Physically-based global downscaling climate change projections for a full century

S J Ghan and T Shippert
Pacific Northwest National Laboratory, Richland WA 99352
steve.ghan@pnl.gov

Abstract. A global atmosphere/land model with an embedded subgrid orography scheme is used to simulate the period 1977-2100 using ocean surface conditions and radiative constituent concentrations for a climate change scenario. Climate variables simulated for multiple elevation classes are mapping according to a high-resolution elevation dataset in ten regions with complex terrain. Analysis of changes in the simulated climate leads to the following conclusions. Changes in precipitation vary widely, with precipitation increasing more with increasing altitude in some region, decreasing more with altitude in others, and changing little in still others. In some regions the sign of the precipitation change depends on surface elevation. Changes in surface air temperature are rather uniform, with at most a two-fold difference between the largest and smallest changes within a region; in most cases the warming increases with altitude. Changes in snow water are highly dependent on altitude. Absolute changes usually increase with altitude, while relative changes decrease. In places where snow accumulates, an artificial upper bound on snow water limits the sensitivity of snow water to climate change considerably. The simulated impact of climate change on regional mean snow water varies widely, with little impact in regions in which the upper bound on snow water is the dominant snow water sink, moderate impact in regions with a mixture of seasonal and permanent snow, and profound impacts on regions with little permanent snow.

1. Introduction
Greenhouse gases are well-mixed in the atmosphere, so the radiative forcing of climate change occurs mostly on global scales. But the climate response to the forcing can be highly localized because local topography interacts with strongly nonlinear processes such as precipitation and melting. For example, in regions with complex terrain a uniform rise in the freezing level can produce a strong orographic signature in the distribution of changes in snowfall, snow water, and runoff on scales less than 10 km.

Projecting the impact of global climate change on water resources therefore requires the ability to represent climate processes on a variety of spatial scales, from global (40,000 km) down to local (5 km). Current computing resources are insufficient to permit global climate simulations explicitly resolving such a wide of spatial scales for more than a few months. Century climate simulations spanning the full range of spatial scales will not be feasible for a decade or more.

Recognizing this, the climate impacts community has developed a variety of methods for downscaling global model projections of climate change. One method is to apply to a climate model a physically-based treatment of the climatic influence of the subgrid distribution of surface elevation [1]. Here we present the results of the application downscaling method to century climate change simulations by a global climate model, the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM3) [2] for one Intergovernmental Panel on Climate Change
(IPCC) scenario. Section 2 describes the downscaling scheme. Section 3 describes the design of the experiment. Section 4 presents results from the climate change downscaling simulation. Conclusions are summarized in section 5.

2. Subgrid Orography Scheme and Load Balancing

Figure 1 illustrates how the subgrid scheme works. Further description of the scheme can be found in [1].

![Subgrid Orography Scheme](image)

Figure 1. Steps in the application of the subgrid scheme. A high-resolution surface elevation dataset (upper left) is used to determine the frequency distribution and mean elevation of a set of elevation classes within each grid cell (upper right). A mountain flow model is used to diagnose the displacement of air parcels with respect to the mean elevation. Conservation of energy and moisture is used to determine the temperature and humidity profiles for each elevation class. Full model physics is applied to those profiles (bottom right), and written to the model history. The history for each elevation class is interpolated according to the high-resolution surface elevation dataset, producing a high-resolution distribution of the climate (bottom left).

The heterogeneous distribution of elevation classes could produce a serious imbalance in the computational burden of the column physics if the domain decomposition distributes grid cells evenly across processors. Model column physics typically comprises 75–80% of the total model run time, so a large load imbalance in the column physics could seriously degrade model performance in a massively parallel simulation. But since the distribution of classes is static, static load balancing can be used to distribute the elevation classes uniformly across processors. Load balancing is accomplished first by distributing the number of classes evenly within each process. The number of
physics chunks on processes is distributed uniformly across processes and the dynamics-physics transpose cost is minimized by assigning chunks to processes with the most dynamics grid cells from that chunk. Parallel efficiency with the subgrid scheme and load balancing exceeds parallel efficiency without the subgrid scheme for up to 128 processors. Load balancing across processes decreases runtime by 10–30% depending on configuration [3].

3. Experiment Design
The subgrid orography scheme has been applied to the NCAR Community Atmosphere Model (CAM3) [4] and Common Land Model (CLM3) [5], which are two components of the CCSM3. In this study CAM3 and CLM3 are run in an offline mode, i.e. driven by ocean surface conditions taken from a CCSM3 climate simulation [6] of the Intergovernmental Panel on Climate Change A1B emissions scenario [7]. The ocean surface temperature and sea ice cover have been adjusted to correct for biases in the CCSM3 simulation. The downscaling simulation was run at a horizontal resolution of 2x2.5 for the period 1977-2100. The history for the multiple elevation classes was mapped in postprocessing to a global 2.5 minute grid.

4. Climate Change Downscaling Simulation
The complexity of the climate response can only be appreciated by focusing on selected regions. Figure 2 shows the response for the western U.S. Although changes in precipitation and temperature are significant, there is little relationship between the change and surface elevation. Changes in snow water are highly dependent on altitude. Absolute changes usually increase with altitude, while relative changes decrease. Similar conclusions apply to other regions.

Figure 2. Difference (above) and ratio (below) of simulated annual mean precipitation (left, mm/day), surface air temperature (middle, in °C), and snow water equivalent (right, in m) for the western U.S. for the periods 2080-2100 and 1980-2000. The surface elevation (in m) is shown for reference in the lower center panel.
The time-dependence of the response is illustrated in Figure 3, which shows the regional mean snow water equivalent for nine regions for the period 1980-2100. The simulated impact of climate change on regional mean snow water varies widely, with little impact in regions in which the upper bound on snow water is the dominant snow water sink, moderate impact in regions with a mixture of seasonal and permanent snow, and profound impacts on regions with little permanent snow. In places where snow accumulates, an artificial upper bound on snow water limits the sensitivity of snow water to climate change considerably.

Figure 3. Annual mean snow water equivalent for nine regions for the period 1980-2100.

5. Conclusions
The subgrid orography scheme provides an unprecedented level of detail in the simulated climate response to increasing greenhouse gases. The spatial distribution of the simulated change in precipitation and surface air temperature exhibits little evidence of an orographic signature in regions with complex terrain, but the response of snow water is highly correlated with surface elevation. Snow water decreases in a warmer climate as the freezing level rises. The absolute decrease is greatest in regions with heavy snow, which is typically at the highest elevations within a mountain range.

However, evaluation of the simulated climate [8] reveals several biases that compromise the interpretation of this simulation. These include poorly resolved rain shadows, excessive summertime snow area, and a 1 m upper bound on snow water equivalent. These biases suggest an underestimate of the sensitivity of snow water to climate warming in regions where snow accumulates, whether or not the accumulation is correct [9]. Considerable effort will be required to correct these biases.
References

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