Models, Methods and Tools for Regional Models of the Response of Ecosystems to Global Climate Change

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ABSTRACT

Central to the analysis of the future sustainability of forest, rangeland, and agricultural landscapes are the effects of potential future climates. While no tools exist to *predict* future climates (which depend upon human choices, in any case), techniques for computing physically-consistent future climates are improving. In this paper, we present a methodology in which results from global climate models (General Circulation Models of the ocean and atmosphere) are interpolated for specific regions using limited-area climate models with significantly finer spatial representation of orographic and biotic influences on climate. Climate model results then serve as inputs into land surface models for evaluation of climate and climate change effects. The output from the nested climate model is not a better prediction of future climate, but does include the effects of mountains, strong vegetation contrasts, and inland water bodies on regional climate, and indicates how those effects modify large scale patterns simulated for a doubled-CO_2 climate. The land surface models serve to estimate the vulnerability of terrestrial ecosystems, agriculture and water resources, to climate change.

Climatic information generated by the nested model can be formatted to serve as input to ecosystem, agricultural, and hydrological models, for either point calculations or regional estimates. We have used output from a nested climate model to examine consequences of a doubled-CO_2 climate on productivity and nutrient cycling in rangeland and cropland ecosystems. The results demonstrate ecological sensitivity to the modeled climate, and extreme sensitivity to climate model resolution of orography.

However, the exercise of coupling terrestrial and atmospheric models has illuminated deficiencies in both models, the data sets employed for surface description (soils, land cover), and in our current coupling procedures. Using climate information from atmospheric models requires translating modeled quantities into the quantities normally observed at the surface, and used in terrestrial models. This includes corrections to surface temperatures, radiation, and humidity profiles, as near surface gradients are strong but not well resolved in atmospheric models. A key deficiency in using one-way linkage of climate and terrestrial models to evaluate regional-scale changes is that, as climate changes, vegetation and soil moisture, the feedback from the land surface to the atmosphere, should change. In the current procedure, the ecosystem simulations are run "offline", and so, predicted changes in ecosystem state have no feedback to the atmosphere (one-way coupling).

Eventually, fully coupled simulations are required. However, even preliminary exercises show problems with the simulation of the variables which couple systems. For example, downwelling radiation in climate models is biased low relative to observations (because of the treatment of clouds), which will

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cause errors in photosynthesis and surface energy balances. In ecosystem models which do an excellent job of predicting annual productivity and yield, monthly leaf area indices are very poorly simulated. Errors in these coupling variables will lead to errors in surface energy balance calculations and erroneous feedbacks to the atmosphere. Developing coupled models as a tool will require the improvement of the component models in ways that are not motivated by disciplinary questions.

While reliable and well-tested process models are the foundation for assessments of sustainability, spatial data bases are required to translate site-specific case studies into analyses of regional impacts. Current technology for spatial analysis and modeling (geographic information systems) are inadequate and ill-suited to these types of analyses (regional extrapolations using process models) because of poor coupling to analytical software and inability to deal effectively with temporal data. Analytical functions such as geostatistics, time-series analysis, and multivariate statistics are very difficult to couple to contemporary GIS systems. Treating each time-step of a model as a separate data layer in a GIS is impossibly cumbersome. The alternative is to only map very select time-slices. Improved tools for handling spatial time-series are required. Current data sources for soil, management, and land use characteristics are often of limited quality. Better integration of existing survey data and increased use of inherently spatial data sources, such as satellite data, are required. The limitations of existing tools and data sources are compared to modeling objectives, and future system requirements are discussed.

INTRODUCTION

The best defined results from global change research are changes to mean global quantities, such as temperature. One-dimensional models of the atmosphere, general circulation models and the paleorecord all suggest a sensitivity of mean global temperature to atmospheric CO_2 of between 1 and 2.5 °C at 600 ppm CO_2. Mean global temperature increase is, however, of little use in estimating the climatic impacts of global atmospheric pollution by radiatively active trace gases, since it is certain that global temperature changes will not occur uniformly over the globe or the seasons, and reliable predictions of regional changes continue to be elusive. While our ability to model the effects of climate on ecosystems is good, our projections of future climates are faulty. The situation is inverted for the direct effects of CO_2 on ecosystems: we can predict future concentration ranges fairly well, but we understand very little about the system-level impacts of CO_2 increases.

The risk of climate change damaging agriculture and other natural resources, and the potential impacts of changing CO_2 concentrations, are of sufficient concern that consider-able effort should go into analyzing consequences and devising mitigation strategies. However, the sensitivity of ecosystems to the subtleties of climate is such that regional climate scenarios, including possible changes to precipitation, radiation, and other climate variables, are required for useful impact studies to be conducted. This poses a contradiction: regional climate change scenarios from global models are not credible, except in the broadest terms, yet detailed projections of climate are required for most natural resource models. This paper will review (1) the use of global and regional climate models to generate climate change scenarios, (2) the implementation of climate change scenarios in natural resource models, (3) data requirements for integrated regional modeling, and (4) analysis of regional model results. At each step, we briefly review the state of the art, provide case study examples, identify major limitations, and discuss future prospects.

GLOBAL AND REGIONAL CLIMATE PROJECTION

The output and limitations of general circulation models (GCMs) are now fairly well known. These models are adequate for representing large scale features of the earth's

general circulation; however, many important parameters, including surface temperatures and precipitation, are not simulated very well (Kiehl 1992). GCM simulations of perturbations (changes from the current state) are generally thought to be more reliable than the quantitative simulation of the current state of the atmosphere, though some models have been "tuned" to reproduce the current climate better than their underlying unmodified physics would otherwise permit.

GCMs evolved from models designed for numerical weather prediction and, in their basic state, represent processes which generate primarily high frequency variation (minutes-weeks).   Obviously, if forced by varying radiation (diurnal, seasonal, or solar cycles), they respond. However, internally generated low-frequency (interannual to decadal) variability in climate is also due to interactions with the ocean and, perhaps, the land surface. As a result, most GCM simulations do not generate events such as the El Niño or droughts, such as those that occurred in 1988, which arise from internal processes (though they may be used to analyze such phenomena in conjunction with observations). So-called coupled GCMs (or OAGCMs, for ocean-atmosphere GCMs), in which ocean circulation is also simulated, now exist and demonstrate some capabilities in generating low-frequency events. Consequently, future simulations will presumably be improved in this regard (Meehl 1992). Since extreme events are often related to large scale processes such as the El Niño (Cane 1992) or other tropical-midlatitude couplings (e.g., the drought of 1988) (Trenberth et al. 1988), understanding these processes is crucial in the long term.

The above discussion focuses on the deficiencies of GCMs in representing large-scale, low frequency phenomena. GCMs also have deficiencies in the representation of surface climate arising from low spatial resolution. Fine-scale effects of terrain, inland water bodies, and land cover (vegetation contrasts,

irrigation) (Sellers 1992) are simply absent in GCMs. To clarify, while many GCMs now represent the transpiration process and other phenomena whereby the land surface influences climate, variability so induced at the landscape scale is absent due to the low spatial resolution of GCMs.   While, at the present, we have no breakthroughs in methodology to project the effects of increasing greenhouse gases on low-frequency variability in regional climates, there have been significant developments in the inclusion of the effects of land surface variability in climate simulations by nesting regional climate models within GCMs. In the nesting procedure, a regional climate model is provided with boundary conditions from either observations or simulated conditions from a global model. This procedure allows the effects of land surface processes, topography, and lakes to be simulated at high spatial resolution, and permits the effects of these processes to be simulated with increased fidelity (Giorgi 1990). In regions where regional variability is controlled by factors exogenous to the region (e.g., West Africa, Australia), this nesting approach will not improve regional climate simulations.

A recent study simulated doubling of CO_2 in the U.S., using a 60 km grid-spacing, by nesting a regional climate model (MM4) within a GCM (Giorgi et al. in press). Figure 1 shows the contrast in the representation of topography on a 30 km versus a 400 km grid, corresponding basically to the difference between those used in GCM and mesoscale simulations. Figure 2 shows the level of climate detail achievable with 60 km simulations, with precipitation and temperature fields reflecting the influence of topography, the Great Lakes, and details of the continent-ocean boundary. The large-scale structures resolved for winter precipitation and temperature are similar in level of detail to those derived from observations.   In this study, nesting markedly improved the representation of the current climate in some regions, and marginally, if at all, in others (Giorgi et al. in press).

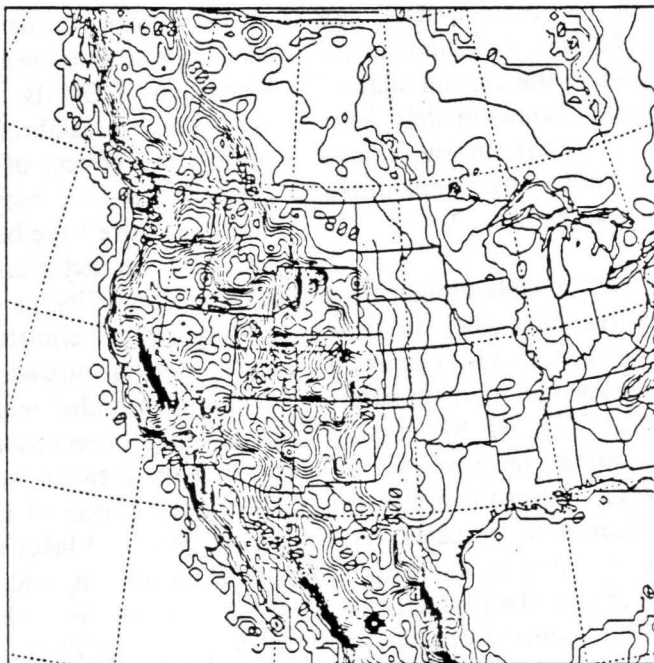## TOPOGRAPHY – 30km GRID

Figure 1a. 30-km grid topography as can be employed in mesoscale atmospheric models.
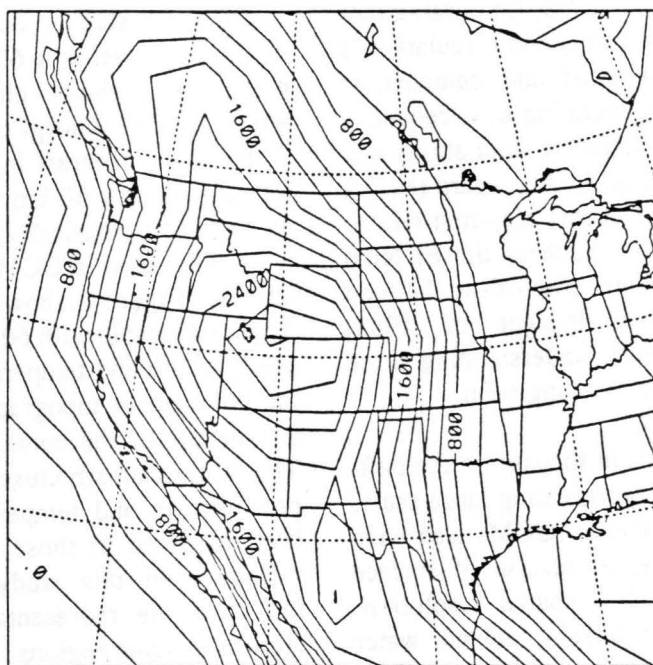
TOPOGRAPHY – 400km GRID

Figure 1b. 400-km grid topography, characteristic of surface representation in GCMs.

MM4 WINTER PRECIPITATION – CONTROL

Figure 2a. Winter precipitation (mm d^{-1}) simulated from a nested regional climate model (MM4) driven by GCM 1xCO$_2$ climate output (after Giorgi *et al.* in press).

MM4 WINTER TEMPERATURE MEANS – CONTROL

Figure 2b. As in Figure 2a, but for winter surface air temperature.

ECOLOGICAL MODEL
RESPONSES TO
SIMULATED CLIMATES

Adapting climate model
output as ecosystem model input

Climate model variables that are used to drive ecosystem and biogeochemical models and vegetation life form models include minimum and maximum temperature, precipitation, wind speed, incident solar radiation, specific humidity, and surface pressure. While these variables are simulated in climate models with time steps of *ca.* 5 to 15 minutes, most ecological models use hourly, daily, or monthly values (Aber 1992). Thus, these values must be aggregated to longer time steps. In general, simple averages are collected, though in principle variables such as solar radiation that affect biological and biophysical processes in a non-linear fashion should be averaged with extreme values weighted more heavily. In many climate models, no exact analog to surface observed temperature is simulated, and so, surface temperatures and temperatures at the lowest model layer (≈ 10 to 40 meters) must be combined to produce a 2 m temperature analog. Wind speed can pose similar problems, as climate models do not simulate the steep gradients in wind speed that often occur near the land surface.

Most climate models compute a hydrological budget for the soil-vegetation system. Most ecological models also compute a water budget, leading to a potential inconsistency, as the algorithms and time steps may differ considerably. This is an inevitable consequence of partially-coupled model experiments. Large differences between atmospheric and terrestrial model water budgets can be a useful diagnostic, and are often instructive. For comparison of water budgets calculated by these models with the driving climate model (e.g., MM4), we look at evapotranspiration, runoff, infiltration, snowpack, and soil mois-

ture. Again, these variables may need to be aggregated to appropriate time-steps.

Current GCM and mesoscale models have significant limitations. A key problem with GCMs is the poor treatment of clouds and radiation. While much attention has centered on the consequences of the inadequacies of the simulated atmospheric water cycle in assessing the sensitivity of global warming to increasing trace gases, these inadequacies also impact land surface models. For example, in some GCMs, when a given grid cell has appropriate conditions for cloud formation, a cell-wide cloud will form, whereas, in nature dense clouds would alternate with clear sky over the same domain. This leads to an underestimate of the frequency of full sunlight events, which significantly impact calculations of surface energy balance and photosynthesis, as these processes are nonlinear functions of incident sunlight. In other models, clouds can "blink" on and off, forming and dissipating with unrealistic speed. This too can affect modeled surface processes (Knapp and Smith 1989). A treatment of clouds which may yield acceptable top-of-the-atmosphere (TOA) radiation fluxes can produce an unrealistic surface climate due to inconsistencies between grid-cell resolution and real-world scales of cloudiness. McGuire *et al.* (1992), and Melillo (personal communication), have demonstrated a sensitivity of their ecosystem model (TEM) (McGuire *et al.* 1992) to modeled cloudiness, and Knapp's experimental work also shows significant sensitivity of plant physiology (Knapp and Smith 1989).

Ecosystem
model requirements and uncertainties

Ecosystem processes in natural and managed systems are constrained by the interactions of climate and site factors. While improved climate scenarios can provide a better sense of the direction of climate-driven changes, the effects of climate are modulated by the specific characteristics of the site,

especially local hydrology and soil properties. As an example, Oechel *et al.* (1993) showed that while unusually warm years through the 1980s caused losses of stored carbon in tundra ecosystems, the effects were largest in moist sites which became progressively drier through that period. Thus, in order to integrate climate and climate change scenarios with ecological and hydrological models, information about land surface characteristics such as soils and topography is crucial.

The importance of soil properties in modulating climatic responses cannot be overemphasized. Soil texture is a key variable, influencing both hydraulic properties and soil organic matter storage. The latter two interact, as decomposition rates of soil carbon are influenced by soil moisture (itself influenced by texture) and by the direct effects of clay on soil carbon stabilization. In a global model analysis, Schimel *et al.* (submitted) showed that for grassland, soil organic carbon (SOC) storage (in g Cm^{-2}) is described by the equation

$$SOC = (6800 \times clayfraction) + (3782e^{-0.047}),$$

where T is mean annual temperature in °C, and *clayfraction* is decimal fraction. The effects of soil texture and mean annual temperature are comparable, so changing texture from 10 to 50% clay at a given T can produce a change in soil carbon storage as large as a change in T of tens of degrees. Similar results have been shown in other studies (Burke *et al.* 1989). Modeling results also show that at a common clay fraction, increasing sand relative to silt decreases carbon storage (Parton *et al.* in press). This occurs because the decreased moisture storage associated with higher sand content decreased net primary production (NPP). This effect can be reversed in dry climates, where increasing sand content results in deeper soil moisture storage and lower evaporation/transpiration ratios (Sala *et al.* 1986).

The above discussions demonstrate the

quantitative or even qualitative modification of climatic effects by soils. We highlight the need for regional and global models to be based on both rigorous application of climate change scenarios, and high-quality information on the distribution of soil and topographic properties. High-quality information on land management practices is also required. For example, fertilization significantly affects the response of agricultural systems to climatic stress, and fertilizer efficiencies and fates vary significantly with texture and drainage status of soils. Most geographic data bases describing fertilization give average and total application rates on a national basis. While better regional fertilizer data exist, these are not integrated with soils information, and are difficult to apply in regional models.

Other biological uncertainties that arise from biology and biophysics preclude confidence in projections of ecosystem change. Uncertainties arising from direct effects of CO_2 are critical. While the effects of CO_2 on physiology are arguably well known, system-level consequences remain to be seen. For example, effects of increasing CO_2 on stomatal conductance will affect the hydrologic cycle. Changes to surface air temperature arising from warmer leaf surfaces will affect boundary layer humidities and, hence, the driving force for evaporation, as well as boundary layer CO_2 concentrations (because the depth of the boundary layer may change).

Changes in stomatal resistance can also affect soil moisture storage. In recent CENTURY (Parton *et al.* in press) calculations of direct CO_2 effects, reductions in canopy conductance caused increases in the persistence of soil moisture in the growing season, which actually reduced soil carbon stocks via increases in decomposition, nearly offsetting the increases in productivity (Parton and Ojima personal communication). So while crop yields increase, carbon storage declined. The realism of this scenario and its generality outside semiarid environments is yet to be assessed,

but it illustrates the complex interactions that can occur.

In other simulations, we showed that the effect of CO_2 fertilization was sensitive to the degree of warming experienced, because, as soils warmed, decomposition and N release were accelerated. Enhanced N availability allowed more NPP for the same increase of CO_2. Warming-induced losses of SOC fuelled the CO_2-driven increase in NPP. Thus, the opposing effects of fertilization and warming on NPP and decomposition interact to control system carbon stocks. Since the sensitivity of ecosystem responses to CO_2 fertilization is modulated by soil organic carbon processes, other factors affecting SOC storage and turnover may well interact with system responses. For example, if N mineralization, driven by warming, permits CO_2 fertilization of ecosystems, then the partitioning of mineralized N between plant uptake, leaching, and gaseous loss will influence ecosystem response to atmospheric CO_2. This partitioning is crucially dependent upon soil properties influencing soil moisture and nitrogen transport.

TOOLS FOR ANALYZING INTEGRATED MODELS

Incorporating coupled models into spatial data bases for creating model runs and for analyzing their output has proved to be more challenging than expected. Several problems have been prominent, mostly arising from the integration of spatial and temporal data. The base environment for spatial modeling is the Geographic Information System (GIS) (Burke et al. 1990; Schimel et al. 1990, 1991). GIS has been developed largely to support static information. The basic data structure is the map, which is a 2-dimensional description of an attribute (i.e., a variable). Other attribute files may be associated with the same map units. For example, a map showing the location of alluvial soils could have an attribute file describing the depth, texture, and composition of the soils. However, the basic analytical unit is the map or data plane. When ecosystem model output is displayed in GIS, the typical fields displayed are values of total annual NPP, soil properties, or nutrient cycling attributes, where the data do not have a time dimension. Occasionally, years are compared (e.g., Burke et al. 1991).

This approach is inconsistent with climate modeling, since the underlying data structure for input and outputs of climate models is a time series. A number of other problems arise when integrating GIS and models. For example, the basic structure of a coupled GIS model is designed to conduct separate model runs in each homogeneous region, either in a raster (grid) or vector (map unit) format. Within each vector or raster unit, one climate time series and set of soil and topographic boundary conditions are applied. If spatial patterns in climate differ significantly during summer and winter, spatial partitioning of the domain can be difficult without going to very small units. More serious problems arise in analyzing time-dependent model results. Ecosystem and hydrological models typically produce hourly, daily, or monthly results. A typical simulation will produce 5 to 20 output variables for each of 100 to 1000 or more time steps. While some simulated properties (e.g., soil carbon) change slowly and lend themselves to time-slice display, others change rapidly. In current GIS configurations, each time-step becomes a data plane or map for storage of time-dependent information.

Obviously, storing and analyzing hundreds to thousands of data planes per output variable is a challenging task and one to which current GISs are poorly suited. Our group has explored two solutions. The first is a "temporal GIS", in which the basic unit of analysis becomes the "data cube", a north-east by time array, which the GIS treats as a unit. In this modification of GIS (Beller et al. 1991), the software understands the structure of temporal data. Thus, simple commands can process temporal data because the GIS understands

order (the arrow of time) and proximity in time as well as in space. This solution does not eliminate problems with data volume, but modern workstations are increasingly capable in this regard. The temporal GIS structure also allows analyzing time-series correlations in a spatial context. While temporal data can be analyzed using conventional GIS, it generally involves cumbersome transfers of large data sets between the GIS and analytical software. Temporal GIS also allows the ready computation and display (as a single data layer) of derived time series properties such as change in a quantity from the beginning to the end of a simulation, the range experienced in a variable during an interval, and the amplitude of cyclic phenomena including diurnal and seasonal cycles.

Second, we have explored analytical data-compression techniques. In examining time-series output of models and temporal data, it is often evident that strong time-series correlations can be found, such as the seasonal cycle, multi-decadal drought cycles, and trends in land use, which may cause long-term trends in soil organic matter depletion or increases in productivity due to fertilization. Not all of the information in a time series is required to understand the processes which have occurred over the simulated interval. Figure 3 shows a time-series decomposition of CENTURY model output. First, a thousand-day trend is fitted to take out the interannual variability associated with precipitation and temperature. Then, the seasonal cycle is fitted by a harmonic. Finally, the residual is displayed.

This approach has two benefits. First, it separates simulated phenomena into relevant time scales for analysis. Second, while the original time series has > 300 points, the trend and seasonal cycle can be represented by < 30 parameters. The trend and harmonic components can be combined to display a reconstructed time-series with known error. The relatively small number of parameters can be

transferred to the GIS, each as a layer, and recombined using a simple equation. Thus a parametric representation of the temporal data can be stored in GIS with one tenth or less data volume, while storing key aspects of the record for ready display (e.g., amplitude and phase of the seasonal cycle). If above-ground biomass is processed in this way, the time of initiation of growth and senescence and integrated productivity are direct mappable products, but evaluated over the full time series. This approach is a compromise in data volume between the conventional approach of only storing "snapshots" of model output and the temporal GIS approach, but has the added advantage of forcing the investigator to focus on the critical aspects of a data set, since only these are stored. Extraction of such key features of temporal data is of value in both assessing the significance of results and in understanding the validity of results, since snapshots can conceal both important features of the results and significant errors. An example of this is the recent observation that most warming over the past decades has occurred at night, a result obscured by the high degree of temporal averaging normally required to study global phenomena. Many other such errors or important results are likely buried in existing models and observational time series.

CONCLUSIONS

Integrated modeling, incorporating atmospheric, ecological, agronomic, and hydrologic processes, is an increasingly important aspect of research in sustainability, climate and management impacts, and basic environmental science. While the obvious power and utility of results from such models motivates their wider application and continued development, significant weaknesses exist in the underlying data bases and in the analytical tools for understanding the results. The variable, low, or unknown quality of many data bases and the inconsistencies between data bases compromises the final quality of integrated calcula-

Time Series Decomposition of Biomass - Kursk Simulation
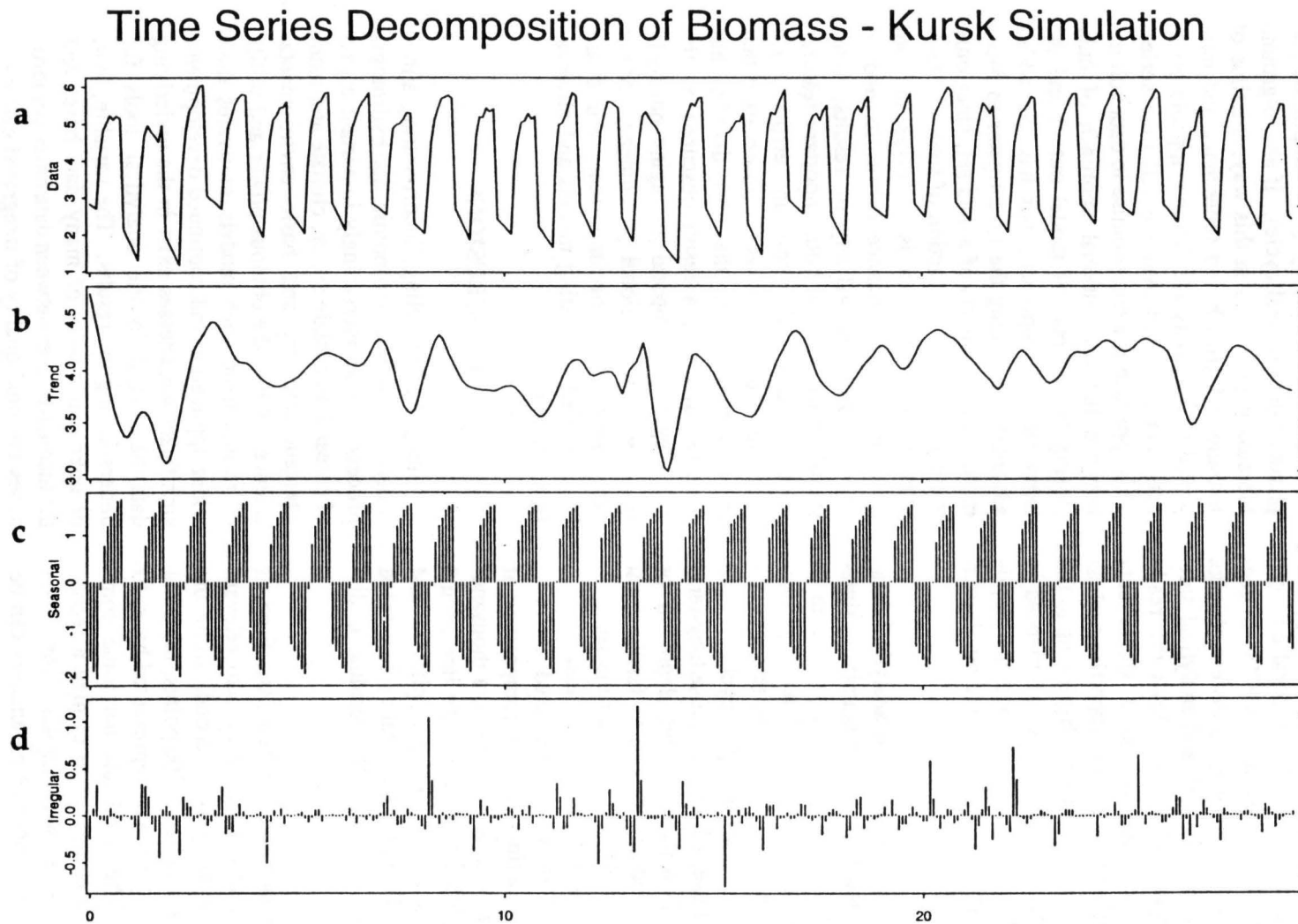

Figure 3. Time series decomposition of CENTURY-simulated biomass from Kursk, Russia.
(a) Original model output data (b) 1000-day fitted trend (c) Seasonal cycle (d) Residual.

tions. The inadequacy of analytical tools compromises the depth and care with which results may be analyzed. Progress is being made on both data and analytical tools as the requirements of integrated models become clearer.

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