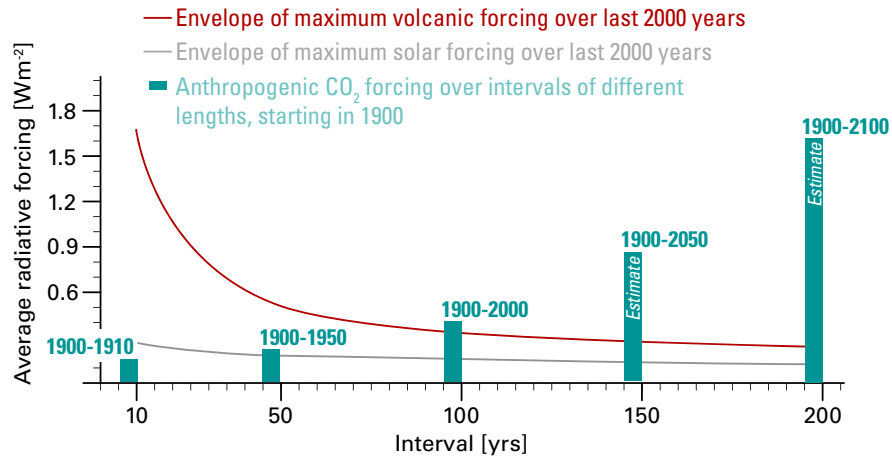
HOW SUSCEPTIBLE IS THE EARTH SYSTEM TO PERTURBATIONS?

and

WHAT ARE THE LIMITS OF EARTH SYSTEM PREDICTABILITY?

Bursting through the envelope of natural forcing variability

Legend:
— Envelope of maximum volcanic forcing over last 2000 years
— Envelope of maximum solar forcing over last 2000 years
■ Anthropogenic CO_2 forcing over intervals of different lengths, starting in 1900

Y-axis: Average radiative forcing [Wm^{-2}] — 1.8, 1.5, 1.2, 0.9, 0.6

X-axis: Interval [yrs] — 10, 50, 100, 150, 200

Bar labels: 1900-1910, 1900-1950, 1900-2000, 1900-2050 (Estimate), 1900-2100 (Estimate)

The burgundy curve shows the maximum of volcanic forcing averaged over intervals of 10 to 200 years, based on a 2000-year reconstruction of volcanic forcing. Because volcanic forcing is episodic, it is smaller when averaged over longer and longer intervals. The maximum at the 10-year interval is therefore an extreme value of natural forcing. By contrast, the other important variability in natural forcing, solar variability (grey curve), is generally smaller than volcanic forcing and shows less dependence on the averaging interval.

The green bars show the greenhouse-gas forcing from CO_2 averaged over longer and longer intervals, each of which starts at year 1900; the future CO_2 forcing is estimated from the SRES A1B scenario. Because this forcing increases monotonically over time, the average forcing increases with interval length.

The striking result is that the CO_2 forcing averaged over the 200-year interval, from 1900 to 2100, has the same magnitude as the largest 10-year average volcanic forcing experienced over the past two millennia. In other words, to have a climatic effect of the same strength as anthropogenic CO_2 by the end of the 21st century, this extreme volcanic event would have to persist for 200 years.

Susceptibility

The susceptibility of the Earth system describes how sensitively it responds to external perturbations. These perturbations could be variability in the strength of the sun, the variations in Earth's orbit, volcanic eruptions, or the anthropogenic increase in greenhouse gases such as CO_2.

An important manifestation of Earth system susceptibility is the **equilibrium climate sensitivity**, which in the field has assumed the role of a reference point. The equilibrium climate sensitivity is usually defined as the change in the globally averaged surface temperature that would result from a doubling of atmospheric concentrations of CO_2. The trouble is that estimates of the equilibrium climate sensitivity have varied between 1.5 and 4.5 K for more than thirty years. To reduce this wide range would not by itself lend insight into the entire Earth system, but it would go a long way toward removing a crucial uncertainty.

The susceptibility of the Earth system is, however, a much broader concept than the equilibrium climate sensitivity. We are thus led to ask questions such as: Will there be more heat waves, or cold spells, droughts and floods in a warmer world? Will the pace of change accelerate as sea ice diminishes? How much more quickly will the high-northern latitudes change and how far poleward will boreal forests migrate? In more general terms, we must ask: To what extent does the response of the system to a perturbation depend on its current state or on the details of the perturbation? Are there tipping points in the system that might cause climate to change abruptly? Can extreme events such as volcanoes or meteor impacts substantially alter the habitability of our planet?

Climate sensitivity depends crucially on the background state
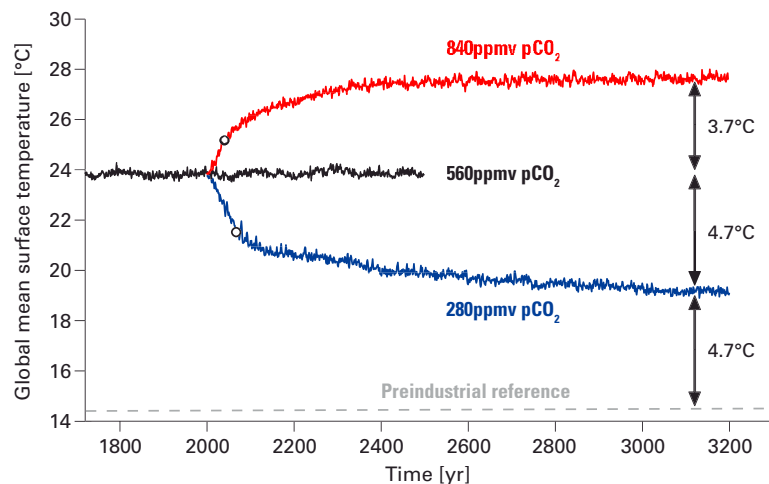
We show climate-model time series of the global mean surface temperature for a time in Earth history known as the late Paleocene (some 55 million years ago). The Paleocene run (black curve) is warmer than the preindustrial reference by 9.4 °C, which is in reasonable agreement with proxy observations. Half of this temperature difference arises because the Paleocene land surface is much darker, as seen by the run with Paleocene configuration but the preindustrial pCO_2 of 280 ppmv (blue curve). The other half arises because the Paleocene run has a higher pCO_2 of 560 ppmv. If we further increase pCO_2 to 840 ppmv (red curve), we obtain an additional warming of 3.7 °C, which resembles one of the most extreme warming events in Earth's history, the Paleocene-Eocene Thermal Maximum (PETM). This warming with only a 50% increase in pCO_2 implies a climate sensitivity of 6.4 °C, much more than our model's "present-day" climate sensitivity of 2.9 °C. The high Paleocene climate sensitivity makes possible a realistic simulation of the PETM with only a modest pCO_2 increase. This increase could have resulted from a number of plausible carbon sources; we have thus offered a solution to the long-standing puzzle of where the carbon came from that caused the PETM.

Heinemann, M., J. H. Jungclaus, C. Li, H. Schmidt, S. Rast, and J. Marotzke, 2011: Paleocene-Eocene Thermal Maximum warming does not require large CO_2 forcing. Under review. The black circles show the points at which the pCO_2 concentrations are stabilized after a transitional phase during which the CO_2 concentration is increased or decreased by 1% per year.

Predictability

Earth system predictability arises from long-term memory within the system, and components of the Earth system with such memory can thus be looked to as sources of predictability. These include: soil properties, sea ice, the stratosphere, the terrestrial and marine biosphere, ocean physics, ocean biogeochemistry, and land ice. Other sources of predictability arise from external forcing such as solar variability, or from anthropogenic forcing such as greenhouse gas emissions.

A fundamental limit to Earth system predictability arises from deterministic chaos, which influences many aspects of atmospheric and oceanic circulation. Practical limits to predictability arise from insufficiently known initial conditions, a situation that must be improved through Earth system data assimilation; but also through limitations to prediction tools, such as model errors. With the exception of research into the origin of external forcings, which is best addressed through cooperation with external partners, all of these issues fall within the scope of existing expertise within the MPI-M.

Research on Earth system predictability leads to a number of conceptual questions, such as whether common processes determine both predictability and susceptibility; and whether there exist fundamental barriers to predictability, caused by processes operating on various space and time scales. More practically we want to know how sources of predictability differentiate aspects of the Earth system. For instance, precipitation may have different sources of predictability than regional or continental-scale temperature anomalies. Processes that dominate error growth and hence predictability on the decadal timescale warrant our concerted attention because this is the planning horizon of modern societies.

The observed time-series from the RAPID/MOCHA program is shown in red, ensemble mean forecasts in dark grey/light blue/dark blue/green for the forecasts starting in Jan 2008/Jan 2009/Jan 2010/Jan 2011. The pale shading represents the 95% confidence intervals of the nine-member forecast ensemble initialized in Jan 2008/Jan 2009/Jan 2010/Jan 2011. Our system predicts a deep minimum in early 2010 and rapid recovery thereafter.

Matei, D., J. Baehr, J. H. Jungclaus, H. Haak, W. A. Müller, and J. Marotzke, 2011: Multiyear prediction of monthly-mean Atlantic Meridional Overturning Circulation at 26.5°N. Under review.

Forecasts of the Atlantic Meridional Overturning Circulation (AMOC) at 26.5° N
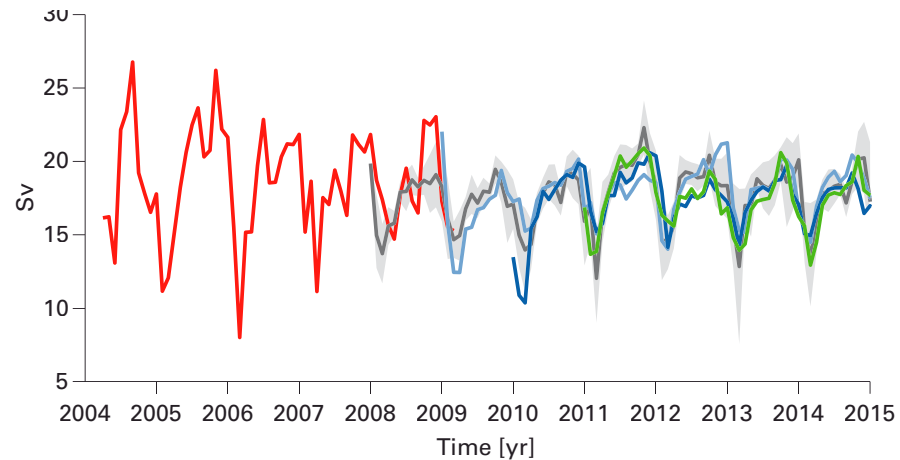
Attribution: linking susceptibility and predictability

To determine how the strength of a climate anomaly relates to a change in a component forcing, requires an understanding of susceptibility, the nature of the imposed change itself, and the inherent predictability of the system, which allows us to link cause and effect. As our climate changes, we witness that our science is increasingly called upon to explain to what extent observed changes can be attributed to natural fluctuations, or to what extent the changes are a response to forcing.

Challenges

The challenge to understand the climate system is as multi-faceted as the climate itself. One central challenge will be to relate susceptibility to a fundamental understanding of the component processes and the constraints they impose. A second challenge will be to better determine the present state of the Earth system, since the question of predictability rests on our ability to think about climate as an initial-value problem.

The **Susceptibility** question asks: To what extent will Earth's climate change if an external forcing agent changes? To answer that question we must understand how climate changes, that is, through what processes. However, there are myriad processes at work simultaneously. We have three prominent approaches with which to accommodate this multiplicity:

Feedback analysis essentially isolates a particular part of the system to glean whether the interaction of processes leads to an amplification or to a dampening of perturbations (positive or negative feedback, respectively). As agents capable of changing the globally averaged surface temperature, feedbacks must alter the flow of energy through the system. Among these are the response of the carbon cycle, clouds, water vapor, and surface albedo.

However, these feedbacks operate on vastly different timescales. Clouds, for instance, can respond immediately to changes in their environment, while carbon cycles through more ponderous reservoirs. A better understanding of the carbon cycle may require a more-complete understanding of the paleo-record, whereas the study of cloud feedbacks may demand a more sophisticated understanding of the satellite record. Hence, our challenge in feedback analysis will be to master emerging data sets on the one hand, and to effectively use a model system spanning a wide range of timescales on the other in order to read causality into the observational record.

Biases in our models indicate that something is amiss, implying that we may have made wrong choices in designing the models, or that we simply do not have enough computing power to make them sufficiently realistic – or both. In practical terms, biases point to specific areas where we must improve our models and our understanding.

For example, maritime boundary layer clouds are often poorly represented in climate models, yet they are widely thought to underlie much of the uncertainty in model-based estimates of equilibrium climate sensitivity. And we do not understand which of the many processes acting in such clouds are crucial. Another example is the persistent surface temperature bias in the North Atlantic, which is considered a crucial area for the processes causing decadal climate variability and hence providing climate predictability.

Despite much wishful thinking, there is also little evidence that additional processes somehow rectify the system so as to ameliorate its biases – quite the opposite. Additional processes, for example those represented in aerosol or carbon-cycle model components, tend to amplify the uncertainty associated with biases. Increasing model complexity is thus by no means equivalent to model improvement.

Scale interactions occur because multiple processes in the Earth system interact non-linearly. Efforts to analyze feedbacks or to reduce biases are complicated by those multiplicities acting across space and time scales. How do the aggregate effects of small-scale processes interact with large-scale flows? This question arises in many guises. It is the cloud problem, the convection and mixing problem, but it also is at the heart of questions related to the representation of the land biosphere, marine ecosystems, sea and land ice. For example, competition of land plants for light and water occurs on the scale of singular plants, while energy and water fluxes drive changes in vegetation composition visible on much larger scales, in part through the action of organisms in reshaping their environment. In some cases the basic equations describing the process of interest are known, but the range of scales involved are computationally intractable. In other cases even the basic equations are unknown, and behaviors must be modeled.

Multi-scale methods that allow spatial, and in some cases temporal, resolution to be concentrated on particular locations, can help to identify regional instabilities or ``hot spots'' wherein fine-scale processes effectively rectify larger-scale circulations. Such techniques will be particularly powerful in those cases when the basic equations describing a component process are known, but presently not used because computational restrictions do not allow for a description of the process on a larger scale – ocean eddies and convective clouds being two examples. However, to work consistently across multiple scales is a great challenge, one that must be overcome if we are to make progress on those questions that guide us.

Discerning between anthropogenic warming and internal climate variability
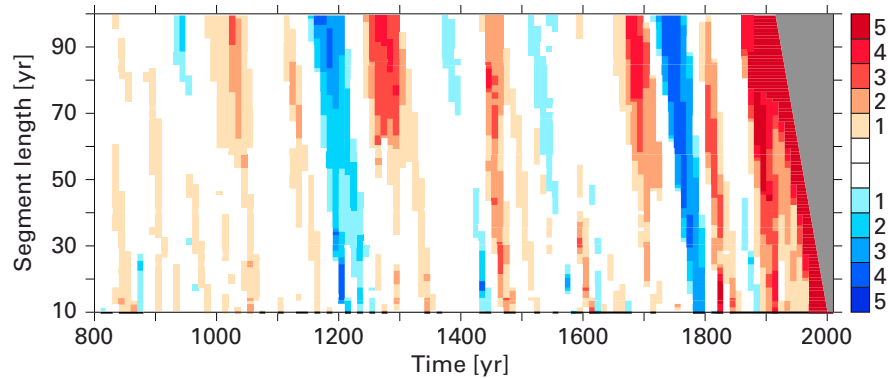
We use a five-member ensemble of simulations of the last Millennium, performed with the MPI-ESM including a fully coupled carbon cycle and forced with our best estimate of solar variability and volcanic forcing. The analysis identifies periods during which warming trends (shades of red) and cooling trends (shades of blue) exceed the 5th-95th percentile range of the respective trends in the control experiment. Starting dates of the trend calculation are shown at the x-axis. The intensity of the color denotes the number of ensemble members showing a trend significantly different from the control run. The two periods in the early 13th and late 18th centuries with significant cooling trends across trend lengths and the ensemble are associated with repeated volcanic eruptions. The 20th century stands out as the only period with warming trends that are significant at all lengths in all ensemble members.

Jungclaus, J. H., et al., 2010: Climate and carbon-cycle variability over the last millennium. Clim. Past, 6, 723-737.

Meanwhile, the **Predictability** question asks to what extent we can predict the future of the climate system given that we have knowledge of its present state. Historically it has been popular to distinguish between climate projection and weather prediction as the difference between a boundary-value problem and an initial-value problem. Climate as an initial-value problem is, however, very much a central aspect of our second guiding question. The use of climate models in forecast mode is also proving valuable to evaluate model biases, because biases in the climate can be related to errors that emerge already on the very short timescales of individual weather or short-term climate forecasts. And transient errors are, given a sufficiently well constrained initial state, readily observable.

For these reasons the next years will see a continued and growing emphasis of the MPI-M on decadal climate prediction as an initial-value problem, as well as the use of techniques from numerical weather forecasting to ameliorate model biases. An important challenge in the development of a prediction system with the capacity to meet these needs will be the provision of accurate and balanced initialization data for the more ponderous elements of the climate system: such as the ocean, sea-ice, upper atmosphere, and the land surface, inclusive of their carbon reservoirs.

Opportunities

We are keenly aware of the challenges that must be overcome to enhance our understanding of Earth's dynamic climate system. But the challenges are not daunting – intellectual and technical opportunities abound as the new decade unfolds.

Our greatest opportunity lies in the advancement of comprehensive Earth system modeling. We will build on the history of research within the MPI-M that started from the development of component models of the atmosphere and ocean, moved to pioneering studies of the coupled atmosphere-ocean system, and recently culminated in the development of the MPI Earth system model. However, increasing further the complexity of our models will not by itself provide answers to our guiding questions; instead, answers will arise from the richness and clarity of the concepts that our models help us create.
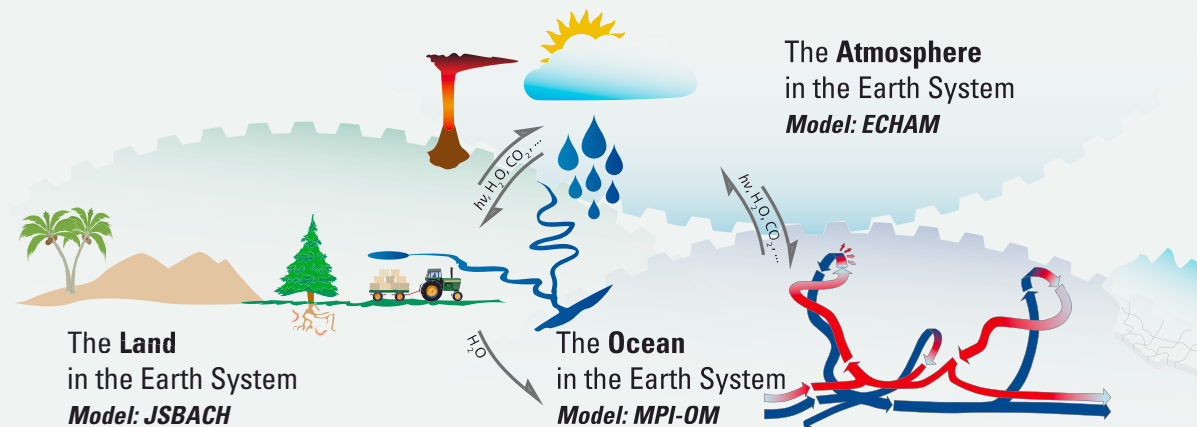
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The MPI-M continues to attract the most talented and creative scientists from around the world. We integrate them into a stimulating institutional environment, which consists of excellent support staff, state-of-the-art facilities, and the physical placement of the MPI-M at the heart of the KlimaCampus in Hamburg, one of Europe's most vibrant and attractive metropolises.

The MPI-M requires and enjoys privileged access to high-performance computing facilities, chief among them the German Climate Computing Centre (DKRZ). The ever-increasing computational capacity makes some tasks easier and others imaginable. For example, the exploration of climate predictability requires the simulation of large ensembles of runs, each differing by a small amount in the initial conditions; this task is greatly aided by a sufficiently powerful computing and data storage system such as at DKRZ. Other simulations have only now become possible, such as replacing cumulus parameterizations by convection-resolving models and thus basing the simulation on much firmer conceptual grounds.

To evaluate and initialize our models, we will increasingly exploit the growing observational record, which allows us to extract fundamentally new insights into the changing Earth system; from the vertical structure of clouds, to the growing uptake of heat by the ocean, to ever richer descriptions of the land biosphere. The global observational record is complemented by a new generation of targeted measurement campaigns aiming at, for example, cloud dynamics in the subtropics or the ocean's meridional overturning circulation.

Opportunities abound. And we have in the Max Planck Institute for Meteorology a practiced, fully functioning institution with a thoroughgoing history in climate research. We have the required quality in our scientific and support staff to develop and use comprehensive Earth system models. We have the technical and scientific capability to augment and integrate into our models a rich and growing observational record. We understand our mission and the questions that must be addressed to realize it. And so, prepared and dedicated, we look forward to the coming decade.

Earth System Science at the Max Planck Institute for Meteorology in Hamburg

The **Atmosphere** in the Earth System
Model: ECHAM

The **Land** in the Earth System
Model: JSBACH

The **Ocean** in the Earth System
Model: MPI-OM

1975	1976	1979	1985	1987	1989	1991	1992	1993

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Climate Dynamics

Physics of the Atmosphere

Climate Processes

Climate Modelling

A new director at the MPI-M:
Hartmut Grassl
Climate Processes
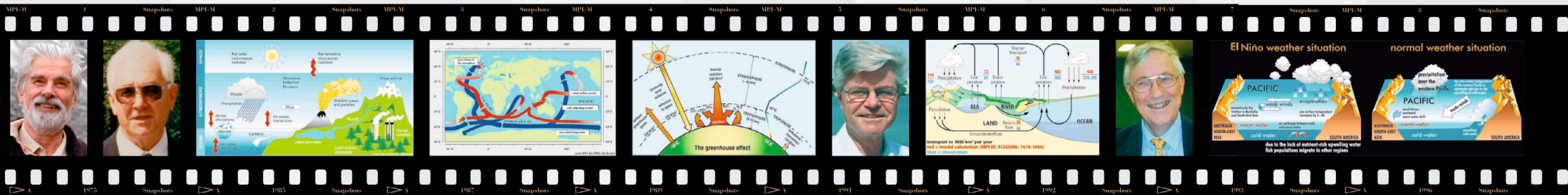
A new director at the MPI-M:
Lennart Bengtsson
Climate Modelling

Foundation of the MPI-M with two directors:
Klaus Hasselmann (left) **Climate Dynamics** and
Hans Hinzpeter (right) **Physics of the Atmosphere**

Start of the **DKRZ**

1975	1976	1979	1985	1987	1989	1991	1992	1993

1994	1996	1999	2002	2003	2005	2006	2008	2010

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Biogeochemical System

The Atmosphere in the Earth System

The Land in the Earth System

The Ocean in the Earth System

A new director at the MPI-M:
**Guy Brasseur**
Biogeochemical System

A new director at the MPI-M:
Jochem Marotzke
The Ocean in the Earth System

A new director at the MPI-M:
Bjorn Stevens
The Atmosphere in the Earth System

A new director at the MPI-M:
Martin Claussen
The Land in the Earth System

Start of the International Max Planck Research School on Earth System Modelling, **IMPRS-ESM**

Earth System Model
MPI-ESM
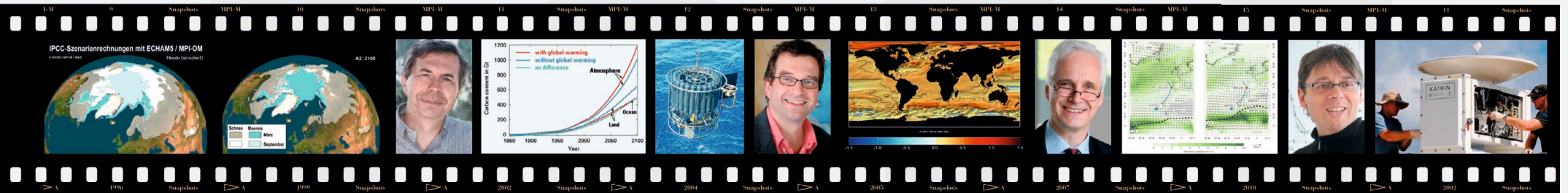
1994	1996	1999	2002	2003	2005	2006	2008	2010

ORGANIZATIONAL OUTLOOK
& INITIATIVES

The fundamental structure of the MPI-M reflects that our science is rooted in the process description of the main compartments of the climate system: the atmosphere, the ocean, and the land surface. Therefore the MPI-M consists of three scientific departments, each led by a director, with the position of the managing director rotating among the three directors. We do not expect this structure to change during the coming decade.

Board of Trustees	The Max Planck Society for the Advancement of Science
	Scientific Advisory Board
supports	Max Planck Institute for Meteorology
External Scientific Members Emeritus Scientific Members	Managing Director Scientific Directors
Independent Research Groups	Strategic Planning - Coordination
Max Planck Fellows	Management Committee
	University of Hamburg

The Atmosphere in the Earth System

The Land in the Earth System

The Ocean in the Earth System

The International Max Planck Research School on Earth System Modelling

Integrated Activities

Scientific Working Groups

Service

The MPI-M is located in the heart of one of Europe's most liveable and vibrant cities. It provides a highly international and interdisciplinary environment for conducting scientific research as well as access to state-of-the-art scientific facilities.

Max Planck Institute for Meteorology, Hamburg

Structure and people

Departments will generally consist of roughly 50-60 people: around 30 PhD-level scientists, around 15 PhD candidates, and 10-15 administrative and technical support staff. Because we do not wish to significantly enlarge the MPI-M, strategic initiatives supported by base funds must, at least in part, be compensated by a reduction in externally funded research.

Research in the departments is further broken down into working groups each led by a senior scientist who works with the director of the department to define the day-to-day scientific activities. To enhance interdisciplinary work and communication across departments, we regularly initiate cross-cutting projects and maintain an active visitor program as well as a lively seminar series.

Our scientific success depends on the dedication and competence of our staff, extending to every level of scientific, technical, and administrative activity. To allow our staff to develop professionally to their fullest potential, we are committed to creating support structures such as family-oriented policies. We place a particular emphasis on the mentoring of young researchers, be it at the level of PhD candidates, postdoctoral researchers, or the leaders of independent research groups.

PhD Candidates – the next generation of researchers: We wish to identify and develop young researchers of exceptional ability from around the world and provide them with doctoral training in Earth system modeling. Doctoral research at the MPI-M is organized through the International Max Planck Research School on Earth System Modeling, the IMPRS-ESM, which is run jointly with the University of Hamburg and which targets a fifty-fifty breakdown between the percentages of international versus national PhD candidates. The IMPRS-ESM has repeatedly been evaluated excellently, and both the research by our PhD candidates and the IMPRS-ESM itself have assumed an indispensable role within the MPI-M.

Each PhD candidate has a primary advisor whose capacity to lead students is formally recognized by the IMPRS-ESM. A crucial further element of supervision is the Advisory Panel, which is comprised of the PhD candidate's advisors and as the chair a senior academic knowledgeable of but unrelated to the concrete research project. The Advisory Panel is a monitoring tool, ensuring timely completion of ambitious research projects, without however interfering with the student-advisor pair's discretion to define their research freely.

In the future all PhD candidates at the MPI-M will be required to be enrolled in the IMPRS-ESM or, in special cases, a related school. The limited capacity of the IMPRS-ESM limits the MPI-M to roughly 50 PhD candidates at any given time. Because students enter the IMPRS-ESM through a competitive admissions procedure, project-funded students will be selected through a mechanism coordinated with the IMPRS-ESM staff and consistent with the IMPRS-ESM selection criteria.

The IMPRS-ESM office will be staffed through two full-time positions, the coordinator and his or her assistant. In addition to overseeing the student selection procedure and the progress of students' research, the IMPRS-ESM office is responsible for the development of the IMPRS-ESM curriculum, a program of social activities, and the organization of workshops and the annual retreats.
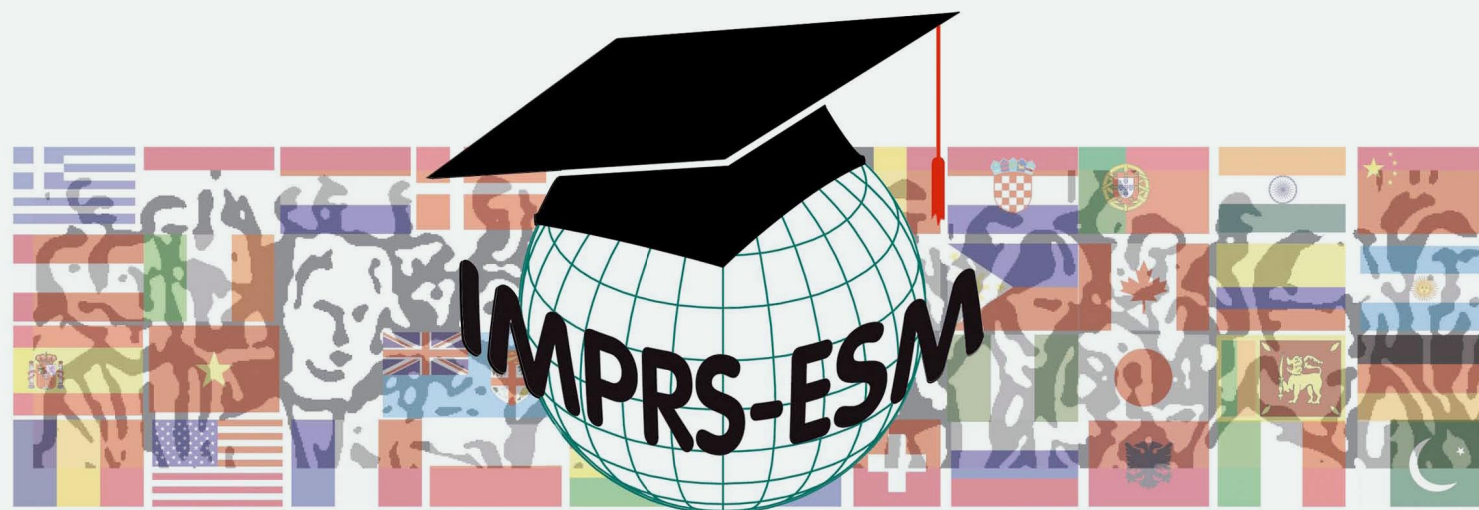
International Max Planck Research School on Earth System Modelling

ICON
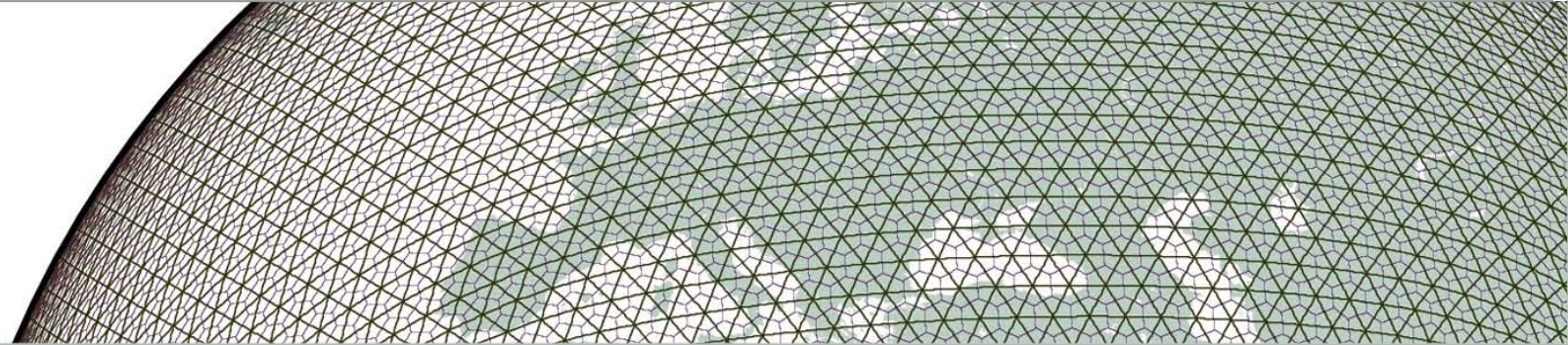
ICON is a joint project between the MPI-M and the German meteorological service DWD with the goal to develop new coupled atmosphere-ocean general circulation models. These models make use of icosahedral geodesic grids and numerical methods ensuring the faithful representation of essential conservation laws of the underlying physical system, including the consistency between air and tracer mass fluxes. This will help remove long-standing numerical errors in the current model system and thus provide a solid basis for the MPI-ESM2. The new models are also designed to scale to much higher numbers of CPUs, to allow experimentation at high resolution, eventually to cloud and ocean eddy resolving scales. Through collaboration with DWD, we will investigate the conceptual design and numerical realization of scale-adaptable parameterizations of atmospheric sub-grid scale processes, aiming at developing a model system that is capable to operate on a wide range of space-time scales: from weather prediction to climate studies in regional and global domains. Furthermore we will explore systematic and property-conserving approaches to grid refinement.

Postdoctoral research and mentoring: The MPI-M is moving toward a more formal approach to post-doctoral research and mentoring. This approach is initially supported through a new and prestigious postdoctoral research fellowship, called the Klaus Hasselmann Fellowship Program. One Klaus Hasselmann fellow will be chosen per year, successively based on the research orientation of the three departments within the MPI-M. Klaus Hasselmann fellows will be given a modest budget to support their research, as well as the opportunity to define, and jointly supervise, doctoral research projects within the IMPRS-ESM. In addition the MPI-M will internally recognize postdoctoral researchers as those researchers within five years of their PhD, and provide organizational support to advance their intellectual development such as the opportunity to organize meetings or seminars, or to participate more actively in IMPRS-ESM supervision and teaching.

Independent research groups are funded from a variety of sources including the Max Planck Society itself, the German Research Foundation, and the EU. In all cases the selection procedure is extraordinarily competitive; as a result scientists awarded an independent research group are typically the very best at their career stage. An independent research group co-exists along with the regular scientific working groups but explores research directions that are independently established by its group leader, typically as a complement to existing activities within the MPI-M. The lifetime of most groups is about five years, and thus they have the potential to contribute to the strategic direction of the MPI-M. We anticipate that the MPI-M will remain an attractive destination for these groups.

Earth system modeling

The principal development effort for the next decade will be to create a next-generation Earth system model: MPI-ESM2. The MPI-ESM2 must have the capacity to simulate the Earth system on machines comprised of hundreds of thousands, possibly millions, of processing elements. It must faithfully represent the essential conservation principles underlying the physical system, it must provide flexible interfaces to sub-models of component processes, and it must allow a representation of the Earth system that spans spatial scales as fine as 100 m over regions, and temporal scales that reach into the millennia. To operate as a predictive system the MPI-ESM2 must also incorporate advanced data assimilation techniques for the varying components of the system. Finally, the MPI-ESM2 must be based around modern and open practices in software engineering, and, most importantly, be readily usable by our scientific staff. The development of the MPI-ESM2 is more than just tool building, but a defining scientific activity of the MPI-M in its own right.

The comprehensive requirements on MPI-ESM2 cannot be fulfilled with a model based on the one currently available. Therefore the MPI-M together with the German meteorological service DWD has embarked on the ambitious development of new dynamical cores for the atmosphere and the ocean – the ICON project. ICON will serve both the atmospheric and the oceanic modeling needs, for both climate research and weather forecasting.

The attention to numerics evident in the development of dynamical cores such as ICON is also essential to the development of parameterizations, for the coupling of different model components, and for advanced data analysis and assimilation techniques. All this means that to meet its strategic goals the MPI-M needs to develop further its expertise in the applied mathematics of Earth system modeling. To this end, we aim at transitioning the current ICON working group to a more permanent structure, with at least two senior scientists at the core.

The coupled model steering group (CMSG) oversees and coordinates the use of the MPI-ESM and the development of the MPI-ESM2. The CMSG maintains a roadmap for the development of the MPI-ESM2; identifies the resource requirements or structural changes necessary to meet the development needs of the MPI-ESM2; and advises the directorate on MPI-M policy related to the use and development of the MPI-ESM.

HOAPS-3 Climatological Evaporation 1988-2005

0 1 2 3 4 5 6 7 8 9 10 [mm/d]
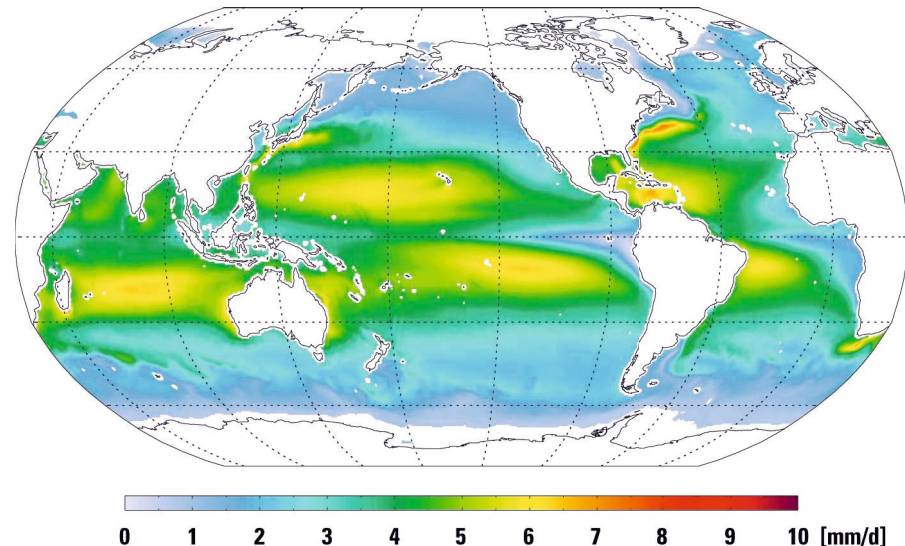
(HOAPS - Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data). HOAPS-3 contains a completely reprocessed time series of global ocean parameters related to freshwater flux. Key features of the update are a new precipitation algorithm, the NOAA/NASA Pathfinder Version5 dataset for sea surface temperature, a new procedure to synthesize a failed microwave channel, and a new twice-daily gridded data-product, HOAPS-C (composite).

Earth system observations

Although the MPI-M is principally a modeling center, progress toward our vision requires that we better integrate observational data into our model development and evaluation.

The point of reference will be the global record, which is principally based on satellite data. However, to be at the cutting edge of the use of such data streams requires expertise in the measurement principles and the associated retrieval algorithms that stand behind the data. Physical properties of the observed system are often extracted on the basis of retrievals that are uncertain. Examples are how to distinguish an aerosol from a cloud, or how to infer changes in upper atmospheric water vapor or temperature, to estimate sea-surface salinity, or to assess changes in biomass. Hence it is essential that the MPI-M maintain a critical amount of expertise in space-based remote sensing. Having this expertise in house will help advance a more nuanced use of the available data and can identify the opportunities to fill gaps in the existing records, for instance by targeted measurement campaigns which we ourselves initiate.

The MPI-M mobile measurement toolkit (M⁴T) is being developed to help us capitalize on our ability to initiate measurements that address key gaps in the global, and publicly accessible, observational record. This toolkit will include the MPI-M's share of HALO, the new High-Altitude, LOng-range research aircraft; the Hamburg Micro-wave Package of radar and radiometers that can be deployed both on HALO and on the surface; but also existing instrumentation such as lidars, in situ sensors, and new sensors as necessary. Any expansion of the MPI-M's measurement capacity will be centered on commodity instrumentation that can be flexibly and strategically deployed.

Examples of this concept include the recently initiated Barbados measurement campaign focusing on processes regulating the distribution of shallow trade-wind clouds, a developing initiative exploring the effect of land-surface heterogeneity on surface-atmospheric exchange, and a series of campaigns centered on the measurement of sea ice in the North Atlantic. In addition to the scientific staff needed to initiate and lead the use of instruments drawn from M⁴T, this initiative requires technical support staff who can deploy and maintain instrumentation, even if this instrumentation is purchased from third parties rather than developed internally. Moreover, continued access to a workshop and a competent technical staff gives the MPI-M the flexibility to support laboratory investigations, or in very special cases even make our own developments when essential instrumentation proves impossible to obtain through outside sources.

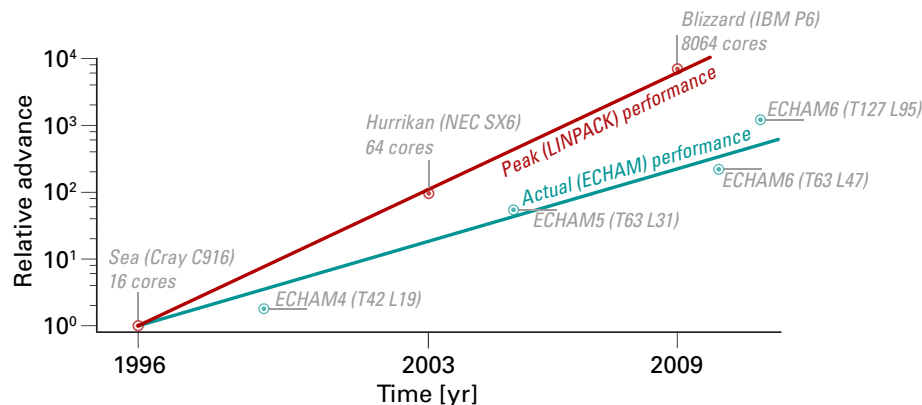The Barbados cloud observatory
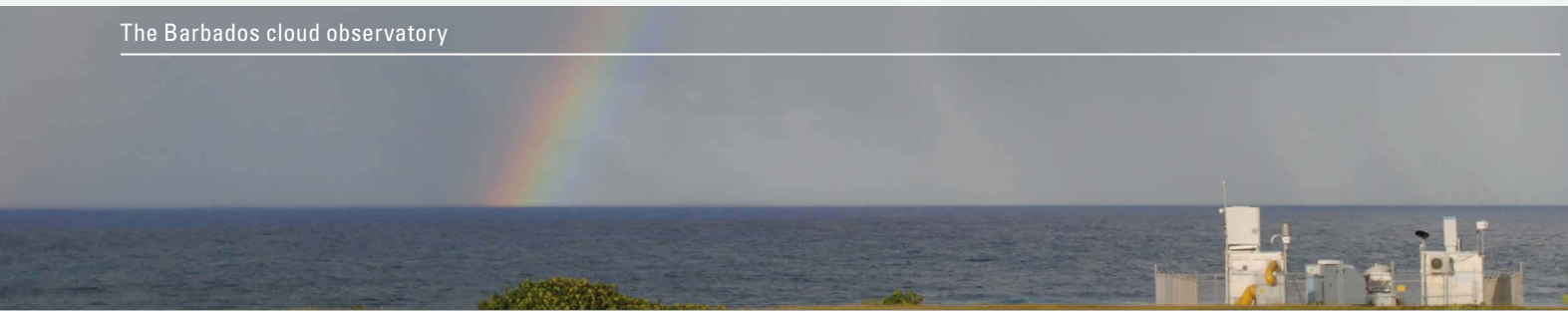
Shallow cumulus clouds are ubiquitous over the subtropical oceans in regions called the "trades", after the steady surface winds that once made foreign commerce flourish. These clouds help regulate the transport of moisture and energy between the ocean and the free troposphere and are therefore crucial to the climate system. Their small footprint and limited vertical extent, however, make it challenging to observe them from space or to simulate them accurately in climate models. The statistical properties of trade-wind cumuli are therefore not well documented, and their behavior is still poorly understood.

The cloud observatory on Barbados, equipped with state-of-the-art remote sensing systems, is a collaborative initiative of the MPI-M and unique in its kind. Since April 2010 it has measured the properties of clouds, precipitation, ambient aerosol, and large-scale meteorology continuously, for a period of at least two years. This rich dataset will help us unravel what controls the aggregate behavior of these clouds and how they would respond to a changing climate.

Computing struggles to keep up with computers

Chart showing "Relative advance" vs "Time [yr]" on logarithmic scale. Data points: Sea (Cray C916) 16 cores; ECHAM4 (T42 L19); Hurrikan (NEC SX6) 64 cores; ECHAM5 (T63 L31); Blizzard (IBM P6) 8064 cores; ECHAM6 (T127 L95); ECHAM6 (T63 L47). Lines labeled "Peak (LINPACK) performance" and "Actual (ECHAM) performance". Y-axis: 10^0 to 10^4. X-axis: 1996, 2003, 2009.

While the computational capacity of machines continues to increase exponentially, it becomes progressively more difficult to harness this power. At MPI-M computing, as measured by the time it takes to advance one grid point of ECHAM by one timestep, increasingly lags the peak performance that one can achieve for relatively straightforward computations as measured by the LINPACK benchmark. The MPI-M's continuing ability to tap advances in computing requires continued investment in technical staff. Even then the potential of the latest generation of machines is only realized by enlarging the calculations. The turn-around time for low resolution workhorse computations increases much more modestly with advances in computational power, as such simulations reach their limit of parallelization at relatively low processor counts.

The observations steering group (OSG) organizes effective access to and use of observational data throughout the MPI-M, as well as the use of institutional resources in support of data collection. The OSG will work with the CMSG to help break down the distinction between datasets derived from archival Earth system simulations and those collected from Earth observations.

Observational work must be anchored within each of the MPI-M's three departments, with sufficient support to ensure that within each department at least one working group is dedicated to working with observational data.

Scientific IT

The ability to effectively use the models we develop, to analyze model output and the associated observations, and ultimately to answer our guiding questions depends crucially on the development of scientific information technology (IT) within the MPI-M. The strategic development of scientific IT must be multi-faceted, comprising high-performance computing, appropriate software environments for Earth system models, and the effective organization of our workflow.

High-performance computing (HPC): To satisfy the extensive computational needs of the MPI-M we will follow a two-tier strategy. The first tier, where most of our efforts will be concentrated, will be centered on the HPC and data-service infrastructure provided by the German Climate Computing Centre (DKRZ). The MPI-M has for a long time benefitted from a close integration of its systems with those of DKRZ, offering the MPI-M seamless access to the DKRZ-managed machines. Likewise the development and support of workflow, through visualization software, archiving systems, or scripting support have been central to the success of our strategy. The strategic partnership with DKRZ depends on our ability to sustain and deepen this level of integration.

The second tier involves working with DKRZ to develop closer cooperation with the wider network of European computing centers so as to secure access to developing technology and prepare for the next generation of production machines. The Gauss Centre for Supercomputing is an alliance of Germany's three national general-purpose supercomputing centers and strives to expand access to the most powerful supercomputer infrastructures within Europe. It is essential that the MPI-M and DKRZ work together to obtain access to next-generation computing.

Software environments for Earth system models: In support of the MPI-ESM2 we need to develop a new, comprehensive software environment. This software environment builds on ongoing efforts within the MPI-M, for instance the Climate Data Operators (CDOs), to unify and homogenize generic elements of the MPI-ESM2. Candidate elements include data structure definition and IO, as well as runtime and post-processing environments. Because it will provide the fabric through which we connect our models to state-of-the-art HPC systems, the development of a comprehensive software environment for the MPI-ESM2 will demand expertise in HPC and informatics that cuts across the individual departments and connects to the broader HPC community.

Workflow: To support our day-to-day work also requires two tiers of support. The first tier is support for basic IT services, such as E-mail, network, and helpdesk services, which will continue to be provided by the Central IT Services (CIS) run jointly with the University of Hamburg. The second tier comprises more specialized services that are tailored to the specific requirements of the MPI-M, such as advanced software project-management systems, analysis software, or advanced scripting support. These services must be provided at the department or MPI-M level, in close cooperation with CIS.

Cooperation

Model development: External partnerships will play an increasingly important role in the development and application of the MPI-ESM2. At the one end of these partnerships is long-term model co-development such as the development of new dynamical cores (ICON) with the DWD, the development of components of the land-surface model JSBACH with the MPI for Biogeochemistry in Jena, and a capacity for coupled chemistry modeling with the MPI for Chemistry in Mainz. A different kind of partnership provides support for defining and maintaining interfaces with externally developed sub-models, such as for the aerosol/chemistry sub-model HAMMOZ developed and maintained by ETH Zürich and FZ Jülich. With the ever-expanding concept of the Earth system we anticipate such partnerships will be increasingly important and must be strategically developed.

Local cooperation: The MPI-M will continue to deepen its cooperation with related institutes within the University of Hamburg (UHH) and as a member of the KlimaCampus, which has evolved as a concept for coordinating and advancing climate-related research in the Hamburg area. The KlimaCampus is comprised of the MPI-M, climate related research units at the UHH, the German Climate Computing Centre (DKRZ), as well as the Institute for Coastal Research (IfK) and the Climate Service Center (CSC), both of the Helmholtz-Zentrum Geesthacht (HZG). The MPI-M is committed to making significant contributions to the educational mission of the University of Hamburg, through course offerings and doctoral research in the framework of the IMPRS-ESM as well as its partner School on Integrated Climate System Science, but also by providing support through the Max Planck Fellows program to excellent university researchers at the University of Hamburg.

National cooperation: Within the Max Planck Society, the Earth System Research Partnership (ESRP) provides a framework for the MPI-M, the MPI for Chemistry in Mainz, and the MPI for Biogeochemistry in Jena to develop more expansive and increasingly interdisciplinary concepts of the Earth system. The MPI-M is also committed to contribute to the German Climate Consortium (DKK), which has been established as an initiative of currently 21 climate research institutes to address urgent climate research questions for society, industry, and government.

International cooperation: The MPI-M will continue to participate in research projects by the European Union and other international funding bodies. Moreover, the MPI-M will continue to make significant contributions to the World Climate Research Programme (WCRP), the International Geosphere-Biosphere Programme (IGBP), and the Intergovernmental Panel on Climate Change (IPCC) assessment process. Through its support for topical workshops, visitors, and international conferences, most prominent among them the International Conference on Earth System Modeling, the MPI-M is committed to advancing the scientific discourse related to Earth system modeling and maintaining its stature as a world-renowned center for Earth system research.

Supporting organizational structures

Every three years the MPI-M is evaluated by a Scientific Advisory Board (SAB) to ensure superior scientific quality and productivity. SAB members are appointed by the President of the Max Planck Society and are scientists of unusual levels of accomplishment and distinction. More than three quarters of our SAB members come from abroad.

The MPI-M is further supported by a Board of Trustees, which helps the MPI-M navigate its relationship with the society at large. The members of the Board of Trustees are appointed by the President of the Max Planck Society and are leading figures from industry, government, media, or academia. The Board of Trustees deliberates on science policy as well as on economic, resource, and organizational questions.

The management of the MPI-M remains the responsibility of the MPI-M directors, who are advised on an ongoing basis by a management committee and a scientific coordinator.