ECHAM6, the sixth generation of the atmospheric general circulation model ECHAM, is described. Major changes with respect to its predecessor affect the representation of shortwave radiative transfer, the height of the model top. Minor changes have been made to model tuning and convective triggering. Several model configurations, differing in horizontal and vertical resolution, are compared. As horizontal resolution is increased beyond T63, the simulated climate improves but changes are incremental; major biases appear to be limited by the parameterization of small-scale physical processes, such as clouds and convection. Higher vertical resolution in the middle atmosphere leads to a systematic reduction in temperature biases in the upper troposphere, and a better representation of the middle atmosphere and its modes of variability. ECHAM6 represents the present climate as well as, or better than, its predecessor. The most marked improvements are evident in the circulation of the extratropics. ECHAM6 continues to have a good representation of tropical variability. A number of biases, however, remain. These include a poor representation of low-level clouds, systematic shifts in major precipitation features, biases in the partitioning of precipitation between land and sea (particularly in the tropics), and mid-latitude jets that appear to be insufficiently poleward. The response of ECHAM6 to increasing concentrations of greenhouse gases is similar to that of ECHAM5. The equilibrium climate sensitivity of the mixed-resolution (T63L95) configuration is between 2.9 and 3.4 K and is somewhat larger for the 47 level model. Cloud feedbacks and adjustments contribute positively to warming from increasing greenhouse gases.

JAMES 20015
02: Evaluating adjusted forcing and model spread for historical and future scenarios in the CMIP5 generation of climate models

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We utilize energy budget diagnostics from the Coupled Model Intercomparison Project phase 5 (CMIP5) to evaluate the models’ climate forcing since preindustrial times employing an established regression technique. The climate forcing evaluated this way, termed the adjusted forcing (AF), includes a rapid adjustment term associated with cloud changes and other tropospheric and land-surface changes. We estimate a 2010 total anthropogenic and natural AF from CMIP5 models of 1.90.9Wm² (5–95% range). The projected AF of the Representative Concentration Pathway simulations are lower than their expected radiative forcing (RF) in 2095 but agree well with efficacy weighted forcings from integrated assessment models. The smaller AF, compared to RF, is likely due to cloud adjustment. Multimodel time series of temperature change and AF from 1850 to 2100 have large intermodel spreads throughout the period. The intermodel spread of temperature change is principally driven by forcing differences in the present day and climate feedback differences in 2095, although forcing differences are still important for model spread at 2095. We find no significant relationship between the equilibrium climate sensitivity (ECS) of a model and its 2003 AF, in contrast to that found in older models where higher ECS models generally had less forcing. Given the large present-day model spread, there is no indication of any tendency by modelling groups to adjust their aerosol forcing in order to produce observed trends. Instead, some CMIP5 models have a relatively large positive forcing and overestimate the observed temperature change.

J. Geophys. Res. 50174
03: Climate extremes indices in the CMIP5 multimodel ensemble:
Part 1. Model evaluation in the present climate

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This paper provides a first overview of the performance of state-of-the-art global climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) in simulating climate extremes indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI), and compares it to that in the previous model generation (CMIP3). For the first time, the indices based on daily temperature and precipitation are calculated with a consistent methodology across multimodel simulations and four reanalysis data sets (ERA40, ERA-Interim, NCEP/NCAR, and NCEP-DOE) and are made available at the ETCCDI indices archive website. Our analyses show that the CMIP5 models are generally able to simulate climate extremes and their trend patterns as represented by the indices in comparison to a gridded observational indices data set (HadEX2). The spread amongst CMIP5 models for several temperature indices is reduced compared to CMIP3 models, despite the larger number of models participating in CMIP5. Some improvements in the CMIP5 ensemble relative to CMIP3 are also found in the representation of the magnitude of precipitation indices. We find substantial discrepancies between the reanalyses, indicating considerable uncertainties regarding their simulation of extremes. The overall performance of individual models is summarized by a “portrait” diagram based on root-mean-square errors of model climatologies for each index and model relative to four reanalyses. This metric analysis shows that the median model climatology outperforms individual models for all indices, but the uncertainties related to the underlying reference data sets are reflected in the individual model performance metrics.

J. Geophys. Res. 50203
This study provides an overview of projected changes in climate extremes indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI). The temperature- and precipitation-based indices are computed with a consistent methodology for climate change simulations using different emission scenarios in the Coupled Model Intercomparison Project Phase 3 (CMIP3) and Phase 5 (CMIP5) multimodel ensembles. We analyze changes in the indices on global and regional scales over the 21st century relative to the reference period 1981–2000. In general, changes in indices based on daily minimum temperatures are found to be more pronounced than in indices based on daily maximum temperatures. Extreme precipitation generally increases faster than total wet-day precipitation. In regions, such as Australia, Central America, South Africa, and the Mediterranean, increases in consecutive dry days coincide with decreases in heavy precipitation days and maximum consecutive 5 day precipitation, which indicates future intensification of dry conditions. Particularly for the precipitation-based indices, there can be a wide disagreement about the sign of change between the models in some regions. Changes in temperature and precipitation indices are most pronounced under RCP8.5, with projected changes exceeding those discussed in previous studies based on SRES scenarios. The complete set of indices is made available via the ETCCDI indices archive to encourage further studies on the various aspects of changes in extremes.

J. Geophys. Res. 50188
The diurnal cycle and the daily mean at the land-surface result from the coupling of many physical processes. The framework of this review is largely conceptual; looking for relationships and information in the coupling of processes in models and observations. Starting from the surface energy balance, the role of the surface and cloud albedos in the shortwave and longwave fluxes is discussed. A long-wave radiative scaling of the diurnal temperature range and the night-time boundary layer is summarized. Several aspects of the local surface energy partition are presented: the role of soilwater availability and clouds; vector methods for understanding mixed layer evolution, and the coupling between surface and boundary layer that determines the lifting condensation level. Moving to larger scales, evaporation-precipitation feedback in models is discussed; and the coupling of column water vapor, clouds and precipitation to vertical motion and moisture convergence over the Amazon. The final topic is a comparison of the ratio of surface shortwave cloud forcing to the diabatic precipitation forcing of the atmosphere in ERA-40 with observations.
06: Parameterization Improvements and Functional and Structural Advances in Version 4 of the Community Land Model

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The Community Land Model is the land component of the Community Climate System Model. Here, we describe a broad set of model improvements and additions that have been provided through the CLM development community to create CLM4. The model is extended with a carbon-nitrogen (CN) biogeochemical model that is prognostic with respect to vegetation, litter, and soil carbon and nitrogen states and vegetation phenology. An urban canyon model is added and a transient land cover and land use change (LCLUC) capability, including wood harvest, is introduced, enabling study of historic and future LCLUC on energy, water, momentum, carbon, and nitrogen fluxes. The hydrology scheme is modified with a revised numerical solution of the Richards equation and a revised ground evaporation parameterization that accounts for litter and within-canopy stability. The new snow model incorporates the SNOW and Ice Aerosol Radiation model (SNICAR) - which includes aerosol deposition, grain-size dependent snow aging, and vertically-resolved snowpack heating – as well as new snow cover and snow burial fraction parameterizations. The thermal and hydrologic properties of organic soil are accounted for and the ground column is extended to .50-m depth. Several other minor modifications to the land surface types dataset, grass and crop optical properties, surface layer thickness, roughness length and displacement height, and the disposition of snow-capped runoff are also incorporated. The new model exhibits higher snow cover, cooler soil temperatures in organic-rich soils, greater global river discharge, and lower albedos over forests and grasslands, all of which are improvements compared to CLM3.5. When CLM4 is run with CN, the mean biogeophysical simulation is degraded because the vegetation structure is prognostic rather than prescribed, though running in this mode also allows more complex terrestrial interactions with climate and climate change.
A mechanistic ecohydrological model to investigate complex interactions in cold and warm water-controlled environments:

1. Theoretical framework and plot-scale analysis

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Numerous studies have explored the role of vegetation in controlling and mediating hydrological states and fluxes at the level of individual processes, which has led to improvements in our understanding of plot-scale dynamics. Relatively less effort has been directed toward spatially-explicit studies of vegetation-hydrology interactions at larger scales of a landscape. Only few continuous, process-oriented ecohydrological models had been proposed with structures of varying complexity. This study contributes to their further evolution and presents a novel ecohydrological model, Tethys-Chloris. The model synthesizes the state-of-the-art knowledge on individual processes and coupling mechanisms drawn from the disciplines of hydrology, plant physiology, and ecology. Specifically, the model reproduces all essential components of the hydrological cycle: it resolves the mass and energy budgets in the atmospheric surface layer at the hourly scale, while representing up to two layers of vegetation; it includes a module of snowpack evolution; it describes the saturated and unsaturated soil water dynamics, processes of runoff generation and flow routing. The component of vegetation dynamics parameterizes life cycle processes of different plant functional types, including photosynthesis, phenology, carbon allocation, and tissue turnover. This study presents a confirmation of the long-term, plot-scale model performance by simulating two types of ecosystems corresponding to different climate conditions. A consistent and highly satisfactory model skill in reproducing the energy and water budgets as well as physiological cycles of plants with minimum calibration overhead is demonstrated. Furthermore, these applications demonstrate that the model permits the identification of data types and observation frequencies crucial for appropriate evaluation of modeled dynamics. More importantly, through a synthesis of a wide array of process representations, the model ensures that climate, soil, vegetation, and topography collectively identify essential modes controlling ecohydrological systems, i.e., that satisfactory performance is a result of appropriate mimicking of internal processes.
08: A mechanistic ecohydrological model to investigate complex interactions in cold and warm water-controlled environments:

2. Spatiotemporal analyses

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An ecohydrological model Tethys-Chloris (T&C) described in the companion paper is applied to two semiarid systems characterized by different climate and vegetation cover conditions. The Lucky Hills watershed in Arizona represents a typical small, “unit-source” catchment of a desert shrub system of the U.S. southwest. Two nested basins of the Reynolds Creek Experimental watershed (Idaho, U.S.A.), the Reynolds Creek Mountain East and Tollgate catchments, are representative of a semiarid cold climate with seasonal snow cover. Both exhibit a highly non-uniform vegetation cover. A range of ecohydrological metrics of the long-term model performance is presented to highlight the model capabilities in reproducing hydrological and vegetation dynamics both at the plot and the watershed scales. A diverse set of observations is used to confirm the simulated dynamics. Highly satisfactory results are obtained without significant (or any) calibration efforts despite the large phase-space dimensionality of the model, the uncertainty of imposed boundary conditions, and limited data availability. It is argued that a significant investment into the model design based on the description of physical, biophysical, and ecological processes leads to such a consistent simulation skill. The simulated patterns mimic the outcome of hydrological and vegetation dynamics with high realism, as confirmed from spatially distributed remote sensing data. Further community efforts are warranted to address the issue of thorough quantitative assessment. The current lack of appropriate data hampers the development and testing of process-based ecohydrological models. It is further argued that the mechanistic nature of the T&C model can be valuable for designing virtual experiments and developing questions of scientific inquiry at a range of spatiotemporal scales.
09: POSSIBLE ROLE OF WETLANDS, PERMAFROST, AND METHANE HYDRATES IN THE METHANE CYCLE UNDER FUTURE CLIMATE CHANGE: A REVIEW

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We have reviewed the available scientific literature on how natural sources and the atmospheric fate of methane may be affected by future climate change. We discuss how processes governing methane wetland emissions, permafrost thawing, and destabilization of marine hydrates may affect the climate system. It is likely that methane wetland emissions will increase over the next century. Uncertainties arise from the temperature dependence of emissions and changes in the geographical distribution of wetland areas. Another major concern is the possible degradation or thaw of terrestrial permafrost due to climate change. The amount of carbon stored in permafrost, the rate at which it will thaw, and the ratio of methane to carbon dioxide emissions upon decomposition form the main uncertainties. Large amounts of methane are also stored in marine hydrates, and they could be responsible for large emissions in the future. The time scales for destabilization of marine hydrates are not well understood and are likely to be very long for hydrates found in deep sediments but much shorter for hydrates below shallow waters, such as in the Arctic Ocean. Uncertainties are dominated by the sizes and locations of the methane hydrate inventories, the time scales associated with heat penetration in the ocean and sediments, and the fate of methane released in the seawater. Overall, uncertainties are large, and it is difficult to be conclusive about the time scales and magnitudes of methane feedbacks, but significant increases in methane emissions are likely, and catastrophic emissions cannot be ruled out. We also identify gaps in our scientific knowledge and make recommendations for future research and development in the context of Earth system modeling.

Reviews of Geophysics 1708
The most important sources of atmospheric moisture at the global scale are herein identified, both oceanic and terrestrial, and a characterization is made of how continental regions are influenced by water from different moisture source regions. The methods used to establish source-sink relationships of atmospheric water vapor are reviewed, and the advantages and caveats associated with each technique are discussed. The methods described include analytical and box models, numerical water vapor tracers, and physical water vapor tracers (isotopes). In particular, consideration is given to the wide range of recently developed Lagrangian techniques suitable both for evaluating the origin of water that falls during extreme precipitation events and for establishing climatologies of moisture source-sink relationships. As far as oceanic sources are concerned, the important role of the subtropical northern Atlantic Ocean provides moisture for precipitation to the largest continental area, extending from Mexico to parts of Eurasia, and even to the South American continent during the Northern Hemisphere winter. In contrast, the influence of the southern Indian Ocean and North Pacific Ocean sources extends only over smaller continental areas. The South Pacific and the Indian Ocean represent the principal source of moisture for both Australia and Indonesia. Some landmasses only receive moisture from the evaporation that occurs in the same hemisphere (e.g., northern Europe and eastern North America), while others receive moisture from both hemispheres with large seasonal variations (e.g., northern South America). The monsoonal regimes in India, tropical Africa, and North America are provided with moisture from a large number of regions, highlighting the complexities of the global patterns of precipitation. Some very important contributions are also seen from relatively small areas of ocean, such as the Mediterranean Basin (important for Europe and North Africa) and the Red Sea, which provides water for a large area between the Gulf of Guinea and Indochina (summer) and between the African Great Lakes and Asia (winter).

The geographical regions of Eurasia, North and South America, and Africa, and also the internationally important basins of the Mississippi, Amazon, Congo, and Yangtze Rivers, are also considered, as is the importance of terrestrial sources in monsoonal regimes. The role of atmospheric rivers, and particularly their relationship with extreme events, is discussed. Droughts can be caused by the reduced supply of water vapor from oceanic moisture source regions. Some of the implications of climate change for the hydrological cycle are also reviewed, including changes in water vapor concentrations, precipitation, soil moisture, and aridity. It is important to achieve a combined diagnosis of moisture sources using all available information, including stable water isotope measurements. A summary is given of the major research questions that remain unanswered, including (1) the lack of a full understanding of how moisture sources influence precipitation isotopes; (2) the stationarity of moisture sources over long periods; (3) the way in which possible changes in intensity (where evaporation exceeds precipitation to a greater or lesser degree), and the locations of the sources, (could) affect the distribution of continental precipitation in a changing climate; and (4) the role played by the main modes of climate variability, such as the North Atlantic Oscillation or the El Niño–Southern Oscillation, in the variability of the moisture source regions, as well as a full evaluation of the moisture transported by low-level jets and atmospheric rivers.
Forest vegetation can interact with its surrounding environment in ways that enhance conditions favorable for its own existence. Removal of forest vegetation has been shown to alter these conditions in a number of ways, thereby inhibiting the reestablishment of the same community of woody plants. The effect of vegetation on an environmental variable along with vegetation susceptibility to the associated environmental conditions may imply a positive feedback: Changes in the internal conditions controlling this variable such as deforestation could inhibit the reestablishment of woody vegetation cover that in turn would act to further degrade the conditions necessary for forest regeneration. Understanding these feedbacks is important because in some cases where these feedbacks are present, deforestation can lead to irreversible state shifts where the forest vegetation cannot recover. In this review, we examine the different cases in which deforestation can lead to a loss of conditions necessary to sustain forest vegetation. We examine the spatial scale and extent of each feedback in addition to considering the temporal scale over which a feedback may be considered irreversible. Juxtaposing the spatial extent of these feedbacks with a map of deforestation enables the identification and discussion of at-risk areas to state changes following deforestation. Last, we discuss the economic implications of these feedbacks and how socioeconomic factors can affect the convergence of a system to a given stable state.
A new framework for modeling the atmosphere, which we call the quasi-3D (Q3D) multi-scale modeling framework (MMF), is developed with the objective of including cloud-scale three-dimensional effects in a GCM without necessarily using a global cloud-resolving model (CRM). It combines a GCM with a Q3D CRM that has the horizontal domain consisting of two perpendicular sets of channels, each of which contains a locally 3D grid-point array. For computing efficiency, the widths of the channels are chosen to be narrow. Thus, it is crucial to select a proper lateral boundary condition to realistically simulate the statistics of cloud and cloud-associated processes. Among the various possibilities, a periodic lateral boundary condition is chosen for the deviations from background fields that are obtained by interpolations from the GCM grid points. Since the deviations tend to vanish as the GCM grid size approaches that of the CRM, the whole system of the Q3D MMF can converge to a fully 3D global CRM. Consequently, the horizontal resolution of the GCM can be freely chosen depending on the objective of application, without changing the formulation of model physics.

To evaluate the newly developed Q3D CRM in an efficient way, idealized experiments have been performed using a small horizontal domain. In these tests, the Q3D CRM uses only one pair of perpendicular channels with only two grid points across each channel. Comparing the simulation results with those of a fully 3D CRM, it is concluded that the Q3D CRM can reproduce most of the important statistics of the 3D solutions, including the vertical distributions of cloud water and precipitants, vertical transports of potential temperature and water vapor, and the variances and covariances of dynamical variables. The main improvement from a corresponding 2D simulation appears in the surface fluxes and the vorticity transports that cause the mean wind to change. A comparison with a simulation using a coarse-resolution 3D CRM is also made.
An advection scheme, which maintains the initial monotonic characteristics of a tracer field being transported and at the same time produces low numerical diffusion, is implemented in the Coupled Chemistry-Aerosol-Tracer Transport model to the Brazilian developments on the Regional Atmospheric Modeling System (CCATT-BRAMS). Several comparisons of transport modeling using the new and original (non-monotonic) CCATT-BRAMS formulations are performed. Idealized 2-D non-divergent or divergent and stationary or time-dependent wind fields are used to transport sharply localized tracer distributions, as well as to verify if an existent correlation of the mass mixing ratios of two interrelated tracers is kept during the transport simulation. Further comparisons are performed using realistic 3-D wind fields. We then perform full simulations of real cases using data assimilation and complete atmospheric physics. In these simulations, we address the impacts of both advection schemes on the transport of biomass burning emissions and the formation of secondary species from non-linear chemical reactions of precursors. The results show that the new scheme produces much more realistic transport patterns, without generating spurious oscillations and under- and overshoots or spreading mass away from the local peaks. Increasing the numerical diffusion in the original scheme in order to remove the spurious oscillations and maintain the monotonicity of the transported field causes excessive smoothing in the tracer distribution, reducing the local gradients and maximum values and unrealistically spreading mass away from the local peaks. As a result, huge differences (hundreds of %) for relatively inert tracers (like carbon monoxide) are found in the smoke plume cores. In terms of the secondary chemical species formed by non-linear reactions (like ozone), we found differences of up to 50% in our simulations.
14: Evaluation of the skill and added value of a reanalysis-driven regional simulation for Alpine temperature

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To determine whether the use of regional climate models improves the representation of climate is a crucial topic in climate modelling. An improvement over coarser scale models is expected especially in areas with complex orography or along coastlines. However, some studies have shown no clear added value for regional climate models. In this study a high-resolution regional climate simulation performed with REMO 5.0 (regional model) over the whole of Europe over the period 1958–1998 is analysed for 2-m temperature over the European Alps and their surroundings called the Greater Alpine region (GAR). The simulation is driven by perfect boundary conditions at the lateral boundaries provided by the ERA40 reanalysis and spectral nudging of the large-scale wind fields towards ERA40 values for the upper layers inside the model domain. The added value of the regional simulation (1/6° resolution) is analysed with respect to the driving reanalysis (1.125° resolution).

Both the REMO simulation and the ERA40 reanalysis are validated against different station datasets of monthly and daily mean 2-m temperature. Correlation analysis shows that the temporal variability of temperature is well represented by both REMO and ERA40, whereas both show considerable biases. The REMO bias reaches 3 K in summer in regions known to experience a problem with summer drying in a number of regional models. The comparison of REMO and ERA40 shows that an added value of the former exists for all regions in winter. For the regions surrounding the Alps, the added value is absent in summer, whereas in the inner Alpine subregions with most complex orography, REMO performs better than ERA40 during the whole year. The only moderate value added by REMO in this hindcast set-up may be partly explicable by the fact that meteorological measurements are assimilated in the ERA40 reanalysis but not in the REMO simulation.

INTERNATIONAL JOURNAL OF CLIMATOLOGY
15: Why models run hot: results from an irreducibly simple climate model

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An irreducibly simple climate-sensitivity model is designed to empower even non-specialists to research the question how much global warming we may cause. In 1990, the First Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) expressed “substantial confidence” that near-term global warming would occur twice as fast as subsequent observation. Given rising CO2 concentration, few models predicted no warming since 2001. Between the pre-final and published drafts of the Fifth Assessment Report, IPCC cut its near-term warming projection substantially, substituting “expert assessment” for models’ near-term predictions. Yet its long-range predictions remain unaltered. The model indicates that IPCC’s reduction of the feedback sum from 1.9 to 1.5 W m⁻² K⁻¹ mandates a reduction from 3.2 to 2.2 K in its central climate-sensitivity estimate; that, since feedbacks are likely to be net-negative, a better estimate is 1.0 K; that there is no unrealized global warming in the pipeline; that global warming this century will be <1 K; and that combustion of all recoverable fossil fuels will cause <2.2 K global warming to equilibrium. Resolving the discrepancies between the methodology adopted by IPCC in its Fourth and Fifth Assessment Reports that are highlighted in the present paper is vital. Once those discrepancies are taken into account, the impact of anthropogenic global warming over the next century, and even as far as equilibrium many millennia hence, may be no more than one-third to one-half of IPCC’s current projections.

Science Bulletin
Continuous four-dimensional source attribution for the Berlin area during two days in July 1994. Part I: The new Euler–Lagrange-model system LaMM5

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The multiple nested three-dimensional (3D) mesoscale Eulerian grid point model MM5 was directly coupled with a Lagrangian particle trajectory model in order to perform a 4D source attribution for the area of Berlin based on the import probability density (IPD) distribution of the according receptor box. Within the resulting model system LaMM5 introduced here, the IPD distributions are not based on backward trajectories, which lack the recognition of the turbulent environment, but on the forward integration of a huge amount (order of million per day) of particle releases according to an emission scenario which is approximately continuous in space and time. Hence, the receptor import yields an accordingly continuous IPD distribution. Much attention has been paid on spatial and temporal resolution at the interface between both model parts (online-coupling) and the interface itself has been extended by the turbulent quantities resulting from the higher-order turbulence closure of the Eulerian model part. LaMM5 is applied on an episode with high photochemical activity across Berlin at two consecutive days (25 and 26 July 1994) with varying meteorological conditions leading to an accordingly different source attribution. The main results are:

* The decay of the Berlin IPD with increasing source-receptor distance and time appears in an exponential manner if only sources out of a constant level (z ¼ 25 m) are regarded.
* Heterogeneous wind fields in time and space enhance the contributions (emissions) of nearby sources to the total import of the receptor in contrast to stationary wind fields which increase the scope of the IPD distribution in upstream direction.

There are further results from several additional sensitivity studies presented in a companion paper B (Part II).

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