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The benefits of global high-resolution for climate simulation: process-understanding and the enabling of stakeholder decisions at the regional scale.

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Capsule summary:

A perspective on current and future capabilities in global high-resolution climate simulation for assessing climate risks over next few decades, including advances in process representation and analysis, justifying the emergence of dedicated, coordinated experimental protocols.

Abstract

The timescales of the Paris Climate Agreement indicate urgent action is required on climate policies over the next few decades, in order to avoid the worst risks posed by climate change. On these relatively short timescales the combined effect of climate variability and change are both key drivers of extreme events, with decadal timescales also important for infrastructure planning. Hence, in order to assess climate risk on such timescales, we require climate models to be able to represent key aspects of both internally driven climate variability, as well as the response to changing forcings.

In this paper we argue that we now have the modelling capability to address these requirements - specifically with global models having horizontal resolutions considerably enhanced from those typically used in previous IPCC and CMIP exercises. The improved representation of weather and climate processes in such models underpins our enhanced confidence in predictions and projections, as well as providing improved forcing to regional models, which are better able to represent local-scale extremes (such as convective precipitation). We choose the global water cycle as an illustrative example, because it is governed by a chain of processes for which there is growing evidence of the benefits of higher resolution. At the same time it comprises key processes involved in many of the expected future climate extremes (e.g. flooding, drought, tropical and mid-latitude storms).

Introduction

Our capability to perform global climate model simulations suitable to inform societal action is constrained by both available computer resources and the efficiency of the algorithms used in our models. Multi-exaflop computer power would be needed for global climate models to produce multi-member ensemble, multi-century simulations at resolutions capable of resolving macroscopic cloud features and ocean mesoscale eddies. Estimates suggest that such computer power is at least a decade away. Yet, given the enormous scale of supercomputing about to be used for the next Coupled Model Intercomparison Project (CMIP6; Eyring et al. 2016), we feel that this is a particularly important time to review our current status in present-day high-resolution global climate modeling.

At one extreme, numerous climate model simulations are performed as part of each CMIP cycle (Meehl et al. 2000; Meehl et al. 2007; Taylor et al. 2012; Eyring et al. 2016), organized by the World Climate Research Programme (WCRP). Such models typically include aspects of Earth System complexity such as biogeochemistry, and simulations including several ensemble members are usually completed. However, in order to achieve this task, the horizontal resolution has traditionally been compromised, typically to ~150km or coarser in the atmosphere and 1 degree in the ocean. This means that important climate processes (such as atmospheric convection, ocean mesoscale boundary currents and eddies) have had to be parameterised rather than resolved, and dynamical processes and interactions can be compromised (Collins et al. 2018).

At the opposite extreme, the next major breakthrough in simulation may be reached at scales below 1 km in the atmosphere, as we come close to resolving the largest of boundary-layer eddies, the macroscopic cloud features and convective organisation (Schneider et al. 2017). Several global models (e.g. NICAM; Satoh et al. 2008, 2014) are now able to complete global simulations at sub-km grid spacing (Miyamoto et al. 2014). Such individual simulations are currently short (<1 year), have only a minimal number of Earth System processes included, and challenge our observational abilities, due to the limited time and space sampling from satellites. However, they can be used to gain insights into poorly understood interactions (such as aerosol-microphysics-cloud interactions, e.g. Hashino et al. 2013). Such models are also generally non-hydrostatic and hence able to better represent organised convective processes and small-scale structures in, for example, tropical cyclones. Considerable uncertainties remain, but such tools are key for future process understanding.

In between these two fundamental scale boundaries, gradual refinements in resolution might be considered to afford only marginal benefits for our understanding of climate variability and change. However, here we aim to demonstrate that significant improvements in understanding are afforded by global models at intermediate resolutions, which are vital for projections over the next few decades. We show evidence that the large-scale circulation is significantly improved in the atmosphere using resolutions finer than 100km, despite the Rossby radius being ~1000km and hence "resolved" in CMIP-type models. For the ocean, the Rossby radius is finer than 100km and hence unresolved in most CMIP-ocean models, with potentially important consequences for climate simulation (Hewitt et al. 2017).

Global NWP models have paved the way for developments in climate modelling and systematically demonstrated the added benefits of enhanced resolution, albeit in the context of initialised forecasts, which also benefit from advances in other components (such as data assimilation, ensemble size, number of observations and other model improvements; Magnusson and Källén, 2013; Bauer et al, 2015). With the advent of seamless modelling approaches (e.g. Senior et al. 2009; Brown et al. 2012), NWP and climate models are becoming equivalent in their scientific configurations, and many biases seen in long term climate simulations are already evident after days of an NWP forecast (Martin et al. 2010). An example of monitoring progress in NWP, citing resolution as one aspect of improvements in skills scores, in shown in Fig. 10 of Rodwell et al. (2010). A more general, high-level review of the benefits of resolution in NWP models is provided by Wedi (2014).

Hence some of the following evidence from climate models is far from unique to them. However, aspects of the hydrological cycle have typically not been a part of NWP skill assessments (which, for example, usually concentrate on large-scale quantities that are relevant to users on short-range timescales, such as 500 hPa height, 250 hPa winds and temperature; see references above and Mittermaier et al. 2016). In addition, and more crucially, the NWP modelling systems are typically neither radiatively balanced nor water-conserving, so are not well-placed for systematic process studies of water cycle processes on longer time- and space-scales.

Regional models are increasingly being used for climate studies at resolutions of several kilometres (Kendon et al. 2017). One could argue that this approach mitigates the need for refinements to global model resolutions. Indeed if the requirement is to understand local processes (such as convective precipitation) and extremes in terms of their local impacts, then such models currently represent our best tools. However, the regional models' representation of the large-scale circulation is no better than that of the driving global model (otherwise it would not be well constrained), and this requires the global model to credibly represent global modes of variability, dynamic and thermodynamic responses to climate forcing. Hence it is key to make the large-scale circulation as accurate as possible, as this provides critical information needed for the regional downscaling to offer added information. We will argue that it is precisely at these synoptic scales that the new generation of high-resolution global models are showing substantial improvement in the mean state and variability.

We ask in this paper what we can learn from the range of models at global resolutions that are now or will soon become affordable on flagship supercomputers worldwide. In particular we ask what added value such enhanced models provide in terms of the simulated hydrological cycle, and thus the trustworthiness and robustness of current climate projections particularly over the next few decades.

The global hydrological cycle

One of the key questions for climate research is how the global water cycle might change in the next few decades. At its most basic, the global water cycle describes the movement of water between the different reservoirs in the climate system - in and on the ocean (including sea-ice and ice shelves), over and below the land surface (surface and ground water, land-ice), and the corresponding energy exchanges. It is therefore implicated in many of the impacts that climate change brings - excess water (flooding, tropical and mid-latitude storms, atmospheric rivers), lack of water (drought), and intensity of storms (concurrently regulated by energy and momentum exchanges).

The representation of the global water cycle in coupled climate models, and in particular some of its governing processes, is subject to much larger variability among models than other (thermodynamic) indicators. One can contrast the significant agreement in CMIP5 (Flato et al. 2013), expressed by model projections of future warming rates and patterns, against the disagreement in projected precipitation changes, which showed little improvement over the earlier CMIP3 assessment. Although precipitation does not represent the whole water cycle, and our observational record is short and uncertain, such fundamental disagreements do not build confidence in future projections.

Part of the reason for this uncertainty is the lack of representation of the dynamical aspects of the coupled climate system, and how these are coupled to the physical aspects of model simulation. At the largest scales, on the order of the Rossby radius, model physics (i.e. column processes) dominate the under-resolved dynamics in atmosphere and ocean (Trenberth et al. 2011; Demory et al. 2014). As resolution increases and the synoptic and mesoscales become better resolved, then they both play an important role – perhaps at a minimal resolution of around 50km (Matsueda and Palmer 2011; Delworth et al. 2012, Demory et al. 2014). As resolution increase continues towards the 1 km-scale, multi-scale dynamics increasingly dominates column physics (see for instance the discussion in Vellinga et al. 2016).

a. Large-scale moisture transports

Studies focusing on the impact of resolution on the simulated global hydrological cycle as a whole remain quite rare (Pope and Stratton 2002; Hack et al. 2006; Hagemann et al. 2006; Demory et al. 2014). Demory et al. (2014) find that the simulation of a select few components of the global hydrological cycle is degraded by increasing model resolution, due to an overall excess in net available energy at the surface that is caused by errors in model physics. However, they find that the overall hydrological cycle is intensified by global grid refinement, and for consistent reasons, resulting in a strength that compares well with observations (e.g. as in Trenberth et al. 2011). This is manifested by less precipitation over the ocean and more precipitation over land, caused by enhanced large-scale atmospheric moisture transport from the ocean to the land, reducing the commonly overestimated precipitation recycling over land. At mid-latitudes, this increase in the large-scale atmospheric moisture transport is particularly associated with the storm track regions. Notably, such multi-scale interactions can only be studied with global models. Demory et al. (2014) also uncovered a locally asymptotic response of the mid-latitude large-scale atmospheric moisture transport, starting at about 60 km grid size, which seems to be within recent observational estimates (Trenberth et al. 2011). There are indications that other models show similar sensitivity to resolution (Terai et al. 2017; Vanniere et al., submitted).

b. Surface water balance and precipitation distribution

Precipitation, evaporation, runoff and storage variations characterise the water balance over any land area. All four of these quantities are difficult to observe and to simulate by global climate models, and our current ability to close the water balance remains highly unsatisfactory over the global land area and much more so at the scales of continents or large river basins. One example of these uncertainties is illustrated in Figure 1: total global precipitation is remarkably resolution invariant, which points to a very robust constraint provided by global long-wave cooling in all model simulations, producing precipitation estimates within the range of significant and persistent observational uncertainty (see estimates by GPCP versus Wild et al. 2015 versus Stephens et al. 2012). Further, increasing the resolution in the HadGEM3 atmospheric GCM (GA3, Mizielinski et al 2014) from about 100 to 25 km changes the model estimate of precipitation partitioning. Land versus sea distribution of precipitation agrees with the findings in Demory et al. 2014; additionally, for the land portion, global (rugged) mountain precipitation increases by about 15%, and available observations, which are sparse over complex terrain, are hardly able to assess these model estimates. Precipitation over comparatively small mountain areas is particularly important since it disproportionately contributes to runoff and therefore the generation of so-called blue water which sustains ecosystems and human livelihood.

Given such uncertainties in global precipitation, it is not surprising that regional distributions are also poorly estimated. Figure 2, reproduced from Wehner et al. (2014), shows an analysis of annual daily total precipitation distributions from three different horizontal resolutions of the Community Atmospheric Model (CAM5.1), for a number of regions. There is some evidence that, at resolutions finer than 25km, grid separation is no longer the limiting factor in reproducing observations (e.g. Hawcroft et al. 2016) and that deficiencies in sub-grid scale parameterisations dominate the model errors (Wehner et al. 2014), particularly when convection is an important contributor to the local atmospheric water budget.

Using the same ensemble of GA3 atmospheric model simulations as Demory et al. (2014) at 130km, 60km and 25km resolution (referred to an N96, N216 and N512 respectively), the precipitation distribution in each IPCC SREX[1] region is used to determine which model resolution best fits the multiple observational datasets available over that region (see Appendix A for details). Figure 3 shows the coarsest best resolution for each region. Several key points become evident:

[1] Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

1. In most regions a resolution finer than 130km is worthwhile;

2. Globally 60km may be sufficient for this metric, but there are some regions (e.g. Western Africa, South Eastern Asia) which consistently favour 25km resolution, often where land-sea contrasts and/or mountainous terrain exist; note also that at latitudes polewards of 50˚, the only long-term global observational datasets have resolutions of 110km and hence it not possible to properly assess higher resolution models;

3. There are some regions which are uncertain, either because no model is clearly better or the observational datasets disagree too much with each other to assign a best model resolution (i.e. we do not know the climatology well enough to validate models).

c. Dynamical processes and moisture transport

Correct attribution of the processes responsible for the global distribution of precipitation is key, because models that produce a reasonable climatology via demonstrably incorrect processes cannot be trusted for climate projections of rainfall.

Extra-Tropical Cyclones

One likely component driving the sensitivity of simulated moisture transport and precipitation to resolution is the moisture transport effected by dynamical processes such as cyclones (both tropical and mid-latitude). Storms provide a considerable proportion of annual rainfall in many regions of the world (Scoccimarro et al 2014; Guo et al 2017), and as such representing their frequency, variability, position and composition is important. Catto et al. (2010) and Zappa et al. (2013) show that extratropical storm structure and intensity are better represented at resolutions finer than 100km, and hence the moisture transport associated with them. Jung et al. (2012) demonstrate significantly improved extratropical cyclone frequency when moving from 130km to 40km resolution, with little change at finer grid spacings.

Tropical Cyclones and African Easterly Waves

There is mounting evidence from many modelling studies that atmosphere resolutions at 50km or finer skilfully represent the interannual variability of tropical cyclones (Zhao et al, 2009; Manganello et al. 2012; Roberts et al, 2014; Kodama et al. 2015). In the Atlantic, much of this improvement can be attributed to better global teleconnections (from El Niño, for example, Bell et al. 2014) providing a constraint on the environment, and improved dynamical precursor features such as African Easterly Waves (AEWs). Despite the latter being relatively large-scale dynamical systems, they are poorly represented at ~100 km grid scales (Martin and Thorncroft, 2015; Caron et al, 2011). This re-emphasises the danger of assuming that representation by at least two grid points is sufficient for resolving features.

Tropical cyclone importance is not only limited to producing high-impact events: Guo et al. (2017) showed that typhoons in East Asia produce about 50% of precipitation in coastal areas at the peak of the season, but also contribute a sizeable portion of the moisture transport that supports all other types of precipitation further inland. Further, their net contribution to the regional moisture budget of China is comparable albeit opposite to that of the monsoon at the time of its recession. Scoccimarro et al. (2014) show a similar result for the North Atlantic tropical cyclones and US precipitation, while Pantillon et al. (2015) show a remote link to Mediterranean rainfall events. These impacts require fidelity in storm characteristics, with Figure 4 (from Manganello et al. 2014) illustrating the improvement of storm genesis and track as model resolution is enhanced, while Scoccimarro et al. (2017) demonstrated the additional importance of high frequency coupling between atmosphere and ocean.

Mesoscale Convective Systems

In addition to storms influencing the mean precipitation, Vellinga et al. (2014) have shown important scale interactions between large-scale variability and smaller scales. Decadal variability in Sahel rainfall is shown to be related to the interaction between the large-scale Atlantic Multi-Decadal Oscillation (AMO) and AEWs. Only model resolutions fine enough (at 60km and finer in that study) to represent stronger, self-organised (at the mesoscale) and propagating rainfall events capture the observed decadal trends. There are indications that other CMIP5 models follow this relationship, but analysis is complicated by confounding factors such as different aerosol loadings, indicating a need for a more systematic set of comparable simulations.

Westerly Wind Bursts

Aforementioned dynamical precursor systems such as AEWs are also found to be important in driving variability in other dynamical systems. If they are poorly represented in models, this can significantly bias the simulated mean state, and hence lead to misleading future projections. One example would be the westerly wind bursts (WWBs) in the tropical Pacific that precede El Niño events: in observations the irregular variability of ENSO has been attributed to such WWB events (Puy et al. 2017). It may be possible that the inclusion of stochastic schemes (Christensen et al. 2017) enables some of the aspects of these precursor systems to be replicated. However development of such stochastic schemes is best informed by models able to simulate the dynamical aspects of these processes, as well as the physics-dynamics coupling.

Monsoons

In the tropics, the monsoon circulations provide a large portion of annual rainfall to many regions. There are many components and individual processes within these circulations (flow reversals, orographic interactions, land-sea contrasts, sensitivity to remote biases), and this may be why increased model resolution does not directly lead to improved monsoon simulation (Ogata et al. 2017; Johnson et al. 2016). Individual components do indicate a resolution sensitivity (such as monsoon depressions, Johnson et al. 2016), but reduction of remote biases to improve the regional mean state may be equally important (Levine and Martin 2017; Martin et al. 2010).

Atmospheric Blocking

At mid-latitudes, the representation of storm tracks and blocking play important roles in the large-scale dynamics of the water cycle. Dawson et al. (2012) demonstrate a large improvement in the structure of Euro-Atlantic weather regimes in a model run at 16km compared to one run at 150km, while Dawson and Palmer (2015) show a 40km simulation has intermediate regime fidelity. The distribution, frequency and development of European blocking has been shown to be influenced by aspects of atmosphere and ocean resolution (Berckmans et al 2013). Schiemann et al. (2017) showed some improvement in blocking in a multi-model atmosphere ensemble at 25km compared to ~100km, consistent with Jung et al. (2012) results when moving from 130km to 40km. Scaife et al. (2011) showed how reducing large-scale model biases in the North Atlantic with a 1/4 degree ocean resolution led to improved frequency of European blocking. O'Reilly et al. (2016) studied blocking and extended cold spells over Europe, and showed that the resolution of remote SST fronts was a key factor in reinforcing the blocking anticyclone and hence extending the timescale of the events.

Ocean dynamics

The impact of resolution on dynamical processes affecting the hydrological cycle is not limited to the atmosphere. In particular, the transport of freshwater is related to the stability of the meridional overturning circulation (Drifhout et al. 2013). Since transport of freshwater can take place in narrow currents and eddies, this points to an important role for ocean resolution. In the South Atlantic, the transport of freshwater is strongly determined by Agulhas eddies which move salt from the Indian Ocean to the Atlantic Ocean (Drifhout et al. 2003). In this region, resolution is key to the simulation of the Agulhas retroflection and the shedding of eddies (Banks et al. 2007; Biastoch et al. 2008). In the North Atlantic, ocean resolution is important for capturing the East Greenland current which transports freshwater from both sea ice melt and potential ice sheet melt into the Atlantic (Böning et al., 2016).

d. Land-Atmosphere coupling strength

The asymptotic behavior with resolution uncovered by Demory et al. (2014) and discussed earlier is directly relevant to the correct representation of land-atmosphere coupling in GCMs: at scales finer than 50km, the systematic overestimation of the contribution of land evaporation to precipitation starts to be mitigated by realistic simulation of atmospheric moisture convergence. However, observational evidence indicates that we must also simulate mesoscale circulations generated by landscape heterogeneity, at horizontal scales of 10km or less. For instance, Taylor (2012) showed that precipitation over the Sahel occurs over dry land patches, but coarse GCMs preferentially produce precipitation over moist patches, where convective parameterisation responds to surface moist static energy. This is because they do not represent the mesoscale horizontal transports of moisture between different land patches. The phase of the diurnal cycle of precipitation over land can also impact land-atmosphere coupling, and is almost uniformly poorly simulated in GCMs (Slingo et al. 1992; Bechtold et al. 2004; Clark et al. 2007; Ackerley et al. 2015) with implications for surface energy and moisture budgets. Recent convective parameterisations (e.g. Bechtold et al. 2014) have improved the diurnal cycle phase, while Birch et al. (2015) demonstrated similar capability by disabling convective parameterisation at around 10km resolution.

e. Air-sea interactions

The ocean's mesoscale influence on the atmosphere in the extra tropics has been known from observational analyses for some time, both near-surface (e.g., Chelton et al. 2004; Xie 2004) and in the free troposphere via precipitation, clouds and upward winds (e.g., Minobe et al. 2008; 2010; Tokinaga et al. 2009; Frenger et al. 2013; Ma, J. et al. 2015, Smirnov et al. 2015). However, it has required deployment of models with sufficient resolution in both the atmosphere and ocean in order to study and understand such interactions at the process level (Small et al. 2008; Chelton and Xie 2010, Kwon et al, 2010; Ma, J. et al.; 2015; Ma, X. et al. 2016).

Coupled simulations demonstrate fundamental changes in the character of atmosphere-ocean coupling once they admit the ocean mesoscale (Bryan et al. 2010; Roberts et al 2016), with modelling confirming that SST forces the local winds at frontal- and mesoscales, as observed (Chelton et al. 2001). In contrast, when the ocean model uses a coarse grid (1.0˚ or coarser), the opposite is found (Kirtman et al. 2012). These results point to the high possibility that frontal- and mesoscale air-sea interactions are poorly represented in CMIP5 models, consistent with the CMIP3 analysis by Maloney and Chelton (2006), with potential consequences for the fidelity of simulations of the hydrological cycle.

Atmospheric resolution is also important to capture coupled responses. For example, the salient feature of the Gulf Stream rain band (Minobe et al. 2008; 2010) is captured by an atmospheric GCM of about 50km grid-spacing (Minobe et al. 2008; Kuwano-Yoshida et al. 2010; Scher et al. 2017). By direct comparisons between high-resolution and low-resolution regional atmospheric model simulations (Willison et al. 2013; Ma, X. et al. 2016; Hawcroft et al. 2017), it is shown that latent heat release associated with extratropical cyclone development is fundamentally important for realistic winter storm simulations, and it is only when the model has sufficient resolution to resolve small-scale diabatic heating that the full effect of mesoscale air-sea interactions on extratropical cyclogenesis can be correctly simulated.

The remote atmospheric response to oceanic fronts and eddies, in comparison to the local response, is generally more difficult to identify using direct observations (Frankignoul et al. 2011; O'Reilly and Czaja, 2015), hence most existing studies are based on high-resolution model experiments. A particularly useful experimental strategy for this type of study is a set of twin atmospheric model simulations, one of which is forced by observed SSTs and the other by spatially smoothed SSTs (Xie et al. 2002; Minobe et al. 2008; Kuwano-Yoshida et al. 2010; Small et al. 2014b; Piazza et al. 2015; Ma, X. et al. 2015 and 2016). These studies reveal how fine scale ocean features influence storm density (Minobe et al. 2008; Piazza et al. 2015), fronts (Masunaga et al. 2015; Parfitt et al. 2016); jet-stream shifts (Piazza et al. 2015; Ma, X. et al. 2015 and 2016; O'Reilly et al. 2017), storm-track strength (Small et al. 2014b) and remote rainfall response along US West Coast to Kuroshio eddies (Ma, X. et al. 2015 and 2016; Kuwano-Yoshida and Minobe 2016).

f. Hydrological extremes

Global models are useful for studying extremes in order to account for both teleconnected events and for events governed by the large-scale environment. For example the Russian heat wave of 2010 was part of the same wave train that led to the devastating Pakistan floods (Lau and Kim 2010; Watenabe et al. 2010), while Atlantic tropical cyclones have been shown to affect Arctic sea ice cover (Scoccimarro et al. 2012). Assessing model skill in tropical cyclone landfalling, where the large-scale steering flow is key, is in its infancy (e.g. Camp et al. 2015; Murakami et al. 2016), but this is clearly an important metric for impacts.

Despite improvements in simulation of tropical cyclones in CMIP5 (Walsh et al. 2013), only a handful of global models showed any TCs reaching category 1 hurricane/typhoon intensity. More recently the grid spacing in state of the art global models has become sufficiently fine (order of 10-30 km) to realistically represent TCs, even in terms of intensity (Manganello et al. 2012; Wehner et al. 2014; Wehner et al. 2015; Murakami et al. 2015; Walsh et al. 2015; Scoccimarro et al. 2016a; Scoccimarro et al. 2017), up to the maximum category 5. Our current understanding of future changes to frequency and intensity (Walsh et al. 2015) is based on these relatively few capable models, hence indicating a more systematic and multi-model study is required to increase our confidence in such interpretations.

The higher gradients of moisture and temperature simulated in high horizontal resolution global climate models are also important beyond the tropics, and projected to become more important in the future. The simulation of extra-tropical transition of tropical systems, and robust future projections thereof, show substantial sensitivity to resolution (Haarsma et al. 2013) thus representing new challenges and opportunities for the prediction of the changing risks posed by extreme precipitation, winds and storm surge impacting Europe.

Future prospects and challenges

There are an increasing number of modelling groups able to push our current modelling capability to the next level. This includes using km-scale global atmosphere and eddy-rich ocean simulations. Different methods are being tried to overcome the many associated technical challenges, ranging from more efficient algorithms to novel numerical methods. One factor that has so far been lacking is a large multi-model, multi-resolution ensemble of global simulations using a common experimental design to enable coordinated analysis. This is the goal of the CMIP6 HighResMIP project (Haarsma et al 2016), which proposes a simple experimental design with the primary goal of assessing the robustness of projections across a multi-model ensemble, as a response to changes in the representation of climate processes with model horizontal resolution.

Using the CMIP6 HighResMIP protocol to create a multi-model reference dataset, work within the EU Horizon 2020 PRIMAVERA[2] project and with collaborators will also assess the costs and benefits of other advances:

1. Stochastic parameterisation schemes, which attempt to represent the variability of unresolved, sub-grid scale processes (Palmer 2009), offer a complementary approach to increasing model resolution. Due to nonlinearities in the system, including a zero-mean noise into a GCM leads to systematic shifts in the climate that can reduce model biases (Jung et al. 2005; Williams 2012; Berner et al. 2015; 2017), and improve variability (Lin and Neelin 2000, 2003; Dawson and Palmer 2015; Christensen et al 2015, 2017), often analogous to refining model resolution (e.g., Berner et al. 2012; Watson et al. 2017)). As model resolution increases, stochastic approaches will become more valuable, as representing the interaction of the resolved scales with the sub-grid through purely deterministic schemes becomes harder to justify (Dorrestijn et al. 2013);

2. Global cloud-system resolving models are a particularly important tool for understanding multi-scale structures, such as the large-scale and synoptic environment of tropical cyclogenesis (Nakano et al. 2017; Yamada et al. 2017), or large-scale sea breezes and convection initiation (Birch et al. 2015). They also demonstrate the potential of models in complementing and enhancing observations, for example the discovery by Miyakawa et al. (2012) of the three-fold structure of convective momentum transport associated with MJO, using the high-resolution data by Miura et al. (2007);

[2] https://www.primavera-h2020.eu

3. Eddy-rich ocean models: the majority of CMIP5 climate projections were undertaken using coarse (1° or coarser) ocean model components (typically with meridional refinement near the equator). At this grid spacing, the first baroclinic Rossby radius is resolved only near the equator (Hallberg, 2013). Hewitt et al. (2017) reviewed the improvements found in going towards eddy-poor/eddy-rich regimes ($1/4^{\circ}$ – $1/10^{\circ}$), with important consequences for large-scale biases (McClean et al. 2011; Delworth et al. 2012; Small et al. 2014a; Hewitt et al. 2016), heat uptake (e.g. Griffies et al. 2015; Kuhlbrodt et al. 2015) and ocean marine ecosystems (Saba et al. 2016; McKiver et al 2015; Stock et al. 2010). Coupled simulations with ocean resolutions up to 1/16 degree will enable investigation of the impact of eddies on the mean state and variability of the coupled system;

4. Unstructured meshes: an alternative approach to globally uniform increases in resolution is offered by a new generation of models for the atmosphere, ocean and sea ice, formulated on unstructured meshes (e.g., Danilov 2013; Ringler et al. 2013; Zarzycki et al., 2014; Sein et al. 2016). Unstructured meshes provide multi-resolution capacity, that is, they have the flexibility to enhance resolution where required. Several of the more mature unstructured mesh models (Finite Element Sea Ice-Ocean Model (FESOM), Wang et al. 2008; Wang et al. 2014; Danilov et al. 2017; Model for Prediction Across Scales (MPAS), Skamarock et al. 2012; Ringler et al. 2013), will participate in aspects of CMIP6 (specifically OMIP and HighResMIP). CMIP6 will thus provide an excellent opportunity to assess and contrast such approaches within a large multi-model framework;

5. Improved physical parameterisations - particularly those that are designed to work at multiple scales (e.g. Arakawa et al. 2016; Fox-Kemper et al. 2013) - are being developed for all components of the climate system, but these efforts need resources and skilled people (Jakob 2014). Such schemes enable seamless modelling across space and timescale with less parameter tuning, albeit requiring the highest resolution global models for testing their efficacy.

Observational requirements

It is also important to exploit global observations that can both assess GCMs and explore independent ways to improve process representation, including their global teleconnections, in these models. An example is provided by the NASA Gravity Recovery And Climate Experiment (GRACE) satellite mission for the global water cycle (Böning et al. 2012), which is able to provide simultaneous assessment of water storage in different components of the climate system. The evolution of high-resolution GCMs represents an important and as yet unmet challenge to develop observational products at matching resolutions: no observational counterparts to the spatially complete and physically consistent GCMs exists, capable of supporting the study of multi-scale interactions. Instead, a wide range of instruments and methods, each with characteristic strengths and limitations, need to be employed. A combination of high resolution modeling and observational datasets are key to WCRP's Global Water and Energy Exchanges (GEWEX) project focus on improved understanding of the relevant geophysical processes of water and energy variability and change on regional to local scales.

At global resolutions affordable over the next decade, the representation of atmospheric convection remains a huge challenge. While it plays a fundamental role in the climate system, the poor quality of current simulations calls into question all processes dependent on it (including all Earth System complexity). This lack of simulation skill is also enveloped in many of the largest uncertainties in climate projections, such as climate sensitivity, in particular due to uncertainties in future cloud changes. However, even once model resolutions should become so refined that we may consider removing convective parameterisation, we would move into regimes in which poorly observed and understood interactions (multi-scale, aerosol-cloud-microphysics processes, air-sea and land-atmosphere interactions) will produce similar uncertainties. The number of ensemble simulations would also be severely limited, due to the huge computational expense. Hence there is no known threshold beyond which we would expect simulations to become independent of parameterisation choices, and therefore we need to continue to develop a manifold of global modelling practices, not limited to exploiting peak resolution.

Summary

Society requires robust information about climate risks over the next few decades in order to make good financial decisions about adaptation strategies, as well as mitigation decisions.

We have shown that enhanced resolution capabilities in global climate modelling have the potential to:

- provide improved, globally consistent information about climate hazards and impacts, as shown by examples pertinent to the global water cycle
- highlight future areas where more investment is required (High Performance Computing, better algorithms, suitable observations)
- use a common simulation protocol to enable deeper understanding

Tackling climate model uncertainty (measured by variability, or range of future projections) from different perspectives can potentially reveal limitations in any framework. We are moving forward with a suite of complementary efforts, spanning uniform grid refinement across the globe in CMIP-class models; improved dynamical mesh designs providing the foundations for cloud-system resolving simulations; unstructured mesh and stochastic approaches. We are implementing these changes at the present time, as part of CMIP6, and continued, albeit accelerated evolution should enable our future models to be significantly less dependent on still-unresolved processes, such as convection.

The computational and analysis cost of this new generation of simulations, in terms of HPC, storage, network speed and analysis platform, is clearly large. New collaborative paradigms will be needed to efficiently address some of these challenges, including use of central analysis platforms, incorporating both data storage and compute, so that algorithms can be moved to the data rather than vice versa. Better coordination of experimental design and collaboration can help to form multi-model datasets to ameliorate the cost of single model ensemble simulations, and greatly enhance the scientific understanding from community analyses of such datasets, using common tools. A current example of such good practice is CMIP6 HighResMIP.

APPENDIX A

Methodology to choose best model resolution

The methodology used to construct Figure 3 is based on the GA3 ensemble of global simulations (Mizielinski et al 2014), with five ensemble members at 25km and 130km resolution, and three members at 60km. Four observational datasets are used: Tropical Rainfall Measuring Mission 3B42 product, version 7 (TRMM; Kummerow et al., 1998a; Huffman et al., 2007, 2010) and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS; Funk et al. 2015) over 50˚S-50˚N, both at 25km grid resolution; Global Precipitation Climatology Centre (GPCC; Schneider et al. 2008) and the Global Precipitation Climatology Project (GPCP; Huffman et al. 2009), both globally at 110km. All data are initially regridded to a common 130km grid. For each region, a histogram of daily precipitation is constructed in two ways; a) using equally-spaced intensity bins, b) using a non-linear distribution of bins following Martin et al. (2017) to show the relative importance of precipitation events in a given intensity bin to the total precipitation. The root mean square difference (RMSD) between a reference histogram (TRMM in the tropics, GPCP in mid-high latitudes) and all other datasets is calculated across all bins using a logarithmic scale, and illustrated in Figure 5. Figure 3 is then determined by using the RMSD for each histogram type, to determine the coarsest best resolution model to fit the observations. When using different bins to calculate the RMSD produces contradictory results, or in regions where the observational datasets span a wider range than the model resolution differences, the “uncertain” category is used.

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Figure captions

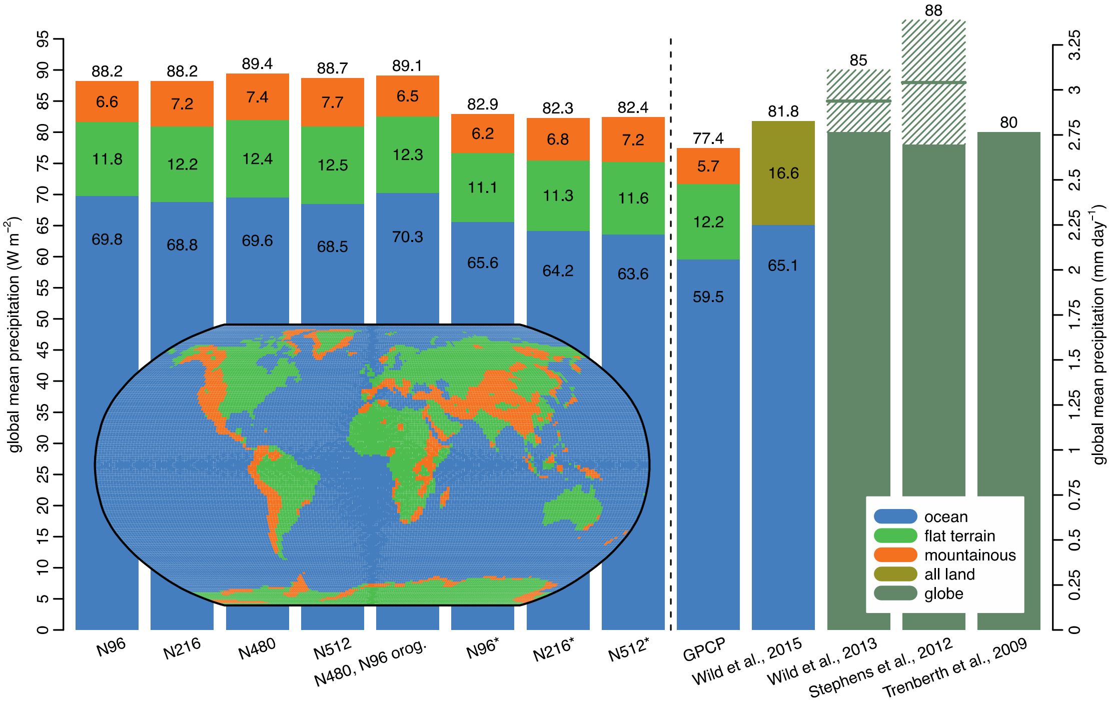
Figure 1: Long-term mean precipitation estimates from different sources over the ocean, flat terrain and mountainous terrain (see inset, mountainous area is 25% of total land area). Bar chart labels: N96, N216, N512 are 130km, 60km, 25km resolution simulations respectively using HadGEM3-GA3 (Mizielinski et al. 2014); N480, “N480, N96 orography” are GA6 (Walters et al. 2016) simulations at 27km resolution, the latter with orography degraded to N96 (130km) resolution; N96*, N216*, N512* are the same N96, N216, N512 as above, but with estimates scaled by the global surface net shortwave radiation bias; Observation-based estimates: GPCP (GPCP v2.2, Adler et al. 2012); Wild et al. (2015) (uncertainties not shown); Wild et al. (2013); Stephens et al. (2012); Trenberth et al. (2009).

Figure 2: Comparisons of the annual probability density distributions (y-axis) of daily precipitation (mm day^{-1}, x axis) between the models and location specific gridded observations as indicated by the dataset name in parentheses. a: Global land and ocean (GPCP), b: Global land only (UW-Global), c: Tropical land and ocean, 20S-20N (TRMM), d: CONUS (UW-CONUS), e: Asia (APHRODITE), f: Europe (E-OBS). Red, blue, green and black lines respectively represent the 2° CAM5.1, 1° CAM5.1, 0.25° CAM5.1. Observations are represented by the black line in Figure 2a and by gray shading in Figures 2b–2f, indicating the range of available data sets. Daily precipitation was remapped onto the 2° grid before computing the distributions in all cases. Any precipitation rates larger than 100 mm/day are assigned to the last bin for normalization purposes that sometimes results in an uptick at the end of the plot. Reproduced from Wehner et al. (2014).

Figure 3: Map showing the lowest best resolution model for each region as defined in the Appendix by comparing daily precipitation histograms. N512=25km, N216=60km, N96=130km mid-latitude resolution. Uncertain implies either no model is clearly better, or that observational uncertainty is too large to determine a best model.

Figure 4: North Atlantic Ocean (left) genesis and (right) track densities as number density per season per unit area equivalent to a 5˚ spherical cap for (a), (f) IBTrACS (Obs) and IFS simulations at (b), (g) T2047, (c), (h) T1279, (d), (i) T511, and (e), (j) T159 resolutions. Reproduced from Manganello et al. (2012) with permission by the authors.

Figure 5: Illustration of comparing Root Mean Square Difference (RMSD) values (see Appendix A for details) from models and observations, with uncertainty in observations and model ensemble spread both indicated as shading, and here RMSD is normalized to one dataset (TRMM in this example). One model is clearly best in case a), two models cannot be split in b) due to overlap in spread, while in c) the observations disagree too much to assign a best model.



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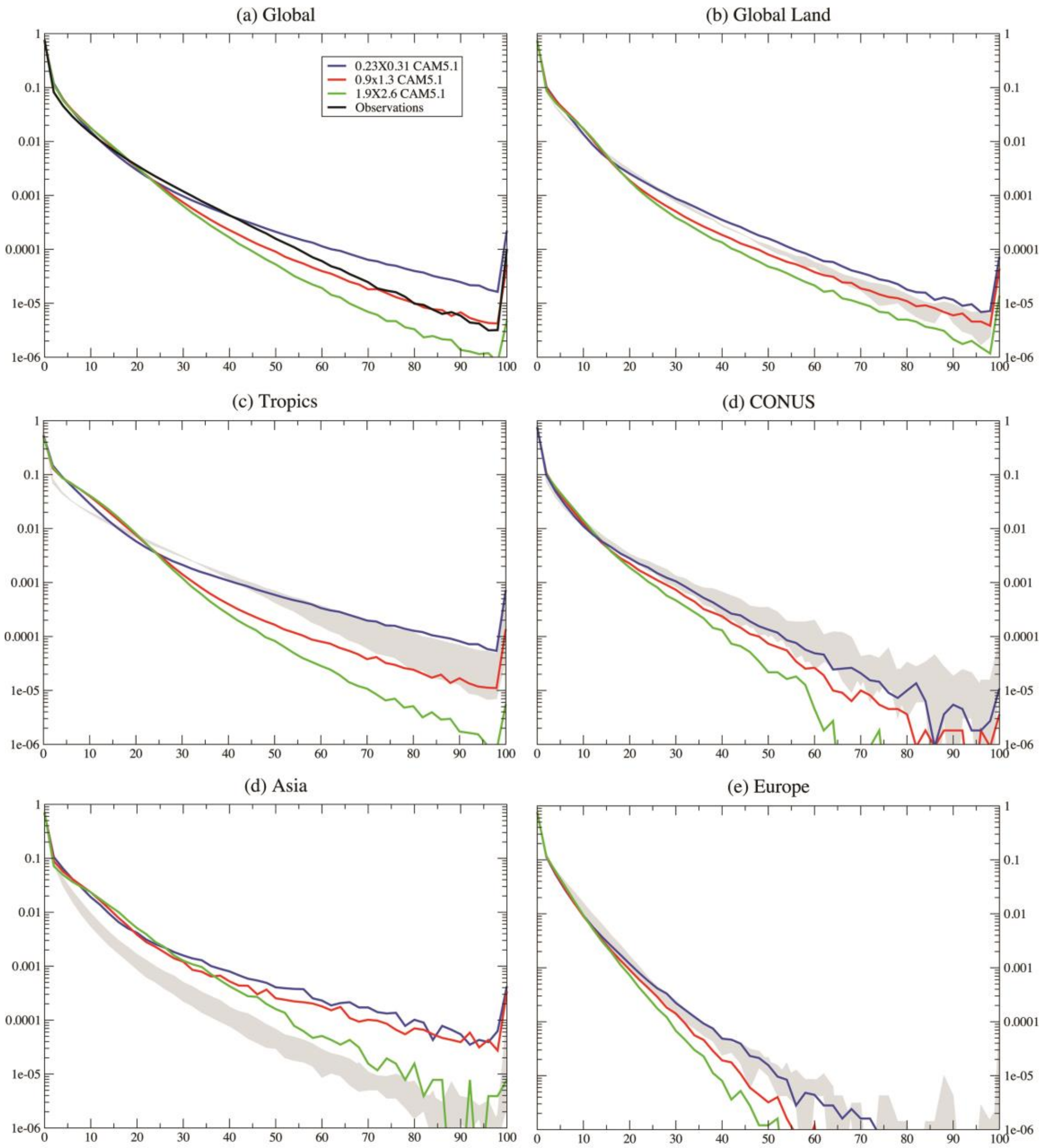

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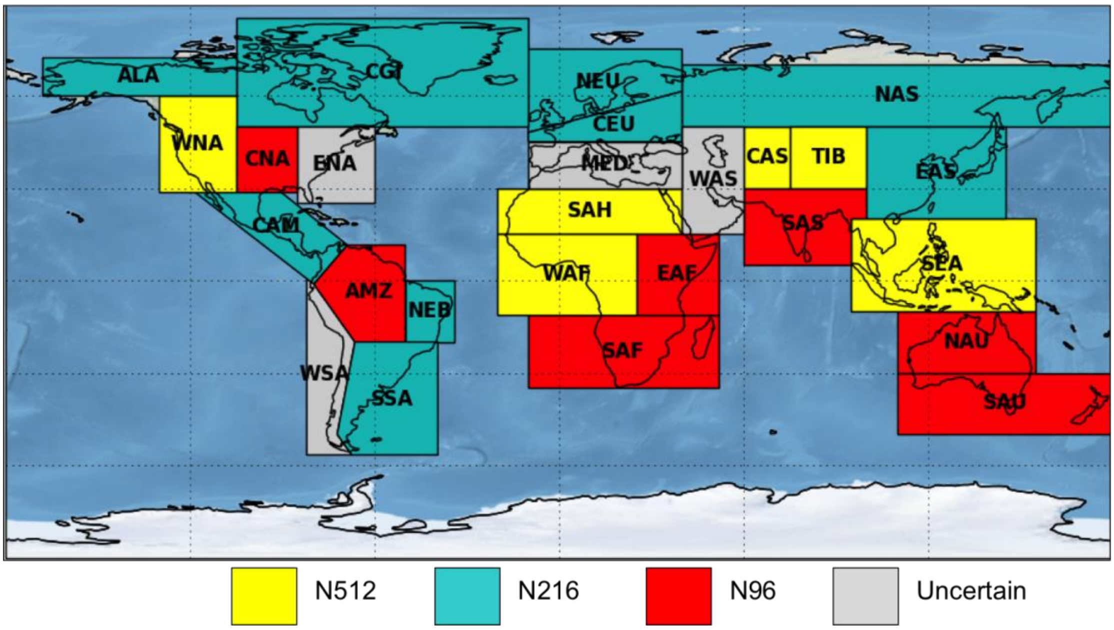

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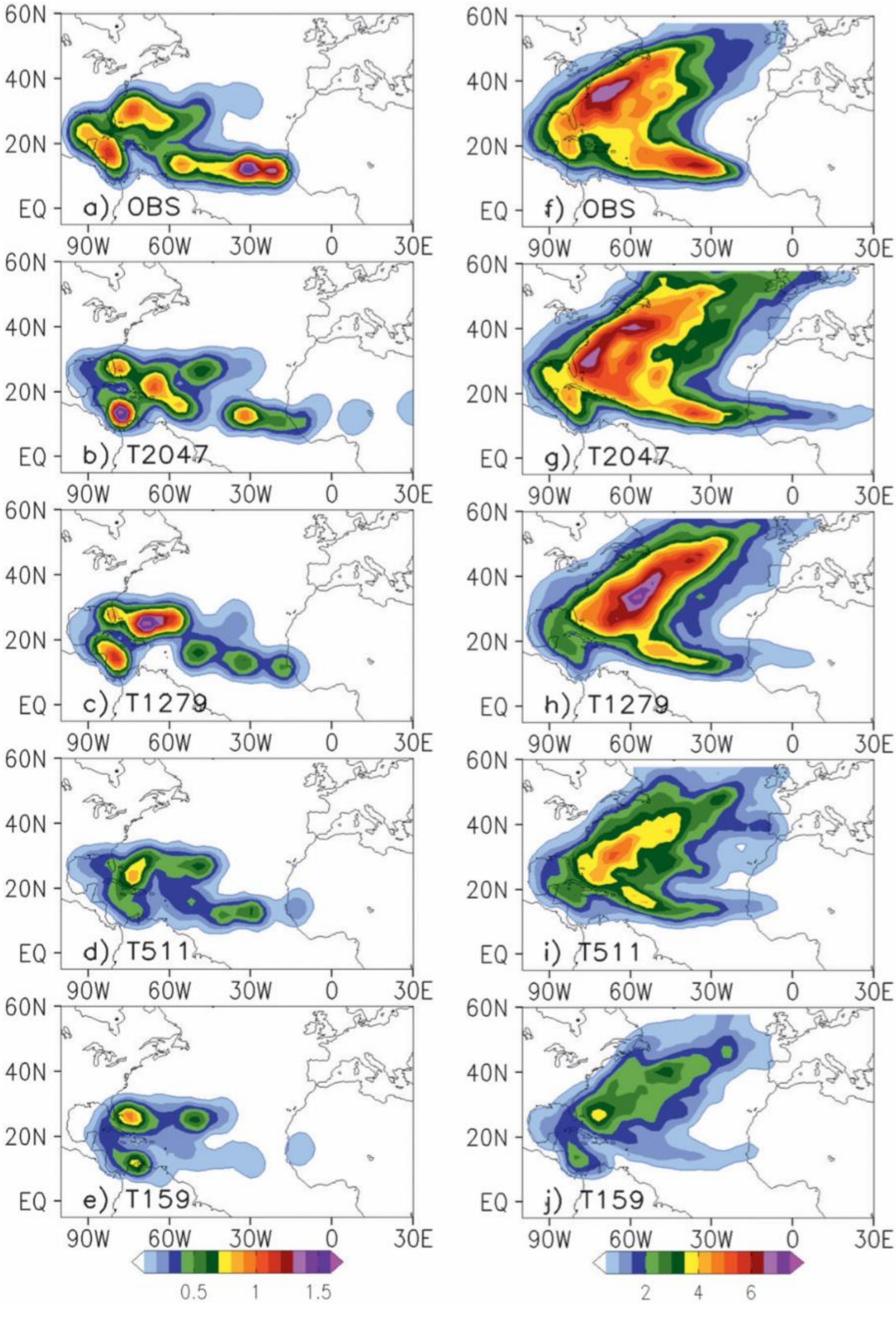

Figure 4: North Atlantic Ocean (left) genesis and (right) track densities as number density per season per unit area equivalent to a 5˚ spherical cap for (a), (f) IBTrACS (Obs) and IFS simulations at (b), (g) T2047, (c), (h) T1279, (d), (i) T511, and (e), (j) T159 resolutions. Reproduced from Manganello et al. (2012) with permission by the authors.

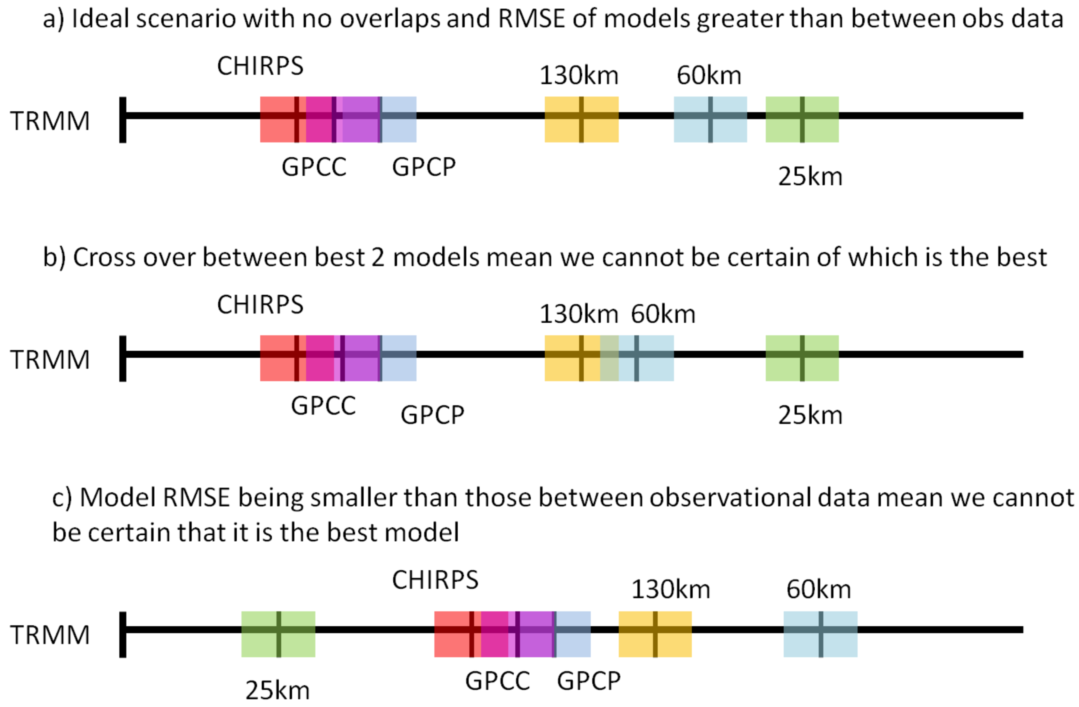

Figure 5: Illustration of comparing Root Mean Square Difference (RMSD) values (see Appendix A for details) from models and observations, with uncertainty in observations and model ensemble spread both indicated as shading, and here RMSD is normalized to one dataset (TRMM in this example). One model is clearly best in case a), two models cannot be split in b) due to overlap in spread, while in c) the observations disagree too much to assign a best model.