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Built-up area and population density: Two Essential Societal Variables to address climate hazard impact

D. Ehrlich*, T. Kemper, M. Pesaresi, C. Corbane

Joint Research Centre, European Commission, Via Enrico Fermi, 2749, I-21027 Ispra, Italy

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ABSTRACT

Scientists use Essential Climate Variables to understand and model the Earth's climate. Complementary to the Climate Variables this paper introduces global built-up area and population density, referred to as Essential Societal Variables, that can be used to model human activities and the impact of climate induced hazards on society. Climate impact scenarios inform policy makers on current and future risk and on the cost for mitigation and adaptation measures. The global built-up area and global population densities are generated from Earth observation image archives and from national population census data in the framework of the Global Human Settlement Layer (GHSL) project. The layers are produced with fine granularity for four epochs: 1975, 1990, 2000 and 2015, and will be updated on a regular basis with open satellite imagery. The paper discusses the relevance of global built-up area and population density for a number of policy areas, in particular to understand regional and global urbanization processes and for use in operational crisis management and risk assessment. The paper also provides examples of global statistics on exposure to natural hazards based on the two ESVs and their use in policy making. Finally, the paper discusses the potential of using population and built-up area for developing indicators to monitor the progress in Agenda 2030 including the Sustainable Development Goals (SDGs).

1. Introduction

Climate impact on human society can be modeled using a combination of Essential Climate Variables (ECV) (Bojinski et al., 2014) and Essential Societal Variables (ESV) that describe the human system. The ECV are the core set of variables used to characterize the Earth's climate. ECVs are used to measure progress towards the objectives and the mandates of the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). The UNFCCC calls for an analysis of the impact of climate change on the human system (that includes settlements as well as the agricultural land, water resources and environmental assets that provide resources and deliver services) and of "mitigation and adaptation measures, to assess risks and to enable attribution of climatic events to underlying causes, and to underpin climate services" (Bojinski et al., 2014). The built-up area and the population density are the two ESV used to quantify what we are trying to protect from the impacts of natural hazards.

Societal variables are needed to analyze the human societal system. We introduce the term human societal system to indicate the integrated system that combines human activities and earth system processes (NASA Advisory Council, 1988; Steffen, 2005). The term includes what is referred to as human natural system integration (Liu et al., 2015, 2007; Noble and Huq, 2014), socio-ecological systems (Young et al., 2006) or coupled human environmental systems analysis (Liu et al., 2015). The term societal system aims to stress that human societies use materials and minerals, environmental assets and services, and are also producing artificial substances (such as nitrogen in the nitrogen fixation process) that affect the biogeochemical cycles, which ultimately modulates changes in climate processes. In fact, human societal activities are also categorized and referred to as socio-economic activities (Haberl et al., 2011; Steffen, 2005) or societal metabolism (Fischer-Kowalski, 1998; Haas and Andarge, 2017; Sorman and Giampietro, 2013) and are studied at local and national scale to assess sustainability of cities (Hoornweg, 2010; Johansson et al., 2012) or nations (Baccini and Brunner, 2012) and at global scale to assess planetary boundaries of earth system processes and global sustainability (Rockström et al., 2009).

We refer to the global built-up area and global population density as ESV for at least three reasons. First, the global population density layers can quantify globally the spatial extent of human presence on Earth, and are used to measure societal impact on climate models at local and

* Corresponding author.
E-mail address: daniele.ehrlich@ec.europa.eu (D. Ehrlich).

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global level. Second, the two variables are used to generate global exposure to hazards: essential information for use in crisis management to assess natural hazard risk globally (UNISDR, 2015a) also within the climate change community (Cardona et al., 2012). Urbanization as an accelerated physical phenomena of city and settlement expansion (Seto et al., 2014) is in fact a major risk factor. Third, the two variables can also be used as digital data infrastructure that uses the geographical location of the built-up area or of the population as spatial reference to add additional information. For example, when age structures, human development, poverty or income are combined with population density they can be used to characterize people's vulnerability to a given hazard. Similarly, when the structural characteristics of the building stock are combined with location and size of built-up areas they can be used to define physical vulnerability to a given hazard. The built-up area and population with augmented information can thus be used to better model human societal activities that may include energy use and emissions. In this paper we refer to Essential Societal Variables to global built-up area and population density, unless otherwise specified.

This work focuses on ESV used as exposure to fast-onset climate related hazard – including cyclones, winds, floods, sea level surge. We address these selected hazards also because corresponding global hazard datasets were made available through the Global Assessment Report (UNISDR, 2015a) and could be used to quantify globally the exposure of built-up area and population. Climate hazard also includes heat waves, cold spells and droughts that may impact on people's health or the food base that can be analyzed with datasets not available within this research and thus outside of the scope of this paper. The aim is not to be exhaustive in listing all climatological related hazards and their interaction as analyzed in (Revi et al., 2014) but rather to describe global built-up area and global population density that can be impacted by those hazards. Their vulnerability – the degree to which they will experience harm as a result of the impact of the hazards (Cardona et al., 2012; Turner et al., 2003), which is related to the characteristics of the built-up area or of population – is not addressed in this paper for the following reasons. Vulnerability of built-up area and population is always hazard specific (Schneiderbauer and Ehrlich, 2006) and location specific, and for which it is difficult to get data globally. It is generally assessed locally or at national level, and requires a range of input data that are outside of the scope of this paper. For example, physical vulnerability requires information on the structural characteristics of the building stock, which is derived from national databases (Dell'Acqua et al., 2013). Population characteristics that in large part define vulnerability are derived from national censuses that are not always available or from expensive field surveys covering only selected regions of the world (Tatem, 2015).

This paper succinctly describes the production of the two global variables and their use. The paper first summarizes the production of the built-up area and population density and their characteristics. It then summarizes their use in modeling hazard impact and in systems of indicators for assessing humanitarian or disaster response needs. Fig. 1 illustrates the layout of the paper starting from the input data, the generation of built-up areas and population, their use in impact assessments and disaster risk models and finally their role in the production of indicators for monitoring the progress towards international frameworks such as the Paris Climate Agreements (United Nations Framework Convention on Climate Change, 2015), Sendai Framework for Disaster Risk Reduction (Sendai FDRR, UNISDR, 2015b); Sustainable Development Goals (UN General Assembly, 2015), and the New Urban Agenda (United Nations, 2016). This sequence highlights the generation of information products that can be directly used by scientists as well as policy makers at different stages; in models, indicators or system of indicators.

2. Essential variables and climate impact

Essential Climate Variables have been extensively reviewed and described (WMO, 2016). Fig. 2 schematically describes the Atmospheric, Oceanographic and Terrestrial climate subsystems (GCOS, 2016) and the interaction with the human system through the societal-environment interaction processes. Human activity affects the biosphere of terrestrial landmasses and oceans from which it derives most of the energy, fibre, water and ecosystem services (Fig. 2, grey arrows). Societal demand for energy and materials is driven in large part by population expansion and the metabolism of society modulated by the economic system (Haberl et al., 2011). The demand for resources can be inferred in part by measuring the spatial extent of settlements, settlement metabolism as well as in land use changes (GCOS, 2015). Emissions, which are part of the undesired outcome of the use of resources, affect the climate variables (grey arrows 2, 4, 6) and in turn, the climate induced hazards.

The climate related fast onset hazards impact societies and their life supporting systems (Fig. 2, black arrows). The largest impact typically occurs within settlements as the destructive energy impacts the physical infrastructure and its resident population. Climate induced hazards include strong winds associated with tropical cyclones or tornados originated from atmospheric processes (arrows 1), storm surge from the oceans generating coastal floods that may be aggravated by climate induced sea level rise (arrow 3) and inundations and flash floods from terrestrial processes (arrow 5). Human activities can also generate man-made hazards that impact society (i.e. technological hazards; arrows 7 and 8) or amplify the outcome of disasters caused by natural technological hazards (Krausmann and Mushtaq, 2008). Slow onset hazards, including droughts, affect water supplies and other natural services, and impact population in the affected areas. This paper aims to quantify global built-up areas and population in human settlements that are exposed to fast-onset climate induced natural hazards.

The climate variables (describing climate processes) and societal variables (describing human activities) must be collected globally at fine geographical scale. In fact, "The climate system may be global in extent, but its manifestations – through atmospheric processes, ocean circulation, bioclimatic zones, daily weather, and longer-term climate trends – are regional or local in their occurrence, character and implications. Moreover the decisions that are or could be taken on the basis of climate change science play out at a range of scales, and the relevance and limitations of information on both biophysical impacts and social vulnerability differ strongly from global to local scale, and from one region to another. Explicit recognition of geographical diversity is therefore important for any scientific assessment of anthropogenic climate change" (Hewitson et al., 2014). That fine granularity is even more important in the measurement of the human dimension of climate change as settlements are covering only a small fraction of the surface of the Earth and hazard impact is always local.

Human settlements are the outcome and centre of activity of the human system, and host what is most valuable to societies (Fig. 2). Natural hazards impact is best understood by crossing hazard with settlement information (Pesaresi et al., 2017), for a number of reasons. First, the physical infrastructure of the settlement (the built-up area) and its population is what we are trying to protect. Second, both variables contribute to define exposure to hazards that in crisis management is used to quantify and model disaster risk and hazard impact. Third, the spatial detail of the built-up area "anchors human activity to the land" and provides the spatial reference that can be used to standardize in space and time other variables including carbon or energy emissions. Fourth, built-up area and population density can be used to partition the built-up space in settlement types such as towns, cities, megacities. The spatial extent of settlements can be used as geographical reporting units for generating settlement statistics as required in SDG reporting.

3. Human settlements and essential societal variables

The built-up area and population density layers are derived from

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