4.6 SUMMARY AND CONCLUSION

The response to global climate change will probably exhibit significant regional variations. This chapter has focused on the Alpine region and provided an overview of the possible future evolution of the region's climate. The distinctiveness of Alpine weather systems and their relationship to the global-scale circulation (chapter 2) implies that a change in the global climate could also generate special features in the Alpine region.

Our consideration of Alpine climate focussed on physically induced atmospheric changes operating in isolation from other environmental and human components of the system. The main thrust was to derive regional climate scenarios. The competing constraints placed on the one hand by the inherent uncertainties associated with climate prediction and on the other by the desirability of having available assessments of the nature of possible climate change influenced the methods adopted. The discussion has emphasized that the derived scenarios are not forecasts but applications-oriented descriptions of conceivable future climate changes geared for the examination of one or a range of possible impacts.

Our discussion involved a study of the approaches currently available for generating climate scenarios, providing examples for the Alpine region based on these approaches, and commenting on the range of their application. The scenarios provided for the Alpine region were derived using the extant range of approaches: the analyses of past climates, the continuation of recent trends, the semiempirical downscaling of future global climates as simulated by coarse-resolution climate models, and the simulation of future climate with high-resolution global and nested regional climate models. Attention was drawn to the specific advantages and limitations of each approach.

The techniques discussed are subject to a series of basic limitations that introduce large uncertainties into any assessments of future Alpine climate. Nevertheless, taken together, they provide a set of complementary tools for studying Alpine climate change and its possible implications. In the following, we discuss these two aspects of basic limitations and practical utility.

In relation to the limitations several points need to be stressed: First, the limitations arise because projections of future climate change inevitably assume future anthropogenic forcings and are unavoidably obscured by the stochastic component of the variability associated with natural forcing (e.g. solar irradiance and volcanic activity) and the climate system's chaotic nature (see chapter 7). These limitations are mitigated to the extent that current GCM results suggest anthropogenic effects with an amplitude exceeding that of the natural variability experienced in the past several thousand years. More trenchantly studies of the combined effects of several, possibly counteracting, anthropogenic forcings (e.g. the increasing concentration of both aerosols and greenhouse-gases) are in their infancy. Aerosol effects, not considered in the present study, could not only reduce future warming over Central Europe (at least temporarily) by several tenths of a degree Celsius but also modify the presently projected changes in the general circulation (e.g., Taylor and Penner 1994; Mitchell, Davis, et al. 1995; Mitchell, Johns, et al. 1995).

Second, present climate models, in spite of their sophistication, inadequately represent several important processes and interactions. Feedbacks related to the biosphere and the global carbon cycle can be important particularly on longer time scales (decades and beyond). The oceans are huge reservoirs for heat and CO_2, and simulation studies addressing the role of oceanic variability have only just started (e.g., Delworth, Manabe and Stouffer 1993; Manabe and Stouffer 1994). In this context the oceanic subsystem might exhibit multiple steady states (e.g., Marotzke and Willebrand 1991), and possible future subtle shifts in the boundary conditions of the oceanic circulation related to meltwater inflow and precipitation could influence the transitions between the different modes (see also chapter 7). These unrepresented or partially represented processes influence the comparative evolution of the real and modelled atmosphere-ocean system.

Third, the amplitude of future climate change could exceed the range of the data available to construct statistical and physical models of climate. This in turn limits the range of applicability of empirical and semiempirical regionalization approaches and the validity of the parameterizations in the physical models, because these have been tuned for current climatic conditions.

Fourth, the departure of GCM control simulations of current-day climate from the observed climate limits the credibility of scenarios based upon such models. Removal of the bias by comparison of 1 x CO_2 and perturbed states (rather than a comparison of the perturbed states with observed climate) becomes questionable if the bias's relative amplitude is large compared to the climate change signal. Indeed, at present, GCMs typically show large biases over the European sector and the Alpine region, and thus care must be taken in interpreting the resulting scenarios.

Finally we comment on the scenarios' utility. The results demonstrate the potential for complex and significant climate change in the Alpine region. Comparison of the scenarios provides initial estimates of the sensitivity range of Alpine temperature and precipitation to a doubling of atmospheric

GHG forcing. The estimates suggest a general warming of the Alps under increasing GHG concentrations and indicate that in most subregions of the Alps an increase rather than a decrease in precipitation could accompany such a warming. Additional studies are needed to better understand the differences between the present estimates, to investigate a broader range of conditions, such as combined sensitivities due to a simultaneous increase of GHGs and aerosols, and to assess more reliably the relative importance of regional-scale feedbacks for the region's climate.

Several of the scenarios this chapter presented are comprehensive enough to allow for detailed impact and sensitivity studies in a range of sectors affected by climate. They provide first-order estimates of possible climatic changes and can be used to test and simplify impact models, to detect sensitive areas, and to explore the possible interactions of climate change with other aspects of global and regional change. The scenarios have already proven useful for initial sensitivity studies in the ecological, agricultural and touristic sectors. (For ecological applications, see chapter 6 and Bugmann and Fischlin 1994, Brzeziecki, Kienast, and Wildi, 1995, and Fischlin and Gyalistras, 1997; for agriculture, see Flückiger 1995, Fuhrer 1997 and Riedo et al. 1997; for tourism, see Abegg 1996.)