Abstract of Research Project
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RESEARCH PROJECT

INFLUENCE OF GLOBAL WARNING ON THE WATER CYCLE BUDGET STUDIED THROUGH NUMERICAL MODELING TOOLS

Earth is a closed system and its primary source of energy is the incoming solar radiation, which is unevenly distributed on the surface due to Earth's inclination. This means an excess of energy at the equator and a deficiency at mid and high latitudes. This equator-to-pole temperature gradient, together with the Earth's rotation results in a large scale system of circulation that, with the oceans, acts to transport heat polewards to achieve an overall energy balance. The Earth's radiative equilibrium at the Top of Atmosphere [TOA] is represented by the balance between the incident solar radiation that reaches the surface (~342 W/m2), the reflected solar radiation and the radiation left to warm the earth's surface and atmosphere (~235W/m2) which then leaves as Outgoing Longwave Radiation (OLR) [Kiehl & Trenberth (1997)].

An imbalance in this radiation budget implies net heating of the Earth (global warming). Combining observations and climate model simulations the radiative imbalance can be assessed to be N = 0.62 ± 0.43 W/m2 in the period 2000-2012 [Allan 2014]. The latter is due, besides internal variability of the system, to an anthropogenic change in atmospheric composition, especially the generation of carbon dioxide through fossil fuel burning [Karl & Trenberth (2003)].

This sign of a rising temperature has many consequences for the climate system and its current instability. One of the main responses of climate to an increase in temperature is the change in the hydrological cycle. Water resources (globally and regionally) depend strictly on the latter, thus making its assessment in the context of climate change is of primary importance.

The hydrological budget in the atmosphere can be thought as a balance between the local rate of change of water vapor storage, evaporation E, precipitation P and the inflow and outflow of water vapor (where is the humidity horizontal transport); where the quantities are averaged in time and over a region bounded by virtual vertical walls (river-drainage basin). The therm establishes the connection between the terrestrial and the atmospheric branches of the hydrological cycle [Peixoto 1992]. The robustness of the response of each term of the water budget to a warming climate has been assessed in many studies, matching observation with General Circulation models [GCM] simulations; but there are still some open questions.

The change in water vapor amount is constrained by the Clausius-Clapeyron (CC) relationship, which predicts an increase in the saturation water vapor pressure (the water holding capacity of air) of approximately 7% per °C rise in temperature [Held & Soden 2006]. This might lead to a strengthening of the global evaporation (E) minus precipitation (P) pattern with global warming [Allen & Ingram 2002], as projected by climate models under anthropogenic forcing scenarios. In contrast, model-predicted changes to global precipitation increase happen at a rate of 2% per °C rise (CMIP3), significantly less than the CC predicted rate. This discrepancy leads to the necessity of studying other atmospheric processes that would constrain precipitation besides the moisture availability following previous studies [Neagele & Randall 2016]. Furthermore, it seems that precipitation distribution does not increase uniformly in all regions, following the pattern distribution of water vapor [Meehlet 2005] and the frequency of precipitating events decreases overall, although events of heavy rain seem to become more frequent [Pall 2007]. These global changes are predictable as far as not only increases in water vapor but also cloud’s distribution are predictable [Stephens 2010].

In our view, the main way to study the hydrological cycle and its variability is to combine observations with modeling. Atmospheric modeling is a method built to describe all the components of the atmosphere from fundamental physical-mathematical energy-momentum and mass conservation laws governing the physical behavior of the atmosphere. The governing equations are then discretized on a horizontal and vertical grid representing the atmosphere for a given amount of time, to be integrated with High-Performance Computing Facility (HPCF) as the supercomputer (two Cray XC40 clusters) at the European Centre for Medium-Range Weather Forecasts [ECMWF]. The latter have the computing capability of resolving the governing equation in time and for all grid points for high resolutions, which have reached the horizontal spacing of 31 Km (ERA-5).

Here, at the University of Perugia an idealized Climate simulation [Held and Suarez 1994] was performed at a much coarse resolution (ECMWF ERAInterim dx=78 km). The OpenIFS (Integrated Forecast System of the ECMWF) GCM was used to assess the climate equilibrium as a starting point to understand the energetic budget of the atmosphere.

Indeed the use of modeling provides physical intuition and enables to examine the driving forces of atmospheric phenomena. Besides running GCM, to investigate the hydrological cycle other suitable tools would be Single Column Models [SCM], mesoscale regional weather prediction models and Cloud Resolving Models [CRM]. Running a SCM means simulating a single vertical column of the GCM, while using mesoscale regional models and/or CRM, means modeling a piece of the atmosphere at high resolution to capture highly non-linear, non-hydrostatic, processes that happen to be unresolved on global scales [Xu and Randall 1996]. The use of these models is the most used tool in literature to assess and study physical processes. It has benefited in the last decades from the upgrade in computing power, which enables researchers to run them on larger domains and with increasingly higher resolutions, including also more processes as, for example, chemistry unresolved distributions.

SCMs, with different physical processes representation schemes, can be compared in their simulation of a vertical profile evolving in time. The available numerical models for us would be the OpenIFS SCM and the SCM of the MIT (Massachusetts Institute of Technology). SCM can be run under idealized forcing to develop understanding about the atmosphere, such as studying radiative-convective equilibrium [Emanuel et al 2014]. In the context of the Global Energy and Water Cycle Experiment Cloud Systems Study [GEWEX] SCM have been used for modeling and understanding cloud systems [Bechtold et al 2000; Petch et al 2007].

CRMs are capable of resolving most of the transport and heating associated with clouds and can explicitly simulate convective moist phenomena, calculating quantities that are not measurable. The models which can be used in this context are the Advanced Regional Prediction System [ARPS], the System for Atmospheric Modeling [SAM] and the Weather Research and Forecasting [WRF] Model.

All these models are different for initialization and boundary conditions, as well as for the physical processes representation schemes. This makes models comparison (e.g comparing CRM to SCM) suitable to understand the physics behind processes [Randall et al. 1996]. Moreover, their output concerns temperature, water species content (water vapor, liquid water, rain water, graupel, hail), cloud variables and mass fluxes (E, P, Latent Heat, Sensible Heat, etc..) needed for hydrological and hydraulic scopes and tools.

The extensive use of modeling should be combined with the use of climate data set (reanalysis) as observations. The reanalysis method combines models with observations to estimate the main atmospheric parameters such as air temperature and pressure, as well as wind intensity and humidity for all locations on Earth. These latter can be used as forcing for regional hydrological simulations [with data assimilation], but mainly their importance lies in the fact that they give a global description of the climate in time which is reflected in local atmospheric conditions.

For our purpose, it would be suitable to use the high-resolution reanalysis of ERA5 and others which can be downloaded from the Copernicus Climate Service (C3S) Climate data store. Hence, reanalysis products would allow us to identify the water cycle variation in response to global warming, and to prepare predictions on the hydrological cycle [Lorenz & Kunstmann, (2012)]. This would be relevant when looking at regional climate change and its implications for water resources.

The combination of modeling and the vast use of data would be a suitable tool to study climate change in our region, reflected in the variability of the water cycle.

This work requires, besides theoretical knowledge, practical know-how in computing and programming. Part of the work is learning how to compile and run models. The latter consists in using different languages and compilers (Fortran, C++, Python, etc.. and related compilers) and running in interactive and/or batch on our machine, on the DICA Cluster and at the ECMWF (on the Cray) to which we have access as a ECMWF Member or Co-operating State. The work involves studying the models' codes flow and setup, as well as the technical management of how the model uses the computer available resources (e.g memory allocation and parallel computing). Another needed skill is the output management, the statistical analysis of data with different languages, as Python, NCL, and others if required and the use of tools as Metview (ECMWF Product for modeling simulation visualization), CDO (Climate Data Operators), NetCDF format. Forcing regional models to reproduce energy and water budgets on local scales will require learning how to handle new tools as data assimilation in models; while using reanalysis data implies learning the downscaling techniques to get from global to local scales to analyze regional water resources.

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