Noname manuscript No.
(will be inserted by the editor)

A hierarchical collection of political/economic regions for analysis of climate extremes

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Received: date / Accepted: date

Abstract This paper describes five sets of regions intended for use in summarising extreme weather over Earth's land areas from a climate perspective. The sets differ in terms of their target size: ∼10 Mm^2, ∼5 Mm^2, ∼2 Mm^2, ∼0.5 Mm^2, and ∼0.1 Mm^2 (where 1 Mm^2=1 million km^2). The regions are based on political/economic divisions, and hence are intended to be primarily aligned with geographical domains of decision-making and disaster response rather than other factors such as climatological homogeneity. This paper: de-

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, under contract number DE-AC02-05CH11231. This work was partially funded using Strategic Science Investment Funding from the New Zealand Ministry of Business, Innovation and Employment.

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scribes the method for defining these sets of regions; provides the final definitions of the regions; and performs some comparisons across the five sets and other available regional definitions with global land coverage, according to climatological and non-climatological properties.

1 Motivation

Identification and experience of extreme weather is almost always within a local or regional setting, rather than at the global scale. This means that some events that may be labeled as extreme in one location may not be considered such at another location. In that sense, developing a thorough understanding of any extreme event requires bespoke analyses that examine particular processes and mechanisms relevant for that particular event or class of events, and each of those processes and mechanisms may be local, more broadly regional, or geographically distant. Hence, for instance, a detailed study of drought over the U.S. state of Texas can involve analyses of the precipitation total within Texas' borders, of the atmospheric circulation over a vaguely defined area including and surrounding the southern U.S., and of oceanic conditions in the tropical Pacific Ocean thousands of kilometres away (Hoerling et al 2013). But this specificity also means that there is little economy of scale, neither in application of the same set of analyses nor in translating the conclusions across to another extreme event elsewhere.

An alternative is to use some event classification approach, implemented in a way that it can be deployed over a broad, perhaps global, area. The simplest such approach is to define a set of spatial regions and a fixed event duration. If an "extreme" is defined as the exceedance of a percentile estimated for a reference period for each region, then this type of analysis can be deployed at scale (e.g. Jones et al 2008; Christidis et al 2013; Angélil et al 2014b, 2016; Risser et al 2017b). Perhaps the most verbose example of this is the Weather Risk Attribution Forecast version 3 (http://climate.web.runbox.net/wraf, Lawal et al 2015), which produced estimates of the degree to which anthropogenic greenhouse gas emissions have affected month-long hot, cold, wet, and dry events for 58 land regions for each month during the January 2009 through March 2017 period, a total of 22 968 events (most of which never occurred).

For the systematic, regional-based approach, the central distinguishing feature of each calculation is the specification of the region. We argue that a suitable set of regions for systematic analysis of extreme weather/climate events should satisfy several criteria.

Shape: The regions should have borders that align with the boundaries of interest for a selection of potential users, preferably as many potential users as possible.

Spatial scale: The regions should cover a scale that is representative of extreme weather. Representativeness depends on the context of what is colloquially considered "extreme weather", which rarely exceeds more than a few Mm^2. It also depends on what available climate model products can represent, as well as what available observationally-based products can represent, if the latter are used for defining the extremes or for evaluation of a dynamical climate model.

Comprehensive: Collectively, the regions should comprehensively cover the domain of interest, whether that is on a global or smaller scale. In this paper we are only considering extreme events within the atmospheric system over land areas, on the grounds that essentially all human population and capital are based on land. Nevertheless, ignoring the ocean should be considered a limitation, especially, for instance, when considering impacts on ecological systems.

Bias: The regions should not be biased in terms of overly focusing on any particular parts of the full domain, according to measures unrelated to the purpose of the set of regions. In this paper, we use wealth, as measured by per capita annual gross domestic product (pcGDP, Murakami and Yamagata 2016), as sample metric to ascertain whether there might be a consequential systematic bias in region definitions. Wealth is selected because public disaster response is based on the "ability to pay principle", and global negotiations on funding to adapt and cope with the impacts of anthropogenic climate change are at least partly based on it too.

In this paper, it is argued that the climate research community currently lacks a standard global set of regions that are useful for the study of extreme weather, as specified by the above four criteria. Consequently, we propose a framework for developing sets of regions applicable to analysis of extreme weather, and apply this framework to develop a hierarchy of five global-land sets of regions, varying according to size. Advantages and shortcomings of this hierarchy, and each of the five individual sets, are then explored and discussed.

2 Limits of current regional definitions

A very simple regional definition is to use the boxes from the native grid (if it is gridded) of the data product being examined. This can be problematic for analysis of variability in climate model output, however, because the effective dynamical resolution of a model (at which it can resolve a full wavelength) is at least 4× the grid spacing. Hence, the dynamical processes involved in producing extreme variations at an individual grid box are not specifically represented in a climate model. In theory, parameterisation schemes representing sub-grid scale processes should produce that variability; however, in practice these schemes are not designed or tuned to emulate the most extreme weather, but rather to emulate more mundane weather situations. Dispersiveness in the dynamical core and parameterisation schemes also helps to ensure numerical stability of the climate model. Hence, climate models are not designed to generate an accurate representation of extreme weather at or near the grid scale (von Storch 2004).

Regional definitions thus need to be at a larger spatial scale. The first commonly-used set of such regions covering most of the global land area was developed by Giorgi and Francisco (2000) and Giorgi (2002) (commonly termed “Giorgi regions”). This divided the world into 22 regions that are rectangular when viewed with a cylindrical projection with the axis coincident with

Earth's rotation axis. These regions were designed for diagnosis of mean long-term climate changes. They have been used frequently during recent years, as have the non-rectangular modifications developed by Seneviratne et al (2012) (commonly called "SREX regions") and variations involving partial merging of these regions (Flato et al 2013; Bindoff et al 2013; Christensen et al 2013; van Oldenborgh et al 2013; Hewitson et al 2014; Magrin et al 2014; Nurse et al 2014).

How do the Giorgi and SREX regions fare according to the four criteria listed above? The regions are comprehensive, in the sense that they almost fully cover the global land area, with the exception of Antarctica and small islands. In terms of the shape criterion, though, we are not aware of any potential users whose interests coincide with the rectangular or simple-polygonal shapes of the Giorgi and SREX regions. Those regions also tend to be large in comparison with the types of events most frequently referred to as "extreme weather". Figure 1 provides an illustration of this for the unprecedentely intense and expansive heatwave that struck Eastern Europe in July-August 2010 (Barriopedro et al 2011; Dole et al 2011; Rahmstorf and Coumou 2011). The spatial extent of the event straddled the border of two SREX regions (the corresponding Giorgi regions are almost identical). This unprecedented event is not obvious in either region though. Despite being colloquially termed "the 2010 Russian heatwave", the SREX "NAS" region, representing the bulk of Russia, experienced only mildly (2.6°C) warmer-than-normal temperatures in mid-July, and rather average temperatures during early August. In compari-

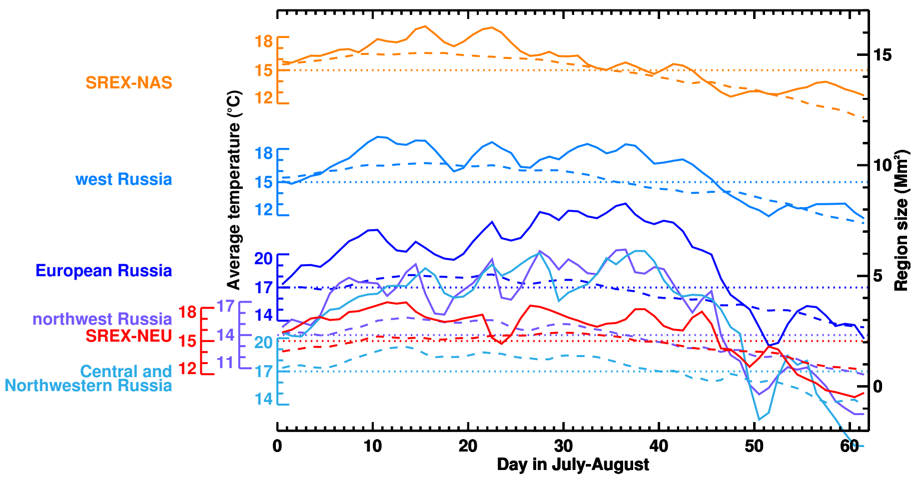

Fig. 1 Daily mean 2-m temperature during July-August 2010 over various regions which include areas hit by the major heatwave that occurred in Eastern Europe. The time series for each region are placed vertically along the right-hand axis according to their size. Dashed lines denote the respective 1979-2009 climatological mean for each day of the year. Temperature data are from the ERA-INTERIM reanalysis (Dee et al 2011). In order to avoid clutter, no 0.1 Mm^2-scale region has been included.

son, local anomalies exceeded 10°C (Barriopedro et al 2011). The "NEU" region covers a much smaller area (about 2 Mm^2 rather than 14 Mm^2), but with the heatwave area on its eastern edge it still only registers a maximum daily anomaly of 3.4°C. The SREX (and Giorgi) regions were therefore unhelpful for detecting one of the largest heatwave events of recent memory (Barriopedro et al 2011). The SREX regions also have a substantial bias toward wealthy areas, with the wealthiest quartile of regions covering only 59% of the area of the poorest quartile of regions (Table 1).

Other sets of regions have been developed specifically along borders defined by interests of potential users of climate information in various scientific research disciplines. However, many of these are not generally transferrable to other disciplines. So for instance regions defined along ecological properties (Kovats et al 2014; Hoegh-Guldberg et al 2014) will generally not make sense for hydrological systems.

One method of defining regions is transferrable, however: along political/economic boundaries. While the spatial extremes of events as well as their impacts may not always closely follow national borders, the decision-making processes and actions involved in emergency response, as well as in the development of adaptative and coping measures, do take place within national (or provincial) settings. Thus a number of recent international climate change assessments have used regions based on borders defined by nations and/or economic associations (Niang et al 2014; Hijioka et al 2014; Reisinger et al 2014; Angélil et al 2016; Risser et al 2017b). National climate monitoring services are increasingly using provincial-level regions. For instance, the 2017 version of the U.S. NOAA National Centers for Environmental Information includes "State Climate Summaries" (https://statesummaries.ncics.org), noting "These NOAA State Summaries were produced in response to a growing demand for state-level information in the context of the Third National Climate Assessment (NCA) and subsequent sustained activities.".

3 Defining the regions

The regional definitions developed for this paper are designed for use in version 4 of the Weather Risk Attribution Forecast (WRAF), a climate-model based activity providing assessments of the role of anthropogenic emissions in specific extreme weather events in advance of the (possible) occurrence of those events (http://climate.web.runbox.net/wraf, Lawal et al 2015; Wolski et al 2014; Angélil et al 2016; Risser et al 2017a).

Because events have not yet occurred at the time of the assessments, the assessments have to be performed systematically for a defined set of regions. Out of convenience, version 1 (an internal version) used boxes from the native grid of the climate models. Version 2 (the first public version) used political/economic regions of about 10 Mm^2 size ("WRAF10-v2.0"). The experience of the "2010 Russian heatwave" (in which the region of "Russia" registered no noticeable temperature event) indicated that smaller regions were required for version 3, which adopted regions of approximately 2 Mm^2 ("WRAF2-v3.0" Angélil et al 2016).

The version 4 regions developed in this paper follow the practice from the two previous versions in terms of being based on political/economic regions, on the basis that disaster response and climate change policy are based broadly along such boundaries. The extent to which that rationale is justified varies from place to place. In this new version, the regions are split into a hierarchy of five sets, each targeting a different size range. "WRAF10-v4.1" aims for regions 10 Mm^2 in size, "WRAF5-v4.1" for 5 Mm^2, "WRAF2-v4.1" for 2 Mm^2, "WRAF0.5-v4.1" for 0.5 Mm^2, and "WRAF0.1-v4.1" for 0.1 Mm^2, with some allowable variation from the target size as indicated in Table 1. Some of the regions in the WRAF10-v4.1 and WRAF5-v4.1 regions were in the earlier

WRAF10-v2.1 set, while the WRAF2-v4.1 set is essentially an upgrade on the WRAF2-v3.0 set. The 0.5 Mm^2 and 0.1 Mm^2 are new.

Several rules are used in defining the new regions for each size range:

Borders: Regional boundaries should match current (ca. 2015) political boundaries, whether defined by a multi-national association, countries, provincial-level (one level down from national) adminitrative divisions, county-level (two levels down from national) administrative divisions, or subcounty-level (three levels down from national) administrative divisions. This rule does not apply for Antarctic regions. For the WRAF0.5-v4.1 set of regions it is also relaxed when splitting the Qikiqtaaluk Region in the Canadian territory of Nunavut, in which case the natural division of Lancaster Sound and Prince Regent Inlet is used. It is relaxed more often in the WRAF0.1-v4.1 set of regions, because a number of lowest-level administrative divisions are considerably larger than the 0.1 Mm^2 scale.

Merging: Regions can be formed by the merging of national, provincial, county, or subcounty administrative divisions, but merging may only be performed at one administrative level. For instance, a province may not be joined with a country.

Association: Administrative divisions joined in a region must share some substantial political and/or economic links. At the international level, this could involve a trade agreement. The "merging" rule guarantees the "association" rule for sub-national regions.

Contiguity: Administrative divisions joined in a region must be neighbours. For this purpose, the existence of intervening small bodies of water, for instance in archipelagoes, is ignored. This rule is relaxed in the single case of splitting South Australia into two 0.5 Mm^2 regions: the Unicorporated Far North, and remaining areas. This rule does not apply within existing administrative divisions; so, for instance, the states of Alaska and Hawai'i are included within the WRAF10-v4.1 region of the United States of America.

Size: Regions must be within the size range stipulated in Table 1.

Hierarchy: A region of one size range must fit entirely within a single region in the next-largest set of regions, or fit entirely outside of any regions in the larger set.

Some effort has also been made to have both cultural and climatic homogeneity across each region, but this is not a strict rule. In order to arrive at reasonably comprehensive sets of regions, some generous interpretation of the rules is occasionally required beyond those listed above; these situations will be highlighted in the discussions below.

Antarctica lacks any form of formal administrative domains, so if we are to include regions for Antarctica then some of the rules above will have to be ignored or interpreted loosely. In an attempt to be as comprehensive as possible, we also define sets of regions for Antarctica at the four larger spatial scales (the WRAF0.1-v4.1 scale is left out on the grounds that current observational products are unable to monitor or provide evaluation of dynamical climate models at such small scales). Ironically, the loosening of rules means that Antarctica ends up being the most comprehensively covered continent at those four spatial scales.

4 Geographic data

The definition of administrative divsions are obtained from two data sources. National and provincial-level (i.e. one level down from national) borders are obtained from Natural Earth (http://www.naturalearthdata.com, v3.1.0 at 10 km for national borders and v3.0.0 at 10 km for provincial borders). County-level and subcounty-level (i.e. two and three levels down from national) borders within a number of countries are obtained from GADM (http://gadm.org, 3 November 2015 issue). Administrative divisions are taken explicitly from these data, and thus inherit the intention to represent de facto borders without intending any commentary on sovereignty. While borders should be representative of the situation during the year 2015, there may be discrepancies due to the ambiguity of county-level status in some countries and due to developments that had not yet been implemented in the Natural Earth and GADM data.

5 10 Mm^2 and 5 Mm^2 regions

The twelve WRAF10-v4.1 and thirty WRAF5-v4.1 regions, covering approximately 10 Mm^2 and 5 Mm^2 respectively, are listed in Supplementary Table A1, detailed in Supplementary Tables B1 through B16, and plotted in Figures 2 and 2. For the 10 Mm^2 regions, no nations have been split in order to form a region except for Russia, which has been divided into an eastern domain consisting of the Far East and East Siberian Economic Regions except for Krasnoyarsk Krai, and a western region containing the remainder of the country. This emphasis on completeness leads to a lack of continuity in some cases, with for instance Alaska and Hawai'i being included in region 2 (United States of America), Kaliningrad being included in region "7 west Russia", Somalia being included in region "4 Arab League", and Mauritius being included in region "6 Southern African Development Community". The emphasis on completeness is maintained for the 5 Mm^2 regions, with the more dramatic situation of region "X.2 European Economic Area" including Réunion in the Indian Ocean, Bouvet Island in the South Atlantic Ocean, and French Guiana in South America, amongst other cases. At 5 Mm^2 Canada, the USA, China, Australia, and Antarctica are all divided in two, while Russia is divided in four.

Because of restrictions on minimum region size, the WRAF10-v4.1 regions are far from comprehensive in the sense of mutually covering the entire global land area. The WRAF5-v4.1 regions improve on this by adding much of northwestern South America, Europe, India, and Southeast Asia. However, sizeable areas including Mexico, Greenland, much of East Africa, and Mongolia remain unrepresented. According to the rules used here, smaller regions are necessary if comprehensiveness is a priority.

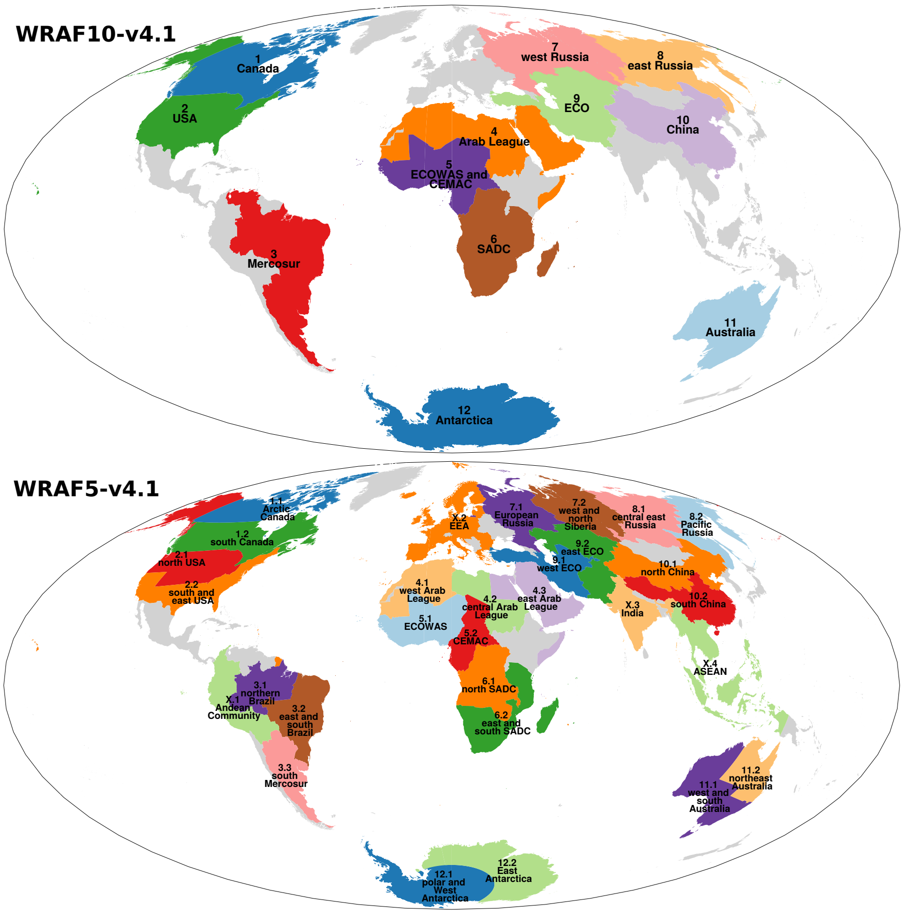

Fig. 2 Map of all of the ∼10 Mm^2 regions ("WRAF10-v4.1", top) and of all of the the ∼5 Mm^2 regions ("WRAF5-v4.1", bottom). Further details are listed in Supplementary Table A1, and in Supplementary Tables B1 through B16. Land areas not covered by these regions are shown in light grey, while ocean/sea is shown in white.

6 2 Mm^2 regions

The 68 WRAF2-v4.1 regions, targeting 2 Mm^2 in size, are listed in Supplementary Table A1, detailed in Supplementary Tables B1 through B17, and plotted in Figure 3. There are 58 regions in the WRAF2-v3.0 set of regions

(Angélil et al 2016), with half of the additional members coming from the inclusion of Antarctica. Notable rearrangements and additions have occurred in West Africa, East Africa, the Economic Cooperation Organization, India, the Pacific coast of Russia, the Association of Southeast Asian Nations, and Australia. The 2 Mm^2 size corresponds to an area about 1600 km in diameter, thus being the largest size considered here that can document mid-latitude synoptic scale weather systems. For instance, the maximum extents of European areas experiencing record-breaking temperatures during the summers of 2010 and 2003 were $\sim$2 Mm^2 and $\sim$1 Mm^2 respectively (Barriopedro et al 2011).

7 0.5 Mm^2 regions

The 237 WRAF0.5-v4.1 regions, targeting 0.5 Mm^2 in size, are listed and detailed in Supplementary Tables B1 through B18, and plotted in Figure 3. This scale corresponds to a diameter of about 800 km, hence about eight times the grid resolution of a current-generation model resolution climate model, and about twice the effective dynamical resolution of such a model if it uses a non-diffusive numerical scheme. These 237 regions present a novel division of the world's land surface, in comparison for instance to the 26 SREX regions or the 58 WRAF2-v3.0 regions.

In contrast to the larger regions, the emphasis for these regions has been more toward contiguousness over completeness. Thus for instance neither Hawai'i, nor Kaliningrad, nor the Andaman and Nicobar Islands are included in any

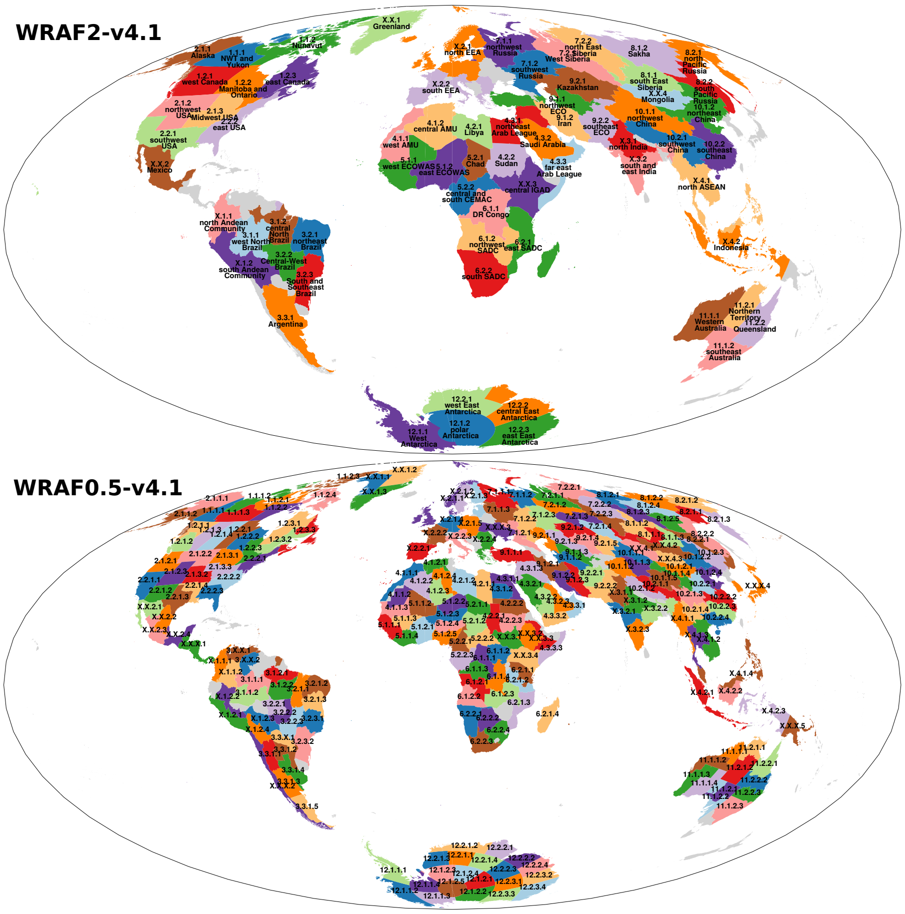

Fig. 3 Map of all of the ~2 Mm^2 regions ("WRAF2-v4.1", top) and of all of the 0.5 Mm^2 regions ("WRAF0.5-v4.1", bottom). Further details are listed in Supplementary Table A1, and in Supplementary Tables B1 through B18. Land areas not covered by these regions are shown in light grey, while ocean/sea is shown in white.

regions (of the United States of America, Russia, or India, respectively). However, the shift of emphasis does not involve slicing up an administrative division that is of the appropriate size, so for instance region "X.2.2.2 France" retains Réunion, French Guiana, Guadaloupe, and Martinique.

It is easier to cover most land areas with the smaller region size. However, there are a few areas that remain unclaimed by a region, such as Armenia, much of the Balkans, Bangladesh, Cuba and most of the Caribbean islands, Belarus, Georgia, Guyana, Nepal, New Zealand, North Korea, Somaliland, Sri Lanka, Suriname, Taiwan, and most of the Pacific island nations. In some cases the restriction of the smaller spatial scale and the need to satisfy the various rules have resulted in the omission of some further areas that had been included in larger regions. The largest of these include Azerbaijan, Ecuador, Iceland, Kyrgyzstan, Tajikistan, Tunisia, Uruguay, Zimbabwe, the Brazilian states of Acre, Amapá, Rondônia, and Roraima, and the Australian states of Tasmania and Victoria. These places represent an unfortunate consequence of the rules used in formulating these regions.

Whereas all the WRAF2-v4.1 regions within Canada, the United States of America, Brazil, Russia, China, and Australia consist entirely of provincial-level divisions or combinations thereof, the WRAF0.5-v4.1 size restriction requires the largest provinces to be split. The smallest county-level division of the northern and eastern area of Canada's Nunavut, Qikiqtaaluk, is split in two along the natural division of Lancaster Sound and Prince Regent Inlet, in order to produce regions within the WRAF0.5-v4.1 size range.

The definitions of some regions are based on robust administrative borders. This is particularly the case for regions based on a single country, because national borders tend to be relatively stable, as well as for some provincial-level regions which have historically stable boundaries, such as within the United

States of America (Supplementary Table B2). However, in other cases the administrative borders may be more tenuous. International groups are not always highly stable, gradually incorporating new members and occasionally losing existing members. At the provincial level, Russia is currently undergoing a reorganisation of its regional structure, which may mean an updated version will be required in a few years time (Supplementary Tables B7 and B8). And boundaries at the county level can be in a state of flux, or at least poorly defined. For instance, some Australian states do not have official comprehensive spatially-based county-level divisions, instead having a variety of definitions for various purposes (e.g. agriculture, development, water management) and/or numerous small municipal entities surrounded by an unincorporated remainder. In the case of South Australia, the Unincorporated Far North, comprising almost half the area of the state, divides incorporated and other unincorporated areas in the northwest from other areas in the south; the WRAF0.5-v4.1 region of "11.1.2.2 south South Australia" thus includes an area in the northwest of the state that is not continguous with the bulk of the region in the south of the state (Supplementary Table B11).

Some multinational regions consist of reasonably tightly integrated nations. The 5 Mm^2 region of the European Economic Area (EEA) is a particular example (Supplementary Table B14): the European Union, which forms the bulk of the EEA, participates as the equivalent of a single nation in international fora, such as within negotiations under the United Nations Framework Convention on Climate Change. Members of the Visegrád Group ("X.2.1.5

Visegrád EEA") have had formal associations as far back as 1335 (SupplementaryTable B14). However, some other multinational regions are less established. The WRAF0.5-v4.1 region of "X.X.X.4 far east ACD", comprising 0.478 Mm^2, is the only region here identified as part of the 47 Mm^2 Asia Cooperation Dialogue: it is essentially a loophole to include Japan and South Korea (Supplementary Table B18).

8 0.1 Mm^2 regions

The 1231 WRAF0.1-v4.1 regions are plotted in Figure 4 and detailed in Supplementary Tables C1 through C67. These regions target 0.1 Mm^2 in size, corresponding to a diameter of about 350 km. This scale is slightly smaller than the effective dynamical resolution of a current 1×1 degree longitude-latitude numerical grid, i.e. of the current generation of climate models. However, the upcoming High Resolution Model Intercomparison Project (HighResMIP, Haarsma et al 2016) will use atmospheric models with a numerical grid of approximately 0.25×0.25 degrees in longitude and latitude, making the 350 km scale approximately 14 times the grid resolution. Hence, from a dynamical perspective, one might expect the HighResMIP models to be able to simulate extreme weather at the scale of these regions.

Antarctica has been excluded from the WRAF0.1-v4.1 region list, on the grounds that observational datasets are not capable of supporting analysis at that fine a resolution over Antarctica. Nevertheless, adding Antarctic regions would be a fairly straightforward job of dividing the WRAF0.5-v4.1 boxes into

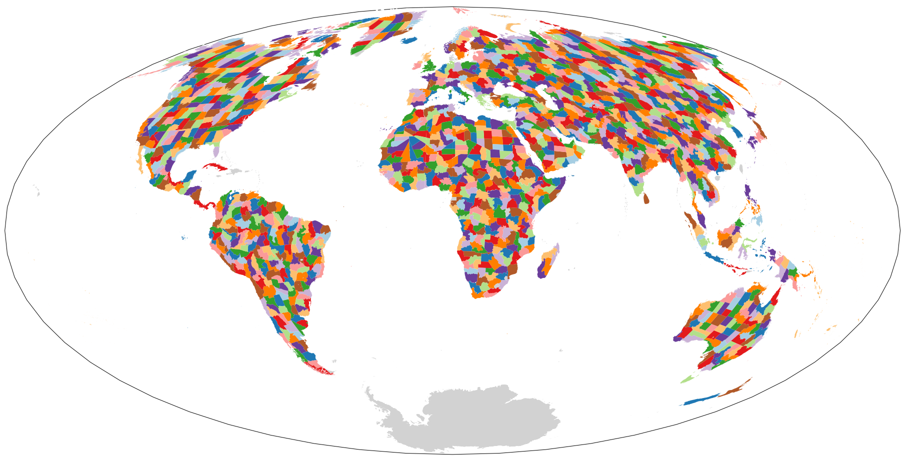

Fig. 4 Map of all of the 0.1 Mm^2 regions ("WRAF0.1"). Further details are listed in Supplementary Tables C1 through C67. Land areas not covered by these regions are shown in light grey, while ocean/sea is shown in white. Labels have not been included because of insufficient space.

five or six arbitrary boxes. Outside of Antarctica, most of the remaining gaps in coverage in the WRAF0.5-v4.1 regions are filled with the WRAF0.1-v4.1 regions. However, a few new gaps emerge: Brazil's Distrito Federal; Argentina's Tierra del Fuego; Saudi Arabia's Qassim; Equatorial Guinea; Russia's Anabarksky (in Sakha), Khakassia, and Yevrey; China's Beijing, Hainan, Hong Kong, Macau, Ningxia, and Tianjin; Denmark; India's Uttarakhand; Brunei; and Greenland's Kujalleq. In contrast to the larger scales, the "borders" rule has had to be broken in the definition of many of these regions. This scale is frequently smaller than the size of provincial-level divisions, and many of these provinces lack a county-level system of divisions. Furthermore, some county-level divisions are much larger than the 0.1 Mm^2 target size. In these cases regions have been formed either by sensibly grouping islands in archipelagoes (e.g. in some of Canada's Nunavut territory), by somewhat sensibly at narrow mid-points in WRAF0.5-v4.1 regions (e.g. where fjords almost divide Baffin Island), or by arbitrarily splitting into shapes that are as close to squares as feasible.

9 Discussion

At the beginning of this paper, we suggested four criteria by which a set of regional definitions should be evaluated: usefulness of the shapes; appropriateness of the spatial scale; spatial comprehensiveness; and spatial bias (here tested by wealth). How do the proposed five sets of regions fare?

In terms of usefulness of the shapes, it was argued above that emergency response, decisions on adaption actions, and decisions on loss and damage mechanisms tend to be taken along the lines of standard administrative institutions, whether they be multilateral international (e.g. the European Union), national, provincial-level, or county-level. The degree to which these responsibilities fall across the different administrative levels varies from place to place, so for instance the boundaries used in the WRAF0.5-v4.1 set of regions may be more closely aligned with decisions and actions in some places than in others. Conservation efforts sometimes cross standard administrative boundaries, in which case the regional definitions developed here may be less useful. Comparison the WRAF v4.1 regions against geographically shifted versions of these regions indicate that correspondence between the WRAF v4.1 regions and boundaries of Köppen climate classes, population clustering, and per capita gross domestic product clustering is no better than random (not shown). However, any method that is inspired by use based on, for example, climatological, ecological, physical geographical, or industrial characteristics will not be easily transferrable to other uses.

There are two aspects of the spatial scale to consider: ability of available climate data to adequately describe extreme weather, and relevance to users. In terms of climate model data, the models in the international Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al 2012), C20C+ D&A (Stone et al 2019), and HAPPI (Mitchell et al 2017) project archives have grid resolutions of about 9000 km^2 to 60 000 km^2 and about 600 km^2 to 18 000 km^2, respectively. This places the effective dynamical resolution (taken as 4 times the grid resolution) somewhere above 0.15 Mm^2 to 1.0 Mm^2 and 0.1 Mm^2 to 0.3 Mm^2, respectively. The approximate 0.5 Mm^2 scale of the WRAF0.5 regions is thus comfortably resolved for the higher resolution models in C20C+ D&A and HAPPI, and probably adequately resolved for the higher resolution models in CMIP5 and lower resolution models in C20C+ D&A and HAPPI, but more questionable for lower resolution models in CMIP5. The 0.5 Mm^2 scale is thus generally about the smallest possible with the current collection of climate models, and likely as well with most of the next generation of climate models anticipated in the upcoming international Coupled Model Intercomparison Project Phase 6 (CMIP6, Eyring et al 2016). Most CMIP6 models will likely be run at a resolution comparable to those under C20C+D&A, with the exception of the $\sim$500 km^2 models expected for the

HighResMIP component of CMIP6 (Haarsma et al 2016); the 0.1 Mm^2 scale is intended for use in HighResMIP analyses. Table 1 indicates the appropriate region sizes for some past and imminent multi-model climate products.

As to the relevance to users, this depends strongly on the event(s) and the circumstances of the user(s) and their interests. The hierarchy of five scales developed here is intended specifically to allow some degree of flexibility, whilst still maintaining a manageably small number of regions in total. The usefulness of this property is visible in Figure 1. While the SREX "NAS" and overlapping WRAF10-v4.1 regions are too large to have captured the July-August 2010 heatwave in Eastern Europe, the event was not focused within the confines of the smaller SREX "NEU" region. In contrast, the WRAF0.5-v4.1 and WRAF2-v4.1 regions closest to the event registered daily region-averaged temperature anomalies of up to 10.7°C and 7.7°C respectively. By chance optimal alignment, the corresponding WRAF5-v4.1 region registered 7.8°C.

More generally, Figure 5 shows the correlation between the 1961-2005 annual mean exceedance rates in neighbouring regions in large initial condition ensembles of historical simulations with two climate models. The measures are the annual rates of exceedance of the $\frac{360}{365}$ quantile of regional-average daily precipitation total and daily maximum near-surface air temperature (Tmax). Regions are considered neighbouring if they are of the same size (e.g. 2 Mm^2) and both within the same larger region in the next size. 10 Mm^2 regions are not included, not having a larger region within which to be nested, and 0.1 Mm^2 regions are deemed too small for accurate simulation by these climate models.

The first model is CESM1-LE, a fully coupled model of the atmosphere, land, ocean, and sea-ice, with 42 simulations (Kay et al 2015). The second model is CAM5.1-1degree, a model of the atmosphere and land only, with 50 simulations driven with observed sea surface temperatures and sea ice concentrations (Stone et al 2018). The CAM5.1-1degree model is the same version (albeit a different subversion) of the atmosphere-land component of CESM1-LE, so the comparison approximately diagnoses the difference between imposing observed sea surface temperatures (and sea ice conditions) and allowing them to evolve consistently with the atmosphere. For this quantile and these numbers of simulations, we expect a decent sampling of 200–250 exceedances per year on average. The inter-region correlations are usually greater than 0.7 for Tmax, but only usually larger than zero, and smaller than 0.8, for precipitation. The degree of correlation is not visibly related to region size, and the only difference between models is for CAM5.1-1degree to have some very large correlations for precipitation in the tropics. At all sizes, the regional specificity of extremes is clear for daily precipitation, and cannot be dismissed casually for Tmax.

As for the climate change signal, Figure 6 shows the signal-to-noise ratio of the 1961-2005 climate trend versus the interannual variability in the same set of simulations of both climate models. While the general rule-of-thumb of increasing signal-to-noise ratio with increasing region size holds, there are plenty of individual cases where that rule breaks down. For both variables the signal-to-noise ratio is lower for the atmosphere-land model driven with observed ocean conditions. At least in part this arises from CESM1-LE producing only

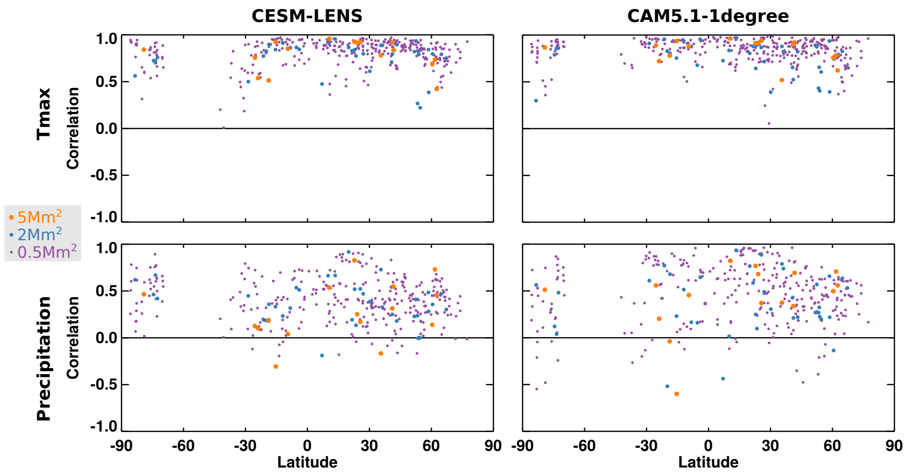

Fig. 5 Inter-region correlation of 1961-2005 annual extreme daily maximum near-surface temperature ("Tmax", top) and daily precipitation (bottom) frequency in simulations of the CESM1-LE coupled atmosphere-ocean model (left, Kay et al 2015) and of the related CAM5.1-1degree atmosphere-only model (right, Stone et al 2018). Extremes are defined as exceedance of the $\frac{360}{365}$ quantile, the correlation is between time series of the annual ensemble mean rates of exceedance. Exceedance rates are calculated from 42 CESM1-LE and 50 CAM5.1-1degree simulations. Values are marked at the mid-point between the median latitudes of each pair of regions. Correlations are only shown for pairs of regions of a given size that share membership within a region of the next size.

about half the interannual variability of CAM5.1-1degree. Additionally for precipitation, CAM5.1-1degree produces negligible trends in extreme precipitation (Antarctica excepted): the larger simulated ocean warming in CESM1-LE than observed (Kay et al 2015) appears to be supplying more moisture into the atmosphere for precipitation over land than is the observed ocean warming used in CAM5.1-1degree. Overall, the differences in the signal-to-noise ratios between region sizes and between different configurations of the same climate

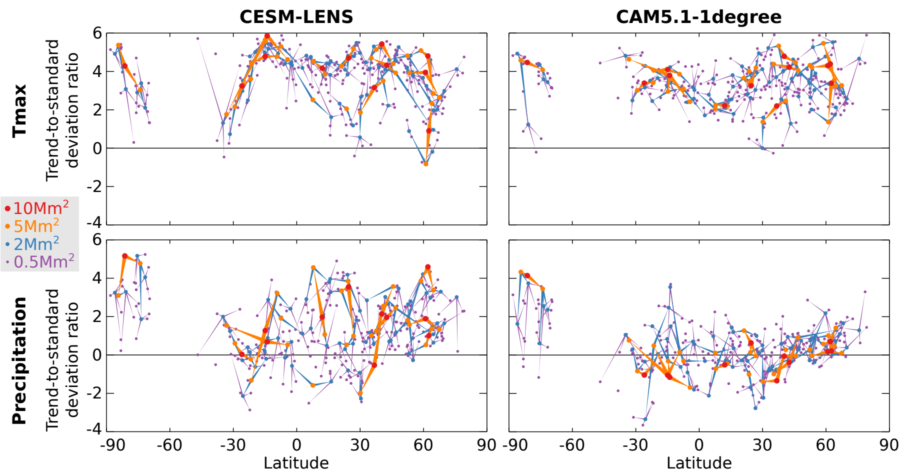

Fig. 6 Signal-to-noise ratio in 1961-2005 annual extreme daily maximum near-surface temperature ("Tmax", top) and daily precipitation (bottom) frequency in simulations of the CESM1-LE coupled atmosphere-ocean model (left, Kay et al 2015) and of the related CAM5.1-1degree atmosphere-only model (right, Stone et al 2018). Extremes are defined as exceedance of the $\frac{360}{365}$ quantile, the signal is defined as the 45-year linear trend in the exceedance rate, and the noise is defined as the standard deviation of the exceedance rate after removal of the trend. Exceedance rates are calculated from 42 CESM1-LE and 50 CAM5.1-1degree simulations. Values are marked at the median latitude of each region, and connecting lines point in the direction of decreasing size within a hierarchy of region sizes, using the colour of the smaller region.

model indicate potential value in the availability of different region sizes, both for diagnostic and application purposes.

The criterion on which these WRAF v4.1 regions are most questionable concern spatial comprehensiveness. The two larger sets are missing large chunks of the world's land mass. While the WRAF0.5-v4.1 set unsurprisingly misses fewer areas, there are still some appreciable gaps, such as Zimbabwe. The gaps are no larger than 0.05 Mm^2 for the WRAF0.1-v4.1 set of regions (notwithstanding Antarctica). For something like the WRAF, the absence of Zimbabwe may be disappointing, but for a global synthesis analysis its absence would be unlikely to affect conclusions. That sort of absence may be rather important though for an official international report, such as from the IPCC, because of an explicit remit to be spatially comprehensive. In that case a modified version of the regions could be used that merges some of the omitted areas with existing regions; violation of the rules used in generating these regions may in some cases be considered preferable if it produces a set of regions fully covering all the world's land area.

Spatial comprehensive has been assisted here by the practice of maintaining territorial integrity of administrative units, even if they are far from contiguous. For example French Guiana is included in WRAF5-v4.1, WRAF2-v4.1, and WRAF0.5-v4.1 as part of a region on another continent, because it is administratively part of that continent (the European Economic Area, the southern European Economic Area, and France, respectively). Will potential users be more interested in administrative completeness, aligning more closely with their interests, or in contiguity, aligning more closely with individual weather extremes? As with the question of comprehensiveness generally, this question will depend on the users and their interests. In generating the five sets of regions here, we have followed the principal of maintaining completeness of an administrative area if it does not need splitting for other reasons, but also not merging separate administrative areas if they are not contiguous (notwithstanding intervening small bodies of water).

The final criterion was to ensure that there is no inherent bias in the inevitable spread of sizes of regions within each set. We have used the metric of pcGDP because wealth is a central topic in international and domestic policy concerning mitigation of, adaptation to, and other assistance for climate change. The WRAF0.5-v4.1 regions perform very well according to the metric of the ratio of the area of the richest quartile of regions to the poorest quartile, with a discrepancy of less than 1% (Table 1). The three larger sets of regions have a non-negligable bias, but the fact that the bias switches from being toward poorer and toward richer regions between the larger scales suggests that it is simply representing a form of sampling error. Perhaps surprisingly, the WRAF0.1-v4.1 regions have a non-negligible bias of 6% toward richer regions. This may have arisen because richer and more heavily populated places may tend to have smaller administrative divisions, making it easier to hit the 0.1 Mm^2 target size, while poorer and sparsely places may tend to have larger divisions which are more difficult to fit to the 0.1 Mm^2 target within the 0.06–0.23 Mm^2 range. For instance, the largest region, Mauritania's Adrar, consists of only three departments which cannot be divided in a way that satisfies the rules that we have adopted. For comparison, the bias of the Giorgi regions is about the same as for the two larger sets of WRAF regions but instead toward richer areas, while the richer SREX regions are a substantial 40% smaller than the poorer regions.

10 Conclusions

Overall, the five sets of regions developed in this paper generally satisfy criteria needed to be useful for systematic analysis of extreme weather around the world's land areas. The 237 regions of about 0.5 Mm^2 size and 1231 regions of about 0.1 Mm^2 size in particular represent two novel sets which approach the limit of what current and imminent dynamical climate models, and in many cases observational products, are capable of describing. Confidence in analyses with these regions will depend on various tests that can be deployed on a large scale (Christidis et al 2013; Angélil et al 2016; Lott and Stott 2016; Angélil et al 2017). But confidence will also depend on the degree to which targeted analyses that examine the various mechanisms behind a specific event, such as for instance in Dole et al (2011) and Barriopedro et al (2011), can be connected to the description of the event provided by a member of a standard set of regions, for instance by the WRAF0.5-v4.1 "7.1.1.3 Central and Northewestern Russia" region (Figure 1). Climate change attribution conclusions concerning temperature extremes appear to be translatable across neighbouring areas, and thus establishing the connection between targeted, mechanistic-based studies and the regions here could be relatively straightforward; however, it is not clear that attribution conclusions for precipitation extremes are generally translatable (Angélil et al 2014a,b, 2017). This question of how much results for one particular event apply to neighbouring events lies at the heart of the field of event attribution, and will be particularly explicit when using the

WRAF v4.1 regions. Comparative analyses across neighbouring WRAF0.5-v4.1 regions may shed further light on this issue.

11 Data availability

All five sets of WRAF regions can be downloaded as NetCDF or GIS shapefiles at http://portal.nersc.gov/c20c/data/C20C/WRAF/All-Hist/est1/v4-1/fx/, subject to the terms of the Creative Commons License: http://creativecommons.org/licenses/by-nc-sa/2.0/.

Acknowledgements The author is grateful for the administrative shapefiles provided by Natural Earth (http://www.naturalearthdata.com) and GADM (http://gadm.org), which were used for forming the regions developed in this paper, and for the climate data from the European Centre for Medium-Range Weather Forecasts and from the National Center for Atmospheric Research. Mark Risser provided helpful comments that guided the development of the region definitions.

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Table 1 Comparison of various global sets of land regions. Only land areas are considered within the Giorgi and SREX regions. The mean ratio in region area is between the upper quartile and lower quartile regions in each global set as measured by per capita Gross Domestic Product (GDP) at purchasing power parity in 2010. Regions with no population or GDP (i.e. in Antarctica) have been removed from the calculations. GDP and population data are from Murakami and Yamagata (2016). Guidance is also given on the coarsest climate model grid resolution that might be considered to adequately resolve dynamics within each WRAF v4.1 region size, assuming dynamics are effectively resolved at 4× the numerical grid scale; resolution values are given for both the area and, in brackets, the diameter of an equivalent circular region. Some past and imminent multi-model climate data products that satisfy these resolution requirements are listed: C20C+ D&A (Stone et al 2019), HAPPI (Mitchell et al 2017), CMIP3 (Meehl et al 2007), CMIP5 (Taylor et al 2012), CMIP6 (Eyring et al 2016), CORDEX (Gutowski et al 2016), and HighResMIP (Haarsma et al 2016).

Region collection	**Area range (Mm^2)**	**GDP area ratio**	**Coarsest model resolution**	**Appropriate climate model products**
WRAF10-v4.1	7.0–13.0	1.24	0.6 Mm^2 (900 km)	All below
WRAF5-v4.1	3.0–7.0	1.18	0.3 Mm^2 (600 km)	All below
WRAF2-v4.1	1.2–3.1	0.89	0.1 Mm^2 (400 km)	CMIP3, CMIP5, all below
WRAF0.5-v4.1	0.4–0.9	0.99	0.03 Mm^2 (200 km)	C20C+ D&A, HAPPI, high-resolution models in CMIP5, standard models in CMIP6, all below
WRAF0.1-v4.1	0.06–0.23	0.94	0.006 Mm^2 (90 km)	CORDEX, HighResMIP, high-resolution models in C20C+ D&A and HAPPI
Giorgi (2002)	2.1–14.3	0.78	—	—
Seneviratne et al (2012)	1.9–14.3	0.59	—	—