



Fig. 3. Combined time series plot of seismic and meteorological observations made during the first five days of the 2004 Grímsvötn eruption. Note the varying timescale. (a) Local earthquake magnitudes. (b) Seismic tremor amplitude in three different frequency bands. (c) Volcanic plume height. (d) Number of lightning. Lightning and tremor amplitude roughly correlate with plume height.

eruption of Grímsvötn volcano. This allowed warnings to be issued up to three days before their onsets, priming NCPA and aviation authorities for immediate action upon receiving the 2010 UTC eruption warning on 1 November.

Lacking visual confirmation, seismic and meteorological observations provided verification of eruption onset and location. During the eruption, these systems monitored eruption energy, plume height and dispersion, and

ashfall areas, thus facilitating real-time hazard assessment.

In light of Grímsvötn's remote location and the small erupted volume ($<0.1 \text{ km}^3$) and jökulhlaup size ($\sim 0.8 \text{ km}^3$), the sensitivity and performance of the systems applied show great potential for monitoring future eruptions and jökulhlaups. Given the likelihood of an oncoming eruption at Katla, a subglacial volcano under the Mýrdalsjökull ice cap (Figure 1a) [Sturkell et al., 2005], these systems

may soon be put to the test again. Unlike Grímsvötn, though, Katla's proximity to populated areas poses a severe risk to human life and habitation.

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MEETINGS

Advances in Large-Scale Crop Modeling

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Intensified human activity and a growing population have changed the climate and the land biosphere. One of the most widely recognized human perturbations is the emission of carbon dioxide (CO_2) by fossil fuel burning and land-use change. As the terrestrial biosphere is an active player in the global carbon cycle, changes in land use feed back to the climate of the Earth through regulation of the content of atmospheric CO_2 , the most important greenhouse gas, and changing albedo (e.g., energy partitioning).

Recently, the climate modeling community has started to develop more complex Earth-system models that include marine and terrestrial biogeochemical processes in addition

to the representation of atmospheric and oceanic circulation. However, most terrestrial biosphere models simulate only natural, or so-called potential, vegetation and do not account for managed ecosystems such as croplands and pastures, which make up nearly one-third of the Earth's land surface.

On the other hand, over the past 30 years numerous models of crop growth have been developed, and these have proved to be extremely useful tools for scientists and managers of agricultural systems. These detailed models, though, are typically application-orientated and therefore usually are applied specifically to particular crops and locations. These models were not originally designed for large-scale studies and do not include complete nutrient or carbon cycles. Though, the models

can provide useful information for large-scale crop modeling, which then has to be adapted for use in terrestrial biosphere models.

A workshop held at the Rothamsted Research Centre, Harpenden, U.K., dealt with the advancing science of including large-scale, generic crop modeling schemes in global terrestrial biosphere models. About 20 scientists from the crop modeling and global biosphere modeling community attended. The workshop was one in a series of workshops sponsored by Quantifying and Understanding the Earth System (QUEST), a program of the U.K. Natural Environment Research Council (NERC). QUEST has several activities, among them the focused strategic activity on Earth system modeling and two research themes: (1) the contemporary carbon cycle and its interactions with climate and atmospheric chemistry, and (2) the implications of global environmental changes for the sustainable use of resources.

Setting the Scene

The modeling of crop productivity and yields on a global scale requires information

on current and previous land cover, land-use practices, and changes in land management over time. For the past, this has been done using a combination of census data on cropland inventories and land cover classification from satellite data. This “statistical data fusion” can produce a calibrated map of croplands.

By using a “hindcast modeling” approach (combining a land cover change model with historical cropland inventory data), Navin Ramankutty and colleagues at the University of Wisconsin-Madison Center for Sustainability and the Global Environment (SAGE) extended the 1992 cropland map back to the year 1700. Recently, SAGE has produced global data sets of the early 1990s distribution of 18 major crop types at a spatial resolution of approximately 10 km. SAGE is continuing its work to derive global maps of present crop types, planting and harvest dates, fertilizer application rates, and irrigation water application rates. All of these data are useful drivers for modeling crops.

While much uncertainty surrounds future agricultural land use and farmer adaptation to climate change, alternative scenarios of future management can be used to drive crop models during the 21st century. Frank Ewert and colleagues at Wageningen University in The Netherlands and Université catholique de Louvain in Belgium have developed such quantitative and spatially explicit scenarios of future agricultural land use across Europe. They constructed future agricultural land-use locations for three time slices (2020, 2050, and 2080) at a spatial resolution of 10-min latitude and longitude. The scenarios were based on an interpretation of the four story lines of the Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC) using a simple supply and demand model of agricultural area quantities at the European scale, and these quantities were disaggregated using scenario-specific, spatial allocation rules.

Assumptions about future technological advancement and estimated changes in crop productivity have significant impacts on future agricultural land use in Europe. If technology continues to progress at current rates, then cropland and grassland areas may decline by as much as 50%. As a result, a large area of agricultural land in Europe could be used for other purposes. Expansion of urban areas, and specific management for bioenergy crops, forests, and recreation are possible alternative land uses for the future.

Different Modeling Strategies

Six different groups representing five different models presented modeling approaches that are currently implemented. The five models are: Lund-Potsdam-Jena, LPJ; Integrated Biosphere Simulator, IBIS; Organizing Carbon and Hydrology in Dynamic Ecosystems, ORCHIDEE; General Large Area Model, GLAM; and DayCent.

Most of the groups have extended their original terrestrial ecosystem models to include the representation of crop growth, but have kept the representation of biophysical processes identical to the original model formulation where possible (e.g., photosynthesis, respiration, and hydrology). Many of the models have been extended by new algorithms for crop management (hybrid selection, planting and harvesting date, irrigation, fertilization, and intercropping and multiple cropping), crop phenology, growth, and carbon allocation.

The models differ mainly in terms of which crop types are represented and also in terms of the detail of processes, which can vary substantially across models. For example, the most detailed models (for applications on a continental scale) include definitions of growth stages (planting to leaf emergence, leaf emergence to the end of silking, and grain fill to physiological maturity) and nitrogen availability (atmospheric deposition, fixation, fertilizer application, and mineralization of soil organic matter). Usually, the major crop types—such as maize, soybeans, wheat, and rice—are incorporated; however, it is an open question about the choice and number of cultivars, which are needed for large-scale, generic crop modeling.

The group at the Potsdam Institute for Climate Impact Research implemented so-called crop functional types (CFTs) to model the phenology and growth of the world's dominant crop or rangeland types within LPJ. The natural vegetation, represented by plant functional types (PFTs), and CFTs can coexist within a mixed grid cell on two different land cover types. PFTs are all mixed within the “natural” land cover and compete for resources, whereas each CFT is located on a distinct stand with its own water budget within the “agricultural” land cover. According to the climate, the model estimates several variety-specific parameters in order to ensure that the crop that is simulated represents the type most likely used by the farmers in that specific environment. Consequently, the model simulates the adaptation by selecting appropriate varieties across the climatic zones and with climate change.

For researchers at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE, Giv-sur-Yvette, France), the mosaic approach is used to allow crops and natural vegetation to coexist within each grid point. In the presence of crops, ORCHIDEE, the French global dynamic vegetation model, permanently assimilates some output from the Simulateur Multidisciplinaire pour les Cultures Standard (STICS), a realistic agronomy model, to correct for some of the variables that are specific to cultivated plants (e.g., leaf area index, root profile, canopy height, irrigation, and nitrogen stress). This strategy has been implemented for three cultivars: wheat, maize, and soybeans.

Similarly, at the University of Reading, GLAM, which adapts traditional crop modeling approaches to operate on larger spatial scales,

has been incorporated into the land surface scheme of the U.K. Met Office climate model to examine the two-way biophysical interactions between crops and their climate.

Currently, all of the models are at about the same development state of having been tested and validated at some specific sites, and all are producing their first results. IBIS has been applied across the Mississippi Basin to investigate the influence of land cover and land-use changes on nitrate export to the Gulf of Mexico, and how climate change and variability may have previously affected crop yields and farmer decision-making. DayCent and LPJ have been applied globally and tested against country data from the Food and Agricultural Organization (FAO) of the United Nations.

One major outcome of this workshop was the agreement to create a data set consisting of all the necessary information (climate, planting and harvesting date, phenology, fertilizer application, irrigation application, yield, carbon, and water and energy fluxes) for validating and driving these hybrid crop-terrestrial ecosystem models.

The creation of this data set involves the collection of the data from various sources as well as quality control of the data (assuring that the same quantities from different sources really mean the same) and the creation of common forcing fields with respect to the different data needs of the different models. This data set, if combined with a standardized modeling protocol, can then also be used for a future modeling intercomparison project. Ideally, this data set should comprise observations on a field scale, and also across larger spatial and temporal scales using available census data. There are various existing data sources such as the FAO data set and other national and subnational statistics as well as remote sensing data, the Global Change and Terrestrial Ecosystems (GCTE) Focus 3 (Agroecology and Production System) networks, FLUXNET, Free Air Carbon Dioxide Enrichment (FACE) experiments, and field observations at the farm level (e.g., the Farm Accountancy Data Network in Europe).

The workshop, “Large Scale, Generic Crop Modelling,” was held 9–11 March 2005 at Rothamsted Research Centre, Harpenden, U.K. More information on the workshop, models, and the participants can be found on the QUEST Web site: <http://quest.bris.ac.uk/workshops/crop/index.html>.

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