Chapter 5

General conclusions

> The mountains have rules. They are harsh rules, but they are there, and if you keep to them you are safe. A mountain is not like men. A mountain is sincere. The weapons to conquer it exist inside you, inside your soul.
>
> Walter Bonatti

Climate change impacts are non uniformly distributed over the globe, with a strong impact on the environment in mountainous areas, especially because mountain ecosystems depend on climatic conditions that vary as a function of altitude. In the recent years, it has become clear that the manifestation of climate change depends on elevation: the measurements so far available in the various mountain regions of the world have confirmed that, on average, mountains are warming more rapidly than surrounding regions. The rate of warming is amplified with elevation, such that high-mountain environments experience more rapid changes in temperature than environments at lower elevations. Significant changes of precipitation are also expected in the changing climate and orographic effects are important in determining the amount of rainfall at a given location. Thus it becomes particularly important to understand how mountains responds to global warming and to anthropogenic forcing.

This dissertation focused on the altitudinal dependencies of meteoclimatic conditions in the Great Alpine Region (GAR), one of the highest and most extensive mountain range system in Europe where both global and local anthropic activities impact it. The Alps serve as a natural barrier, as they surround highly urbanised areas, trapping smog and haze in the valleys of northern Italy.
In Chapter 2, observational data over the GAR have been analyzed to study the actual representation of the status of atmospheric variables such as precipitation. Using a large rain gauge dataset,

we showed that the distribution of annual precipitation among the lowlands and the mountains has varied over time, with an increase of the precipitation at the high elevations compared to the low elevations starting in the mid 20 century and peaking in the 1980s. The simultaneous increase and peak of anthropogenic aerosol load is discussed as a possible source for this inter-decadal change. Indeed a varying aerosol concentration has potential impacts on the orographic enhancement of precipitation essentially for two effects: the corresponding change in atmospheric stability and the possible change in the microphysical properties of clouds. At present it is however unclear what process would dominate in determining the response of precipitation to varying aerosol loads, however results seem to indicate that the increased pollution might have increased the orographic enhancement of precipitation, but it is not clear whether this should be related to a suppression of precipitation in the heavily polluted lowlands or an increased precipitation at higher elevations.
With the aim of shedding more light on the aerosols effects at different altitudes, Chapter 3 describes a numerical study over the GAR: using the Weather Research and Forecasting model, the altitude-dependence of the cloud mediated indirect effects of aerosols have been studied over the GAR. Two different 5-years long simulations have been run, differing only in terms of the aerosol load: in the POLLUTED experiment the mean aerosol concentration in the atmospheric boundary layer is on average about one order of magnitude larger than in the PRISTINE simulation in the lowlands, while similar concentrations are found over the mountains. We show that seasonal mean cloud cover, temperature, and precipitations are affected by the aerosol concentrations in the air column, and that the response to pollution is both elevation and season dependent. The overall cloud cover increase with aerosol levels leads to either surface cooling or warming depending on the surface albedo (snow covered or not). Furthermore, different types of clouds have a different sensitivity to aerosols: while the lifetime of low pressure system clouds and orographic clouds is generally increased at high levels of aerosols, convective clouds (typical of the summer season) can actually decrease at high levels of pollution, due to the reduction of strong updrafts.
A third complementing research topic has been tackled in this research project, based on investigating the expected changes in climate over the GAR with a greater emphasis in understanding changes with altitude. In Chapter 4 we investigate predicted changes using the Weather Research and Forecasting Model running 30-year historical simulations (1979-2008) and climate-change projections (2038-2068) at convection permitting resolution (4Km) to be able to better model the interaction between the air masses and the complex orography of this area. This study focused on the altitudinal dependence of historical and future ETCCDI Climate Change indices, showing that different physical processes at different altitudes describe the elevation dependence of temperature and precipitation: both variables are affected by climate change with an altitude dependence changing seasonally.

Among the future developments of this line of research, it is worth mentioning studies varying the concentration of cloud condensation nuclei and ice-nuclei separately to shed light on their relative role in cloud formation, duration, and precipitation; idealized bidimensional and

tridimensional studies to properly account for small-scale processes not considered in this thesis, such as turbulent mixing; studies that analyze also separately aerosol direct and semi-direct effects on radiation, that could modify, even substantially, the climatic response; studies taking into account an ensemble of simulations on the Greater Alpine Region to obtain even more precise quantitative results, and finally studies on precipitation extremes which, however, can evaluate not only on a daily but also on a sub-daily time scale.

This research project demonstrates that the orographic enhancement of precipitation dependence on anthropogenic forcing is an important research line, and in-depth studies are necessary in order to quantify the effects of both aerosols and global warming on it and on other thermodynamic variables. This is an important key point because it will allow us to make more reliable predictions in the mountain regions in the coming decades.

Appendices

Appendix A

The Weather Research and Forecasting (WRF) Model

The Weather Research and Forecasting (WRF) Model is an atmospheric model born in the early 90's from a collaborative effort between the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration, the U.S. Air Force, the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). The goal of the partnership was to design a model useful both for research purposes and for Numerical Weather Prediction (NWP).
The model can be used for a lot of applications, it works form scales of meters to thousands of kilometers. For researchers, WRF can produce simulations based on real atmospheric conditions or idealized conditions offering operational forecasting, and reflecting advances in physics, numerics, and data assimilation contributed by developers from the expansive research community. Indeed WRF Model is a supported "community model", it has an open-source code in the public domain, and its use is unrestricted, allowing the large worldwide community of registered users to improve the code and the efficiency.

The Dynamical Core usually refers to the Governing Equations and the Numerical Procedure to solve them. NWP models represent the behaviour of the atmosphere which is described by the governing equations. These equations can be derived from various conservation principles and related approximations such as conservation of motion (momentum), conservation of mass, conservation of heat (thermodynamic energy), conservation of water (mixing ratio/ specific humidity) in different forms and conservation of other gaseous and aerosol material. The equations are written in the Eulerian framework in which values and their derivatives are evaluated at fixed locations on the earth.
WRF offers two dynamical cores for its computation of the atmospheric governing equations, and the variants of the model are known as WRF-ARW (Advanced Research WRF) and WRF-NMM

(Nonhydrostatic Mesoscale Model) developed and maintained by the Mesoscale and Microscale Meteorology Division of NCAR. These two dynamical cores include mostly advection, pressure gradients, Coriolis, buoyancy, filters, diffusion, and time-stepping. Physics, the software framework, and parts of data pre- and post-processing are shared between the dynamical cores. The ARW dynamics solver integrates the compressible, nonhydrostatic Euler equations that are cast in flux form using variables that have conservation properties.

WRF Model supports a variety of capabilities:

- fully compressible Euler non hydrostatic equations with hydrostatic option;
- scalar-conserving flux form for prognostic variables;
- complete Coriolis and curvature terms;
- nesting: one-way, two-way with multiple nests, moving nests;
- Mapping to Sphere: 3 map projections are supported for real-data simulations (Curvature terms included);
- Runge-Kutta 2nd and 3rd order time step options;
- 2nd to 6th order advection options (horizontal and vertical);
- positive-definite advection option for moisture, scalar and Turbolent Kinetic Energy;
- time-split small step for acoustic and gravity-wave modes;
- lateral boundary conditions;
- full physics options for land-surface, PBL, radiation, microphysics and cumulus parameterization;

The equations of motion, which form the basis for all NWP models, have their form in pressure coordinates. Pressure coordinate systems are not particularly suited to solving the forecast equations because they can intersect mountains and thus have problems over orographic forecast domain. To address the problem of discontinuous forecast surfaces, the η coordinate was created that is defined as a terrain-following mass vertical coordinate [139]. η is defined as

$$\eta = \frac{p_{\mathrm{h}} - p_{\mathrm{ht}}}{p_{\mathrm{hs}} - p_{\mathrm{ht}}} \tag{A.1}$$

where p_h is the hydrostatic component of the pressure, and p_{hs} and p_{ht} refer to values along the surface and top boundaries, respectively. η varies from a value of 1 at the surface to 0 at the upper boundary of the model domain (Figure A.1).
The η levels allow the bottom atmospheric layer of the model to be represented within each grid box as a flat "step," rather than sloping in steep terrain. They also allow models to have extreme differences in elevation from one grid point to its neighbor, developing strong vertical motions in areas of steep terrain and thus more accurately represent many of the blocking effects that mountains can have on stable air masses. Even when the step-like eta is used as the vertical coordinate, model terrain is still much coarser than real terrain. Although this representation of terrain is a source of error in areas strongly affected by small-scale terrain features, it is still necessary to depict the average elevation within the entire grid box area. Representing terrain in this manner impacts the scale of features that can be preserved in the model's forecast, making the forecast representative of the average conditions in the grid box.

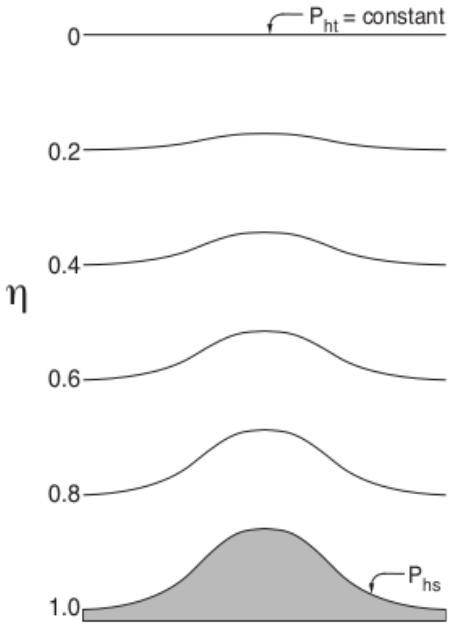

Figure A.1: ARW η coordinates [140]

A.1 Governing equations

The set of the equations used in a NWP model is very large: in this paragraph, the principal equations are described.

The Momentum Equation: the momentum equation is a partial differential equation that describes how the velocity or momentum of a fluid responds to internal and imposed forces. The momentum equation can be stated as:

$$\frac{D\overline{v}}{Dt} = -\frac{1}{\rho}\nabla p - \nu\nabla^2\overline{v} + F_{\mathrm{b}}$$

where $\overline{v}$ is the three-dimensional velocity vector, p is the pressure, ν is the kinematic viscosity and F_b represents external body forces (per unit mass) such as gravity [141]. Equation is called the Navier–Stokes equation.
The horizontal wind is a primary weather variable: the acceleration of the horizontal wind is on the order of 10^{-4} [m/s^{-2}] compared with 10^{-7} [m/s^{-2}] for the vertical acceleration. Primitive equation models assume that horizontal scales are much larger than vertical scales, which applies to synoptic and planetary circulations, thus the vertical momentum equation is replaced by the hydrostatic approximation, in which the weight of the atmosphere balances the vertical pressure gradient and no vertical accelerations are calculated explicitly. However, the hydrostatic assumption does not hold when the length and depth are similar (typically less than 10 Km). Deep convection, which is common in the tropics, is non-hydrostatic. Therefore, the rate of change of vertical motion is calculated as the sum of the advection, local buoyancy, and non-hydrostatic vertical pressure gradient minus the precipitation drag. These models can reproduce mesoscale convection in realistic detail but they are subject to error in timing and placement of convection. Non-hydrostatic models have the disadvantage of being computationally intensive.

The Continuity Equation: a fundamental principle in meteorology is that mass is conserved except for external sources and sinks, as described by the equation below [141]:

$$\frac{D\rho}{Dt} + \rho\nabla\cdot\overline{v} = 0$$

This form of the equation is useful for forecasting as it relates the rate of density increase, following an air parcel, to the velocity divergence.

The Thermodynamic Equation: this equation describes the conservation of energy applied to a moving fluid element. For a system in thermodynamic equilibrium, the change in internal energy is due to the difference between work done by the system and heat added to the system, written as:

$$c_{\mathrm{v}}\frac{DT}{Dt} + \frac{D\alpha}{Dt} = Q$$

where $c_v \frac{DT}{Dt}$ represents the change in internal energy per unit mass and $\frac{D\alpha}{Dt}$ the rate of work by the fluid system per unit mass. Q is the heating rate.

A.2 Parametrization

NWP models are not able to resolve explicitly those processes which are smaller than the grid scale of the model, thus these processes have to be parameterized. Parameterization means the description of the overall effect of a given subgrid scale process on the grid scale values, using the given grid scale variables.
In this section the main parametrizations used in this thesis are described:

1. The Yonsei University Scheme (YSU) is used for the Planetary Boundary Layer (PBL) because it accurately simulates deeper vertical mixing in buoyancy-driven PBLs with shallower mixing in strong-wind regimes. This scheme proposes a revised vertical diffusion package with a nonlocal turbulent mixing in the PBL that is suitable for weather forecasting and climate models. An explicit treatment of the entrainment processes at the top of PBL is included that produces a realistic structure of the PBL in response to an idealized daytime variation of surface heat and moisture fluxes [107].

2. The radiation schemes provide atmospheric heating due to radiative flux divergence and surface downward longwave and shortwave radiation for the ground heat budget. Longwave radiation includes infrared or thermal radiation absorbed and emitted by gases and surfaces. Upward longwave radiative flux from the ground is determined by the surface emissivity that in turn depends upon land-use type, as well as the ground (skin) temperature. Shortwave radiation includes visible and surrounding wavelengths that make up the solar spectrum. Hence, the only source is the Sun, but processes include absorption, reflection, and scattering in the atmosphere and at surfaces. For shortwave radiation, the upward flux is the reflection due to surface albedo. Within the atmosphere the radiation responds to model-predicted cloud and water vapor distributions, as well as specified carbon dioxide, ozone, and (optionally) trace gas concentrations. The radiative transfer treatment in the Rapid Radiative Transfer Model for GCMs (RRTMG) parameterization is the most complex of all schemes available in the WRF-ARW model and the scheme is described in Iacono et al., 2008 [108]. In this study CAM Green House Gases (GHG) has been used: it provides yearly green house gases from 1765 to 2500. Once the model is compiled, RRTMG long-wave schemes reads these time-varying GHG values from a table (annual global means).

3. The WRF model can make use of several cumulus parameterization schemes, that are useful mainly for the summertime convection: warm-season convective events have been shown to be represented less accurately than cold-season events [142]. This is because of

the large-scale dynamic forcing during the cold-season events that are dominant in winter: they are modeled more accurately than the strong thermal forcing at the surface. The convection parametrization is so necessary to account for the vertical motions not explicitly represented at a coarser resolution. In this thesis the outer domain of the climate and the polluted-pristine simulations include the convection parameterization Tiedtke Scheme [109]: Tiedtke scheme uses the mass-flux approach to represent deep, shallow, and mid-level subgrid convections [109], that is triggered if the parcel's temperature exceeds the environment temperature by a temperature threshold of 0.5°K. This scheme distinguishes penetrative, shallow convection, mid-level convection, and convection starting above the planetary boundary layer.

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