Title

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

Permalink

https://escholarship.org/uc/item/0j70s372

Journal

Bulletin of the American Meteorological Society, 99(11)

ISSN

0003-0007

Authors

Roberts, MJ
Vidale, PL
Senior, C
et al.

Publication Date

2018

DOI

10.1175/bams-d-15-00320.1

Peer reviewed

THE BENEFITS OF GLOBAL HIGH RESOLUTION FOR CLIMATE SIMULATION

Process Understanding and the Enabling of Stakeholder Decisions at the Regional Scale

M. J. Roberts, P. L. Vidale, C. Senior, H. T. Hewitt, C. Bates, S. Berthou, P. Chang,
H. M. Christensen, S. Danilov, M.-E. Demory, S. M. Griffies, R. Haarsma, T. Jung, G. Martin,
S. Minobe, T. Ringler, M. Satoh, R. Schiemann, E. Scoccimarro, G. Stephens, and M. F. Wehner

A perspective is given on current and future capabilities in global high-resolution climate simulation for assessing climate risks over the next few decades.

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 multimember-ensemble, multicentury 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, 2007; K. E. 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 ~150 km or coarser in the atmosphere and 1° in the ocean. This means that important climate processes (such as atmospheric convection and ocean mesoscale boundary currents and eddies) have had to be parameterized 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 organization (Schneider et al. 2017). Several global models [e.g., the Nonhydrostatic Icosahedral Atmospheric Model (NICAM); Satoh et al. 2008, 2014] are now able to complete global simulations at subkilometer grid spacing (Miyamoto et al. 2013). Such individual simulations are currently short (<1 year), have only a minimal number of Earth system processes included, and challenge our observational abilities, owing 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 nonhydrostatic and hence able to better represent organized 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 100 km, despite the Rossby radius being ~1,000 km and hence "resolved" in CMIP-type models. For the ocean, the Rossby radius is finer than 100 km and hence unresolved in most CMIP-ocean models, with potentially important consequences for climate simulation (Hewitt et al. 2017).

Global numerical weather prediction (NWP) models have paved the way for developments in climate modeling and systematically demonstrated the added benefits of enhanced resolution, albeit in the context of initialized 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 modeling 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, is 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, e.g., usually concentrate on large-scale quantities that are relevant to users on short-range time scales, such as 500-hPa height and 250-hPa winds and temperature; see references above and Mittermaier et al. (2016)]. In addition, and more crucially, the NWP modeling 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 kilometers (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

AFFILIATIONS: Roberts, Senior, Hewitt, Berthou, and Martin—Met Office, Exeter, United Kingdom; Vidale and Schiemann—National Centre for Atmospheric Science, University of Reading, Reading, United Kingdom; Bates—University of Exeter, Exeter, United Kingdom; Chang—Department of Oceanography, Texas A&M University, College Station, Texas; Christensen—Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, United Kingdom; Danilov—Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany; Demory—National Centre for Atmospheric Science, University of Reading, Reading, United Kingdom, and Center for Space and Habitability, University of Bern, Bern, Switzerland; Griffies—NOAA/GFDL, Princeton, New Jersey; Haarsma—Royal Netherlands Meteorological Institute, De Bilt, Netherlands; Jung—Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, and Department of Physics and Electrical Engineering, University of Bremen, Bremen, Germany; Minobe—Division of Earth and Planetary Sciences, Faculty of Science, Hokkaido University, Sapporo, Japan; Ringler—Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico; Satoh—Atmosphere and Ocean Research Institute, The University of Tokyo, Tokyo, Japan; Scoccimarro—Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, Bologna, Italy; Stephens—Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, and Met Office, Exeter, United Kingdom, and National Centre for Atmospheric Science, University of Reading, Reading, United Kingdom; Wehner—Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, California
CORRESPONDING AUTHOR: Malcolm J. Roberts, malcolm.roberts@metoffice.gov.uk

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-15-00320.1

In final form 10 May 2018

not be well constrained), and this requires the global model to credibly represent global modes of variability and 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 groundwater, 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 midlatitude 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, as well as 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 50 km (Matsueda and Palmer 2011; Delworth et al. 2012; Demory et al. 2014). As resolution increase continues toward the 1-km scale, multiscale dynamics increasingly dominates column physics [see, e.g., the discussion in Vellinga et al. (2016)].

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 because of 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 midlatitudes, this increase in the large-scale atmospheric moisture transport is particularly associated with the storm-track regions. Notably, such multiscale interactions can only be studied with global models. Demory et al. (2014) also uncovered a locally asymptotic response of the midlatitude 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. 2018, manuscript submitted to *Climate. Dyn.*).

Surface water balance and precipitation distribution. Precipitation, evaporation, runoff, and storage variations characterize 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 Fig. 1: total global precipitation is remarkably resolution invariant, which points to a very robust constraint provided by global longwave cooling in all model simulations, producing precipitation estimates within the range of significant and persistent observational uncertainty [see estimates by GPCP vs Wild et al. (2015) vs Stephens et al. (2012)]. Further, increasing the resolution in the Hadley Centre Global Environment Model, version 3 (HadGEM3), atmospheric general circulation model (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 Atmosphere Model, version 5.1 (CAM5.1), for a number of regions. There is some evidence that, at resolutions finer than 25 km, grid separation is no longer the limiting factor in reproducing observations (e.g., Hawcroft et al. 2016) and that deficiencies in subgridscale parameterizations 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 130-,

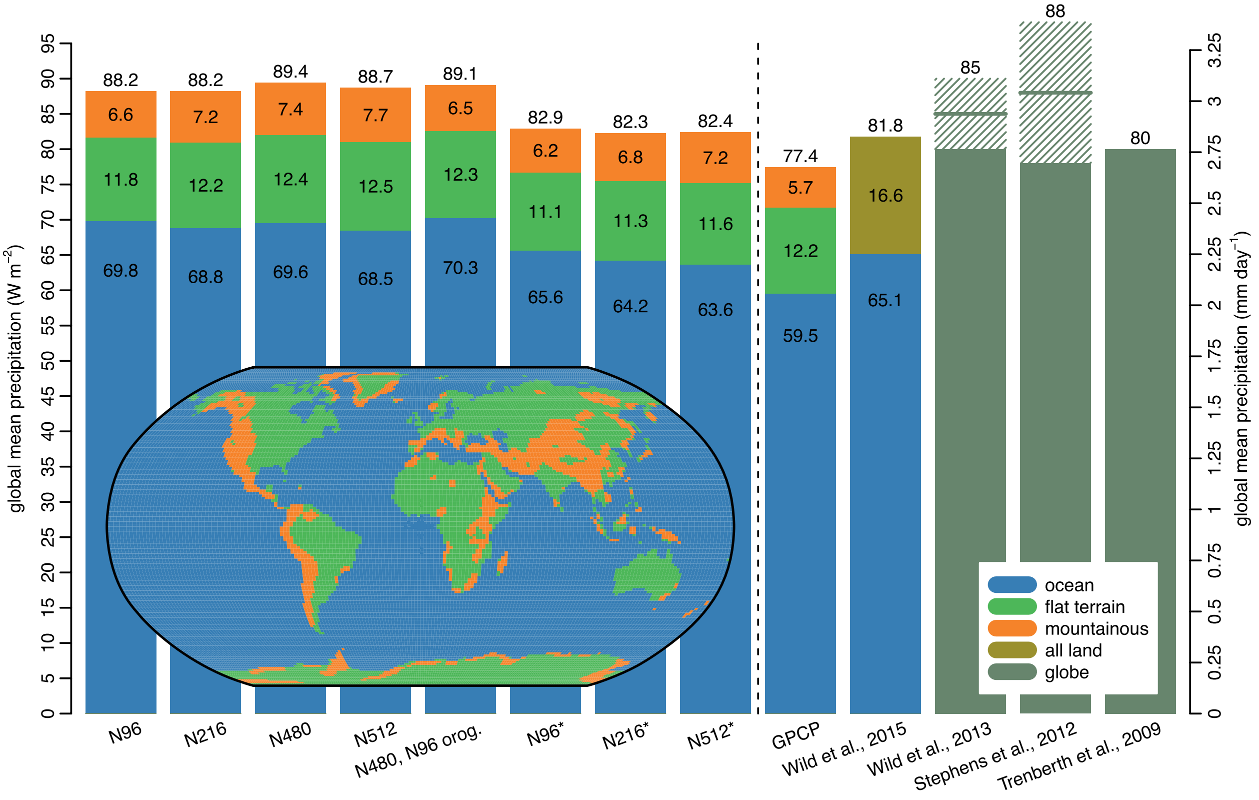


Fig. 1. Long-term mean precipitation estimates from different sources over the ocean, flat terrain, and mountainous terrain (see inset; mountainous area is 25% of total land area). Bar chart labels: N96, N216, and N512 are 130-, 60-, and 25-km-resolution simulations, respectively, using HadGEM3-GA3 (Mizielinski et al. 2014); N480 and "N480, N96 orography" are GA6 (Walters et al. 2017) simulations at 27-km resolution, the latter with orography degraded to N96 (130 km) resolution; N96*, N216*, and N512* are similar to N96, N216, and 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), and Trenberth et al. (2009).

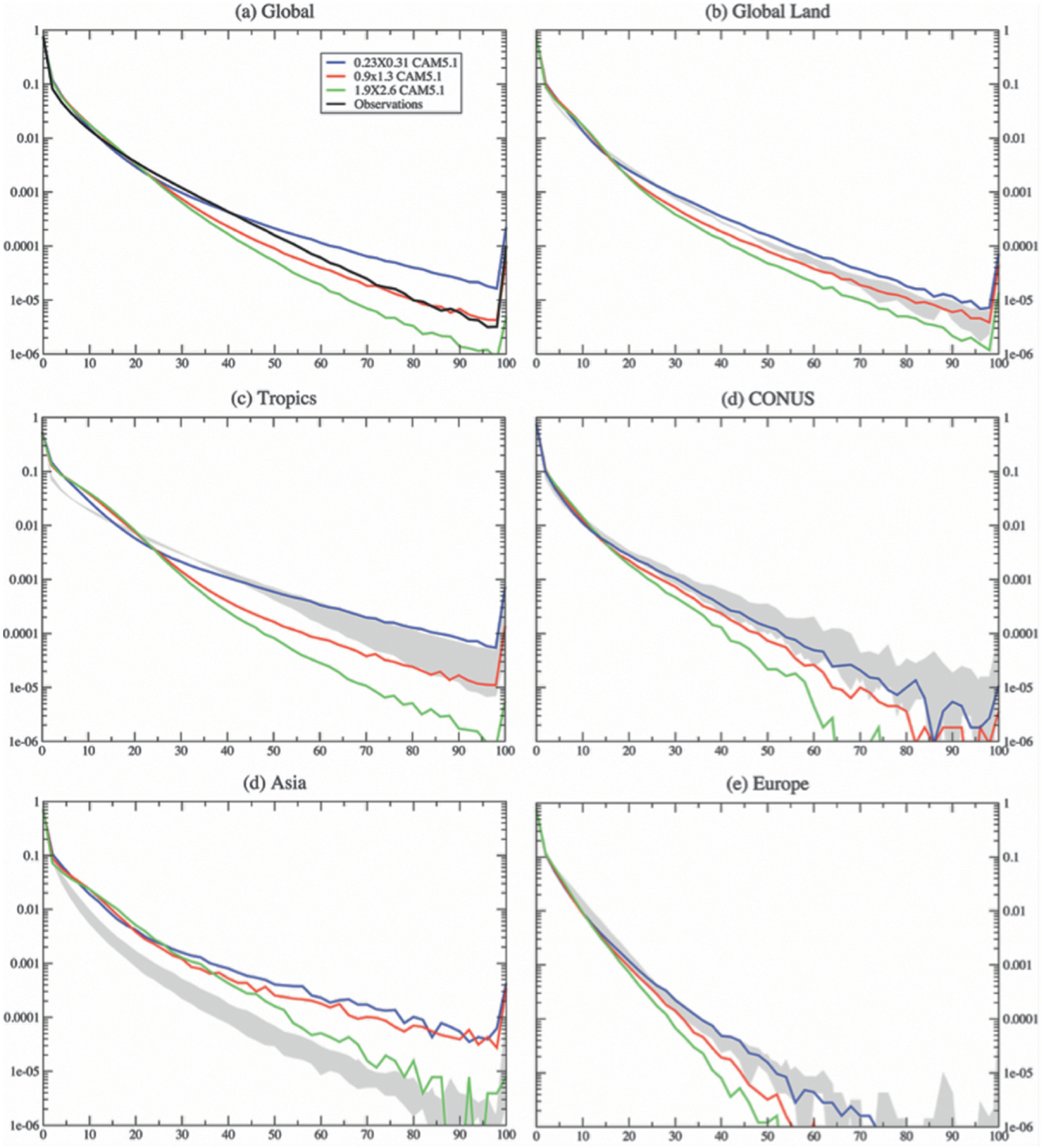


Fig. 2. Comparisons of the annual probability density distributions (*y* axis) of daily precipitation (mm day^{-1}; *x* axis) between the models and location-specific gridded observations as indicated by the dataset name in parentheses. (a) Global land and ocean (GPCP), (b) global land only [University of Washington (UW)-Global], (c) tropical land and ocean, 20°S–20°N (TRMM), (d) continental United States (CONUS) (UW-CONUS), (e) Asia [Asian Precipitation—Highly Resolved Observational Data Integration Toward Evaluation of Water Resources (APHRODITE)], and (f) Europe [European daily high-resolution gridded dataset (E-OBS)]. Red, blue, green, and black lines, respectively, represent the 2° CAM5.1, 1° CAM5.1, and 0.25° CAM5.1. Observations are represented by the black line in (a) and by gray shading in Figs. (b)–(e), indicating the range of available datasets. Daily precipitation was remapped onto the 2° grid before computing the distributions in all cases. Any precipitation rates larger than 100 mm day^{-1} 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).

60-, and 25-km resolution (referred to as N96, N216, and N512, respectively), the precipitation distribution in each Intergovernmental Panel on Climate Change (IPCC) Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) region is used to determine which model resolution best fits the multiple observational datasets available over that region (see appendix for details). Figure 3 shows the coarsest best resolution for each region. Several key points become evident:

1) In most regions a resolution finer than 130 km is worthwhile.
2) Globally, 60 km may be sufficient for this metric, but there are some regions (e.g., West Africa, Southeast Asia) that consistently favor 25-km resolution, often where land–sea contrasts and/or mountainous terrain exist; note also that at latitudes poleward of 50°, the only long-term global observational datasets have resolutions of 110 km, and hence it is not possible to properly assess higher-resolution models.
3) There are some regions that are uncertain, either because no model is clearly better or because 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).

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.

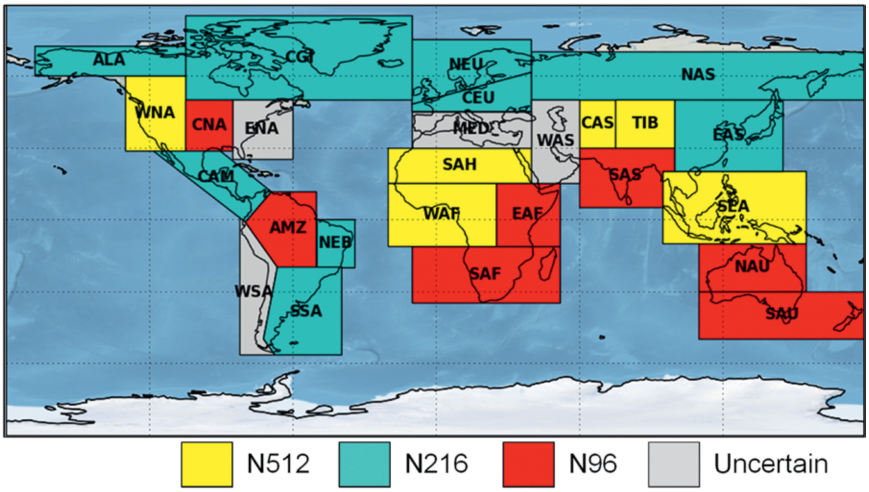


Fig. 3. Map showing the lowest-best-resolution model for each region as defined in the appendix by comparing daily precipitation histograms: N512 = 25-km, N216 = 60-km, and N96 = 130-km midlatitude resolution. Uncertain implies either no model is clearly better or observational uncertainty is too large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

EXTRATROPICAL CYCLONES. One likely component driving the sensitivity of simulated moisture transport and precipitation to resolution is the moisture transport affected by dynamical processes such as cyclones (both tropical and midlatitudes). 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 100 km, and hence so is the moisture transport associated with them. Jung et al. (2012) demonstrate significantly improved extratropical cyclone frequency when moving from 130- to 40-km resolution, with little change at finer grid spacings.

TROPICAL CYCLONES AND AEWS. There is mounting evidence from many modeling studies that atmosphere resolutions at 50 km or finer skillfully represent the interannual variability of tropical cyclones (Zhao et al. 2009; Manganello et al. 2012; Roberts et al. 2015; Kodama et al. 2015). In the Atlantic, much of this improvement can be attributed to better global teleconnections (from El Niño; e.g., 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 reemphasizes 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 sizable portion of the moisture transport that supports all other types of precipitation farther 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 U.S. precipitation, while Pantillon et al. (2015) show a remote link to Mediterranean rainfall events. These impacts require fidelity in storm characteristics, with Fig. 4 (from Manganello et al. 2012) 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.

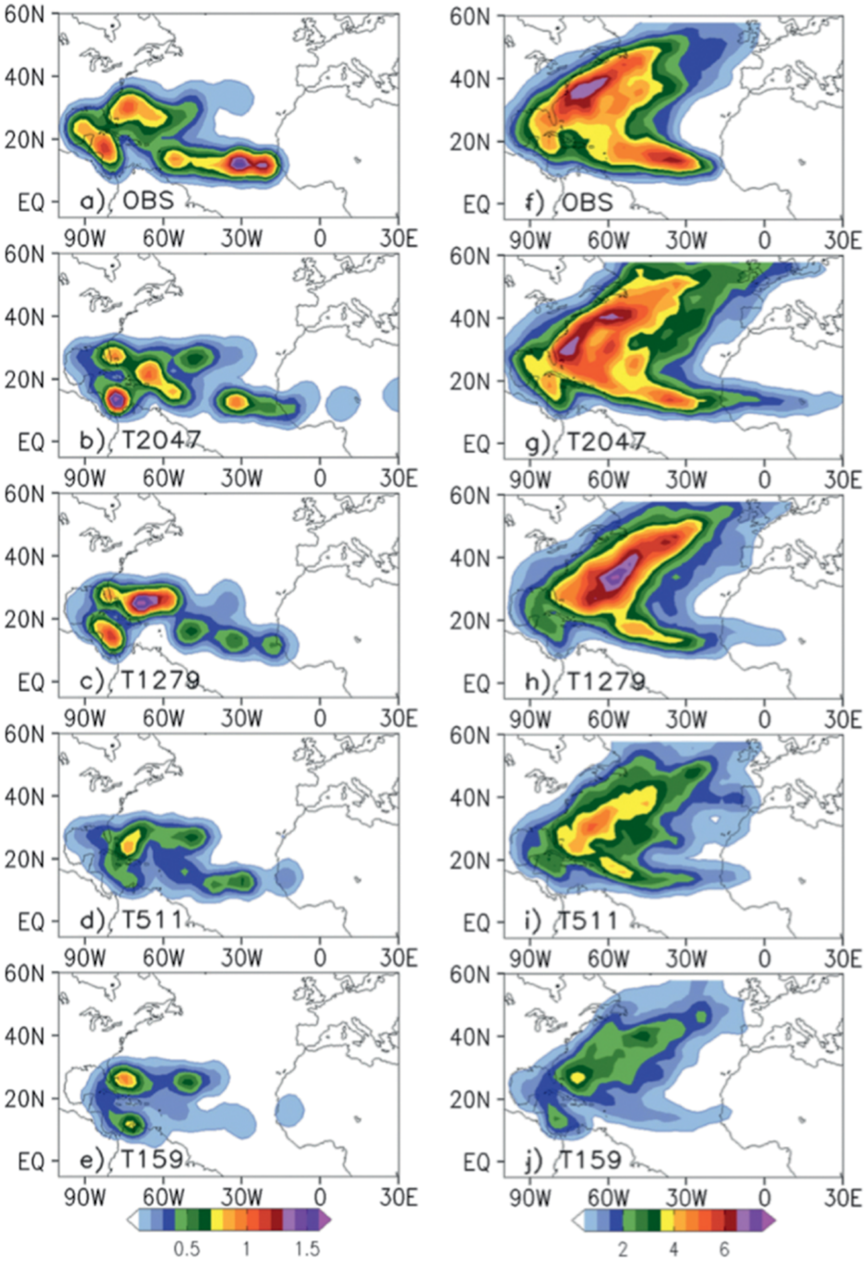


Fig. 4. North Atlantic Ocean (left) genesis and (right) track densities as number density per season per unit area equivalent to a 5° spherical cap for (a),(f) International Best Track Archive for Climate Stewardship (IBTrACS) (Obs) and Integrated Forecast System (IFS) simulations at (b),(g) T2047, (c),(h)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

Mesoscale convective systems. In addition to storms influencing the mean precipitation, Vellinga et al. (2016) 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 multidecadal oscillation (AMO) and AEWs. Only model resolutions fine enough (at 60 km and finer in that study) to represent stronger, self-organized (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 El Niño–Southern Oscillation (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 2018; Martin et al. 2010).

ATMOSPHERIC BLOCKING. At midlatitudes, 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 16 km compared to one run at 150 km, while Dawson and Palmer (2015) show a 40-km 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 multimodel atmosphere ensemble at 25 km compared to ~100 km, consistent with Jung et al. (2012) results when moving from 130 to 40 km. Scaife et al. (2011) showed how reducing large-scale model biases in the North Atlantic with a 1/4° 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 time scale 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).

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 50 km, 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 10 km or less. For instance, C. M. Taylor et al. (2012) showed that precipitation over the Sahel occurs over dry land patches, but coarse GCMs preferentially produce precipitation over moist patches, where convective parameterization 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 parameterizations (e.g., Bechtold et al. 2014) have improved the diurnal cycle phase, while Birch et al. (2015) demonstrated similar capability by disabling convective parameterization at around 10-km resolution.

Air–sea interactions. The ocean's mesoscale influence on the atmosphere in the extratropics has been known from observational analyses for some time, both near the 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; J. Ma 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; J. Ma et al. 2015; Ma et al. 2017).

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 modeling 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 rainband (Minobe et al. 2008, 2010) is captured by an atmospheric GCM of about 50-km 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 et al. 2017; 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. 2016; X. Ma et al. 2015, 2017). These studies reveal how finescale ocean features influence storm density (Minobe et al. 2008; Piazza et al. 2016), fronts (Masunaga et al. 2015; Parfitt et al. 2016), jet stream shifts (Piazza et al. 2016; X. Ma et al. 2015, 2017; O'Reilly et al. 2017), storm-track strength (Small et al. 2014b), and remote rainfall response along the U.S. West Coast to Kuroshio eddies (X. Ma et al. 2015, 2017; Kuwano-Yoshida and Minobe 2017).

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 2012; Watanabe et al. 2013), 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 tropical cyclones (TCs) reaching category 1 hurricane/typhoon intensity. More recently the grid spacing in state-of-the-art global models has become sufficiently fine (of order 10–30 km) to realistically represent TCs, even in terms of intensity (Manganello et al. 2012; Wehner et al. 2014, 2015; Murakami et al. 2015; Walsh et al. 2015; Scoccimarro 2016; 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 multimodel 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 extratropical 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 modeling groups able to push our current modeling capability to the next level. This includes using kilometer-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 multimodel, multiresolution ensemble of global simulations using a common experimental design to enable coordinated analysis. This is the goal of the CMIP6 High Resolution Model Intercomparison Project (HighResMIP; Haarsma et al. 2016), which proposes a simple experimental design with the primary goal of assessing the robustness of projections across a multimodel ensemble, as a response to changes in the representation of climate processes with model horizontal resolution.

Using the CMIP6 HighResMIP protocol to create a multimodel reference dataset, work within the European Union's Horizon 2020 Process-Based Climate Simulation: Advances in High-Resolution Modelling and European Climate Risk Assessment (PRIMAVERA; www.primavera-h2020.eu) project and with collaborators will also assess the costs and benefits of other advances:

1) Stochastic parameterization schemes, which attempt to represent the variability of unresolved, subgridscale processes (Palmer et al. 2009), offer a complementary approach to increasing model resolution. Because of 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 subgrid 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 multiscale 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 the Madden–Julian oscillation (MJO), using the high-resolution data by Miura et al. (2007).
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 toward eddy-poor/eddy-rich regimes (1/4°–1/10°), 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. 2011). Coupled simulations with ocean resolutions up to 1/16° 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 multiresolution 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, 2014; Danilov et al. 2017) and the Model for Prediction Across Scales (MPAS; Skamarock et al. 2012; Ringler et al. 2013)] will participate in aspects of CMIP6 [specifically the Ocean Model Intercomparison Project (OMIP) and HighResMIP]. CMIP6 will thus provide an excellent opportunity to assess and contrast such approaches within a large multimodel framework.
5) Improved physical parameterizations—particularly those that are designed to work at multiple scales (e.g., Arakawa et al. 2016; Fox-Kemper et al. 2014)—are being developed for all components of the climate system, but these efforts need resources and skilled people (Jakob 2014). Such schemes enable seamless modeling across space and time scales 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 National Aeronautics and Space Administration (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 exist, capable of supporting the study of multiscale 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 parameterization, we would move into regimes in which poorly observed and understood interactions (multiscale, aerosol–cloud–microphysics processes and air–sea and land–atmosphere interactions) will produce similar uncertainties. The number of ensemble simulations would also be severely limited, owing to the huge computational expense. Hence there is no known threshold beyond which we would expect simulations to become independent of parameterization choices, and therefore we need to continue to develop a manifold of global modeling 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 modeling 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 (HPC), better algorithms, suitable observations]; and
- 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, and 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 multimodel 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.

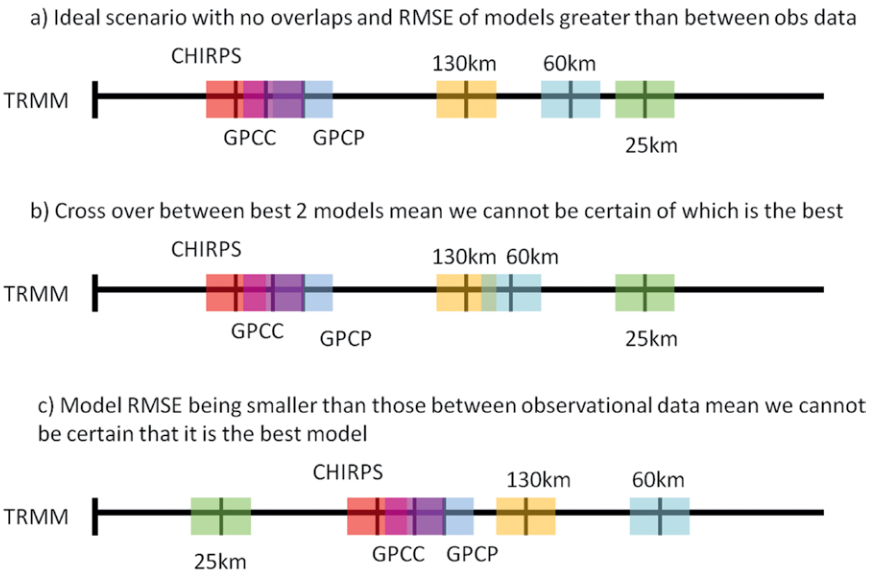
ACKNOWLEDGMENTS.

The authors thank the reviewers and the editors for their efforts and constructive comments to improve the manuscript. We also thank many people for constructive comments, including Hiroyuki Murakami, Yohan Ruprich-Robert, Keith Williams, and Dale Barker.

PRIMAVERA project members (MJR, PLV, HMC, SD, MED, RH, TJ, RS, CS, ES) acknowledge funding received from the European Commission under Grant Agreement 641727 of the Horizon 2020 research program.

Met Office authors were supported by the Joint U.K. BEIS/Defra Met Office Hadley Centre Climate Programme (GA01101). RS acknowledges NERC–Met Office JWCRP HRCM funding. PLV and MED acknowledge NCAS Climate Contract R8/H12/83/001 for the High Resolution Climate Modelling program. MFW was supported by the Regional and Global Climate Modeling Program of the Office of Biological and Environmental Research in the Department of Energy Office of Science under Contract DE-AC02-05CH11231. TJ has received funding from the European Union's Horizon 2020 Research and Innovation program through Grant Agreement 727862 APPLICATE. HMC was supported by the European Research Council

Grant 291406. PC is supported by the U.S. National Science Foundation Grants AGS-146127 and AGS-1067937 and National Oceanic and Atmospheric Administration Grant NA11OAR4310154, as well as by China's National Foundation of China (41490644 and U1406401). SMG acknowledges ongoing support from NOAA/GFDL. SM was supported by the Japan Society for the Promotion of Science (Grant-in-Aid for Scientific Research 22106008 and 22244057). MS was supported by the Strategic Programs for Innovative Research (SPIRE) and the FLAGSHIP2020 project of the Ministry of Education, Culture, Sports, Science and Technology, Japan. GS was supported by NASA Grants NNN13D984T and NNN12AA01C. TR was supported by the U.S. Department of Energy Office of Science program for Scientific Discovery through Advanced Computing (SciDAC).


a) Ideal scenario with no overlaps and RMSE of models greater than between obs data

b) Cross over between best 2 models mean we cannot be certain of which is the best

c) Model RMSE being smaller than those between observational data mean we cannot be certain that it is the best model

Fig. A1. Illustration of comparing RMSD values (see appendix 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). (a) One model is clearly best in this case; (b) two models cannot be split in this case owing to overlap in spread, while (c) in this case the observations disagree too much to assign a best model.

APPENDIX: METHODOLOGY TO CHOOSE BEST MODEL RESOLUTION.

The methodology used to construct Fig. 3 is based on the GA3 ensemble of global simulations (Mizielinski et al. 2014), with five ensemble members at 25- and 130-km resolution and three members at 60 km. Four observational datasets are used: Tropical Rainfall Measuring Mission 3B42 product, version 7 (TRMM; Kummerow et al. 1998; 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 25-km 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 110 km. All data are initially regridded to a common 130-km grid. For each region, a histogram of daily precipitation is constructed in two ways: a) using equally spaced intensity bins and b) using a nonlinear 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 the mid- to high latitudes) and all other datasets is calculated across all bins using a logarithmic scale, and illustrated in Fig. A1. 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.

REFERENCES

Ackerley, D., G. Berry, C. Jakob, M. J. Reeder, and J. Schwendike, 2015: Summertime precipitation over northern Australia in AMIP simulations from CMIP5. *Quart. J. Roy. Meteor. Soc.*, **141**, 1753–1768, https://doi.org/10.1002/qj.2476.

Adler, R. F., G. Gu, and G. J. Huffman, 2012: Estimating climatological bias errors for the Global Precipitation Climatology Project (GPCP). *J. Appl. Meteor. Climatol.*, **51**, 84–99, https://doi.org/10.1175/JAMC-D-11-052.1.

Arakawa, A., J.-H. Jung, and C.-M. Wu, 2016: Multiscale modeling of the moist-convective atmosphere. *Multiscale Convection-Coupled Systems in the Tropics: A Tribute to Dr. Michio Yanai*, *Meteor. Monogr.*, No. 56, Amer. Meteor. Soc., 16.1–16.17, https://doi.org/10.1175/AMSMONOGRAPHS-D-15-0014.1.

Banks, H. T., S. Stark, and A. B. Keen, 2007: The adjustment of the coupled climate model HadGEM1 towards equilibrium and the impact on global climate. *J. Climate*, **20**, 5815–5826, https://doi.org/10.1175/2007JCLI1688.1.

Bauer, P., A. Thorpe, and G. Brunet, 2015: The quiet revolution of numerical weather prediction. *Nature*, **525**, 47–55, https://doi.org/10.1038/nature14956.

Bechtold, P., J.-P. Chaboureau, A. Beljaars, A. K. Betts, M. Köhler, M. Miller, and J.-L. Redelsperger, 2004: The simulation of the diurnal cycle of convective precipitation over land in a global model. *Quart. J. Roy. Meteor. Soc.*, **130**, 3119–3137, https://doi.org/10.1256/qj.03.103.

——, N. Semane, P. Lopez, J.-P. Chaboureau, A. Beljaars, and N. Bormann, 2014: Representing equilibrium and nonequilibrium convection in large-scale models. *J. Atmos. Sci.*, **71**, 734–753, https://doi.org/10.1175/JAS-D-13-0163.1.

Bell, R., K. Hodges, P. L. Vidale, J. Strachan, and M. Roberts, 2014: Simulation of the global ENSO–tropical cyclone teleconnection by a high-resolution coupled general circulation model. *J. Climate*, **27**, 6404–6422, https://doi.org/10.1175/JCLI-D-13-00559.1.

Berckmans, J., T. Woollings, M.-E. Demory, P.-L. Vidale, and M. Roberts, 2013: Atmospheric blocking in a high resolution climate model: Influences of mean state, orography and eddy forcing. *Atmos. Sci. Lett.*, **14**, 34–40, https://doi.org/10.1002/asl2.412.

Berner, J., T. Jung, and T. N. Palmer, 2012: Systematic model error: The impact of increased horizontal resolution versus improved stochastic and deterministic parameterizations. *J. Climate*, **25**, 4946–4962, https://doi.org/10.1175/JCLI-D-11-00297.1.

——, K. R. Smith, S.-Y. Ha, J. Hacker, and C. Snyder, 2015: Increasing the skill of probabilistic forecasts: Understanding performance improvements from model-error representations. *Mon. Wea. Rev.*, **143**, 1295–1320, https://doi.org/10.1175/MWR-D-14-00091.1.

——, and Coauthors, 2017: Stochastic parameterization: Toward a new view of weather and climate models. *Bull. Amer. Meteor. Soc.*, **98**, 565–588, https://doi.org/10.1175/BAMS-D-15-00268.1.

Biastoch, A., C. W. Böning, and J. R. E. Lutjeharms, 2008: Agulhas leakage dynamics affects decadal variability in Atlantic overturning circulation. *Nature*, **456**, 489–492, https://doi.org/10.1038/nature07426.

Birch, C. E., M. Roberts, L. Garcia-Carreras, D. Ackerley, M. Reeder, and A. Lock, 2015: Sea breeze dynamics and convection initiation: The influence of convective parameterization on model biases. *J. Climate*, **28**, 8093–8108, https://doi.org/10.1175/JCLI-D-14-00850.1.

Böning, C., J. K. Willis, F. W. Landerer, R. S. Nerem, and J. Fasullo, 2012: The 2011 La Niña: So strong, the oceans fell. *Geophys. Res. Lett.*, **39**, L19602, https://doi.org/10.1029/2012GL053055.

Böning, C. W., E. Behrens, A. Biastoch, K. Getzlaff, and J. L. Bamber, 2016: Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean. *Nat. Geosci.*, **9**, 523–527, https://doi.org/10.1038/ngeo2740.

Brown, A., S. Milton, M. Cullen, B. Golding, J. Mitchell, and A. Shelly, 2012: Unified modeling and prediction of weather and climate: A 25-year journey. *Bull. Amer. Meteor. Soc.*, **93**, 1865–1877, https://doi.org/10.1175/BAMS-D-12-00018.1.

Bryan, F. O., R. Tomas, J. M. Dennis, D. B. Chelton, N. G. Loeb, and J. L. McClean, 2010: Frontal scale air–sea interaction in high-resolution coupled climate models. *J. Climate*, **23**, 6277–6291, https://doi.org/10.1175/2010JCLI3665.1.

Camp, J., M. Roberts, C. MacLachlan, E. Wallace, L. Hermanson, A. Brookshaw, A. Arribas, and A. Scaife, 2015: Seasonal forecasting of tropical storms using the Met Office high resolution seasonal forecast system. *Quart. J. Roy. Meteor. Soc.*, **141**, 2206–2219, https://doi.org/ht10.1002/qj.2516.

Caron, L.-P., C. G. Jones, and K. Winger, 2011: Impact of resolution and downscaling technique in simulating recent Atlantic tropical cyclone activity. *Climate Dyn.*, **37**, 869–892, https://doi.org/10.1007/s00382-010-0846-7.

Catto, J., L. C. Shaffrey, and K. I. Hodges, 2010: Can climate models capture the structure of extratropical cyclones? *J. Climate*, **23**, 1621–1635, https://doi.org/10.1175/2009JCLI3318.1.

Chelton, D. B., and S.-P. Xie, 2010: Coupled ocean–atmosphere interaction at oceanic mesoscales. *Oceanography*, **23**, 52–69, https://doi.org/10.5670/oceanog.2010.05.

——, and Coauthors, 2001: Observations of coupling between surface wind stress and sea surface temperature in the eastern tropical Pacific. *J. Climate*, **14**, 1479–1498, https://doi.org/10.1175/1520-0442(2001)014<1479:OOCBSW>2.0.CO;2.

——, M. G. Schlax, M. H. Freilich, and R. F. Milliff, 2004: Satellite measurements reveal persistent small-scale features in ocean winds. *Science*, **303**, 978–983, https://doi.org/10.1126/science.1091901.

Christensen, H. M., I. M. Moroz, and T. N. Palmer, 2015: Simulating weather regimes: Impact of stochastic and perturbed parameter schemes in a simple atmospheric model. *Climate Dyn.*, **44**, 2195–2214, https://doi.org/10.1007/s00382-014-2239-9.

——, J. Berner, D. R. Coleman, and T. N. Palmer, 2017: Stochastic parameterization and El Niño–Southern Oscillation. *J. Climate*, **30**, 17–38, https://doi.org/10.1175/JCLI-D-16-0122.1.

Clark, A. J., W. A. Gallus Jr., and T.-C. Chen, 2007: Comparison of the diurnal precipitation cycle in convection-resolving and non-convection-resolving mesoscale models. *Mon. Wea. Rev.*, **135**, 3456–3473, https://doi.org/10.1175/MWR3467.1.

Collins, M., and Coauthors, 2018: Challenges and opportunities for improved understanding of regional climate dynamics. *Nat. Climate Change*, **8**, 101–108, https://doi.org/10.1038/s41558-017-0059-8.

Danilov, S., 2013: Ocean modelling on unstructured meshes. *Ocean Modell.*, **69**, 195–210, https://doi.org/10.1016/j.ocemod.2013.05.005.

——, D. Sidorenko, Q. Wang, and T. Jung, 2017: The Finite-Volume Sea Ice–Ocean Model (FESOM2). *Geosci. Model Dev.*, **10**, 765–789, https://doi.org/10.5194/gmd-10-765-2017.

Dawson, A., and T. N. Palmer, 2015: Simulating weather regimes: impact of model resolution and stochastic parameterization. *Climate Dyn.*, **44**, 2177–2193, https://doi.org/10.1007/s00382-014-2238-x.

——, ——, and S. Corti, 2012: Simulating regime structures in weather and climate prediction models. *Geophys. Res. Lett.*, **39**, L21805, https://doi.org/10.1029/2012GL053284.

Delworth, T. L., and Coauthors, 2012: Simulated climate and climate change in the GFDL CM2.5 high-resolution coupled climate model. *J. Climate*, **25**, 2755–2781, https://doi.org/10.1175/JCLI-D-11-00316.1.

Demory, M.-E., P. L. Vidale, M. J. Roberts, P. Berrisford, J. Strachan, R. Schiemann, and M. S. Mizielinski, 2014: The role of horizontal resolution in simulating drivers of the global hydrological cycle. *Climate Dyn.*, **42**, 2201–2225, https://doi.org/10.1007/s00382-013-1924-4.

Dorrestijn, J., D. T. Crommelin, A. P. Siebesma, and H. J. J. Jonker, 2013: Stochastic parameterization of shallow cumulus convection estimated from high-resolution model data. *Theor. Comput. Fluid Dyn.*, **27**, 133–148, https://doi.org/10.1007/s00162-012-0281-y.

Eyring, V., S. Bony, G. A. Meehl, C. A. Senior, B. Stevens, R. J. Stouffer, and K. E. Taylor, 2016: Overview of the Coupled Model Intercomparison Project phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.*, **9**, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016.

Flato, G., and Coauthors, 2013: Evaluation of climate models. *Climate Change 2013: The Physical Science Basis*, T. F. Stocker et al., Eds., Cambridge University Press, 741–866.

Fox-Kemper, B., S. Bachman, B. Pearson, and S. Reckinger, 2014: Principles and advances in subgrid modeling for eddy-rich simulations. *CLIVAR Exchanges*, No. 65, International CLIVAR Project Office, Southampton, United Kingdom, 42–46.

Frankignoul, C., N. Sennéchael, Y.-O. Kwon, and M. A. Alexander, 2011: Influence of the meridional shifts of the Kuroshio and the Oyashio Extensions on the atmospheric circulation. *J. Climate*, **24**, 762–777, https://doi.org/10.1175/2010JCLI3731.1.

Frenger, I., N. Gruber, R. Knutti, and M. Munnich, 2013: Imprint of Southern Ocean eddies on winds, clouds and rainfall. *Nat. Geosci.*, **6**, 608–612, https://doi.org/10.1038/ngeo1863.

Funk, C., and Coauthors, 2015: The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Sci. Data*, **2**, 150066, https://doi.org/10.1038/sdata.2015.66.

Griffies, S. M., and Coauthors, 2015: Impacts on ocean heat from transient mesoscale eddies in a hierarchy of climate models. *J. Climate*, **28**, 952–977, https://doi.org/10.1175/JCLI-D-14-00353.1.

Guo, L., N. P. Klingaman, P. L. Vidale, A. G. Turner, M.-E. Demory, and A. Cobb, 2017: Contribution of tropical cyclones to atmospheric moisture transport and rainfall over East Asia. *J. Climate*, **30**, 3853–3865, https://doi.org/10.1175/JCLI-D-16-0308.1.

Haarsma, R. J., W. Hazeleger, C. Severijns, H. de Vries, A. Sterl, R. Bintanja, G. J. van Oldenborgh, and H. W. van den Brink, 2013: More hurricanes to hit western Europe due to global warming. *Geophys. Res. Lett.*, **40**, 1783–1788, https://doi.org/10.1002/grl.50360.

——, and Coauthors, 2016: High Resolution Model Intercomparison Project (HighResMIP). *Geosci. Model Dev.*, **9**, 4185–4208, https://doi.org/10.5194/gmd-9-4185-2016.

Hack, J. J., J. M. Caron, G. Danabasoglu, and K. W. Oleson, 2006: CCSM–CAM3 climate simulation sensitivity to changes in horizontal resolution. *J. Climate*, **19**, 2267–2289, https://doi.org/10.1175/JCLI3764.1.

Hagemann, S., K. Arpe, and E. Roeckner, 2006: Evaluation of the hydrological cycle in the ECHAM5 model. *J. Climate*, **19**, 3810–3827, https://doi.org/10.1175/JCLI3831.1.

Hallberg, R. W., 2013: Using a resolution function to regulate parameterizations of oceanic mesoscale eddy effects. *Ocean Modell.*, **72**, 92–103, https://doi.org/10.1016/j.ocemod.2013.08.007.

Hashino, T., M. Satoh, Y. Hagihara, T. Kubota, T. Matsui, T. Nasuno, and H. Okamoto, 2013: Evaluating global cloud distribution and microphysics from NICAM against CloudSat and CALIPSO. *J. Geophys. Res. Atmos.*, **118**, 7273–7292, https://doi.org/10.1002/jgrd.50564.

Hawcroft, M., L. Shaffrey, K. Hodges, and H. Dacre, 2016: Can climate models represent the precipitation associated with extratropical cyclones? *Climate Dyn.*, **47**, 679–695, https://doi.org/10.1007/s00382-015-2863-z.

——, H. Dacre, R. K. Forbes, K. Hodges, L. Shaffrey, and T. Stein, 2017: Using satellite and reanalysis data to evaluate the representation of latent heating in extratropical cyclones in a climate model. *Climate Dyn.*, **48**, 2255–2278, https://doi.org/10.1007/s00382-016-3204-6.

Hewitt, H. T., and Coauthors, 2016: The impact of resolving the Rossby radius at mid-latitudes in the ocean: Results from a high-resolution version of the Met Office GC2 coupled model. *Geosci. Model Dev.*, **9**, 3655–3670, https://doi.org/10.5194/gmd-9-3655-2016.

——, and Coauthors, 2017: Will high-resolution global ocean models benefit coupled predictions on short-range to climate timescales? *Ocean Modell.*, **120**, 120–136, https://doi.org/10.1016/j.ocemod.2017.11.002.

Huffman, G. J., and Coauthors, 2007: The TRMM Multisatellite Precipitation Analysis: Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeor.*, **8**, 38–55, https://doi.org/10.1175/JHM560.1.

——, R. F. Adler, D. T. Bolvin, and G. Gu, 2009: Improving the global precipitation record: GPCP version 2.1. *Geophys. Res. Lett.*, **36**, L17808, https://doi.org/10.1029/2009GL040000.

——, ——, ——, and E. J. Nelkin, 2010: The TRMM Multi-Satellite Precipitation Analysis (TMPA). *Satellite Rainfall Applications for Surface Hydrology*, F. Hossain and M. Gebremichael, Eds., Springer-Verlag, 3–22.

Jakob, C., 2014: Going back to basics. *Nat. Climate Change*, **4**, 1042–1045, https://doi.org/10.1038/nclimate2445.

Johnson, S. J., and Coauthors, 2016: The resolution sensitivity of the South Asian monsoon and Indo-Pacific in a global 0.35° AGCM. *Climate Dyn.*, **46**, 807–831, https://doi.org/10.1007/s00382-015-2614-1.

Jung, T., T. N. Palmer, and G. J. Shutts, 2005: Influence of a stochastic parameterization on the frequency of occurrence of North Pacific weather regimes in the ECMWF model. *Geophys. Res. Lett.*, **32**, L23811, https://doi.org/10.1029/2005GL024248.

——, and Coauthors, 2012: High-resolution global climate simulations with the ECMWF model in Project Athena: Experimental design, model climate, and seasonal forecast skill. *J. Climate*, **25**, 3155–3172, https://doi.org/10.1175/JCLI-D-11-00265.1.

Kendon, E. J., and Coauthors, 2017: Do convection-permitting regional climate models improve projections of future precipitation change? *Bull. Amer. Meteor. Soc.*, **98**, 79–93, https://doi.org/10.1175/BAMS-D-15-0004.1.

Kirtman, B. P., and Coauthors, 2012: Impact of ocean model resolution on CCSM climate simulations. *Climate Dyn.*, **39**, 1303–1328, https://doi.org/10.1007/s00382-012-1500-3.

Kodama, C., and Coauthors, 2015: A 20-year climatology of a NICAM AMIP-type simulation. *J. Meteor. Soc. Japan*, **93**, 393–424, https://doi.org/10.2151/jmsj.2015-024.

Kuhlbrodt, T., J. M. Gregory, and L. C. Shaffrey, 2015: A process-based analysis of ocean heat uptake in an AOGCM with an eddy-permitting ocean component. *Climate Dyn.*, **45**, 3205–3226, https://doi.org/10.1007/s00382-015-2534-0.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Oceanic Technol.*, **15**, 809–817, https://doi.org/10.1175/1520-0426(1998)015<0809:TTRMMT>2.0.CO;2.

Kuwano-Yoshida, A., and S. Minobe, 2017: Storm-track response to SST front in the northwestern Pacific region in an AGCM. *J. Climate*, **30**, 1081–1102, https://doi.org/10.1175/JCLI-D-16-0331.1.

——, ——, and S.-P. Xie, 2010: Precipitation response to the Gulf Stream in an atmospheric GCM. *J. Climate*, **23**, 3676–3698, https://doi.org/10.1175/2010JCLI3261.1.

Kwon, Y.-O., M. A. Alexander, N. A. Bond, C. Frankignoul, H. Nakamura, B. Qiu, and L. A. Thompson, 2010: Role of the Gulf Stream and Kuroshio–Oyashio systems in large-scale atmosphere–ocean interaction: A review. *J. Climate*, **23**, 3249–3281, https://doi.org/10.1175/2010JCLI3343.1.

Lau, W. K., and K.-M. Kim, 2012: The 2010 Pakistan flood and Russian heat wave: Teleconnections of hydrometeorological extremes. *J. Hydrometeor.*, **13**, 392–403, https://doi.org/10.1175/JHM-D-11-016.1.

Levine, R. C., and G. M. Martin, 2018: On the climate model simulation of Indian monsoon low pressure systems and the effect of remote disturbances and systematic biases. *Climate Dyn.*, **50**, 4721–4743, https://doi.org/10.1007/s00382-017-3900-x.

Lin, J. W.-B., and J. D. Neelin, 2000: Influence of a stochastic moist convective parameterization on tropical climate variability. *Geophys. Res. Lett.*, **27**, 3691–3694, https://doi.org/10.1029/2000GL011964.

——, and ——, 2003: Toward stochastic deep convective parameterization in general circulation models. *Geophys. Res. Lett.*, **30**, 1162, https://doi.org/10.1029/2002GL016203.

Ma, J., H. Xu, C. Dong, P. Lin, and Y. Liu, 2015: Atmospheric responses to oceanic eddies in the Kuroshio Extension region. *J. Geophys. Res. Atmos.*, **120**, 6313–6330, https://doi.org/10.1002/2014JD022930.

Ma, X., and Coauthors, 2015: Distant influence of Kuroshio eddies on North Pacific weather patterns? *Sci. Rep.*, **5**, 17785, https://doi.org/10.1038/srep17785.

——, and Coauthors, 2017: Importance of resolving Kuroshio front and eddy influence in simulating North Pacific storm track. *J. Climate*, **30**, 1861–1880, https://doi.org/10.1175/JCLI-D-16-0154.1.

Magnusson, L., and E. Källén, 2013: Factors influencing skill improvements in the ECMWF forecasting system. *Mon. Wea. Rev.*, **141**, 3142–3153, https://doi.org/10.1175/MWR-D-12-00318.1.

Maloney, E. D., and D. B. Chelton, 2006: An assessment of the sea surface temperature influence on surface wind stress in numerical weather prediction and climate models. *J. Climate*, **19**, 2743–2762, https://doi.org/10.1175/JCLI3728.1.

Manganello, J. V., and Coauthors, 2012: Tropical cyclone climatology in a 10-km global atmospheric GCM: Toward weather resolving climate modeling. *J. Climate*, **25**, 3867–3893, https://doi.org/10.1175/JCLI-D-11-00346.1.

Martin, E. R., and C. Thorncroft, 2015: Representation of African easterly waves in CMIP5 models. *J. Climate*, **28**, 7702–7715, https://doi.org/10.1175/JCLI-D-15-0145.1.

Martin, G. M., S. F. Milton, C. A. Senior, M. E. Brooks, S. Ineson, T. Reichler, and J. Kim, 2010: Analysis and reduction of systematic errors through a seamless approach to modelling weather and climate. *J. Climate*, **23**, 5933–5957, https://doi.org/10.1175/2010JCLI3541.1.

——, N. P. Klingaman, and A. F. Moise, 2017: Connecting spatial and temporal scales of tropical precipitation in observations and the MetUM-GA6. *Geosci. Model Dev.*, **10**, 105–126, https://doi.org/10.5194/gmd-10-105-2017.

Masunaga, R., H. Nakamura, T. Miyasaka, K. Nishii, and Y. Tanimoto, 2015: Separation of climatological imprints of the Kuroshio Extension and Oyashio fronts on the wintertime atmospheric boundary layer: Their sensitivity to SST resolution prescribed for atmospheric reanalysis. *J. Climate*, **28**, 1764–1787, https://doi.org/10.1175/JCLI-D-14-00314.1.

Matsueda, M., and T. N. Palmer, 2011: Accuracy of climate change predictions using high resolution simulations as surrogates of truth. *Geophys. Res. Lett.*, **38**, L05803, https://doi.org/10.1029/2010GL046618.

McClean, J. L., and Coauthors, 2011: A prototype two-decade fully-coupled fine-resolution CCSM simulation. *Ocean Modell.*, **39**, 10–30, https://doi.org/10.1016/j.ocemod.2011.02.011.

McKiver, W. J., M. Vichi, T. Lovato, A. Storto, and S. Masina, 2015: Impact of increased grid resolution on global marine biogeochemistry. *J. Mar. Syst.*, **147**, 153–168, https://doi.org/10.1016/j.jmarsys.2014.10.003.

Meehl, G. A., G. J. Boer, C. Covey, M. Latif, and R. J. Stouffer, 2000: The Coupled Model Intercomparison Project (CMIP). *Bull. Amer. Meteor. Soc.*, **81**, 313–318, https://doi.org/10.1175/1520-0477(2000)081<0313:TCMIPC>2.3.CO;2.

——, C. Covey, T. L. Delworth, M. Latif, B. McAveney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor, 2007: The WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bull. Amer. Meteor. Soc.*, **88**, 1383–1394, https://doi.org/10.1175/BAMS-88-9-1383.

Minobe, S., A. Kuwano-Yoshida, N. Komori, S.-P. Xie, and R. J. Small, 2008: Influence of the Gulf Stream on the troposphere. *Nature*, **452**, 206–209, https://doi.org/10.1038/nature06690.

——, M. Miyashita, A. Kuwano-Yoshida, H. Tokinaga, and S.-P. Xie, 2010: Atmospheric response to the Gulf Stream: Seasonal variations. *J. Climate*, **23**, 3699–3719, https://doi.org/10.1175/2010JCLI3359.1.

Mittermaier, M., R. North, A. Semple, and R. Bullock, 2016: Feature-based diagnostic evaluation of global NWP forecasts. *Mon. Wea. Rev.*, **144**, 3871–3893, https://doi.org/10.1175/MWR-D-15-0167.1.

Miura, H., M. Satoh, T. Nasuno, A. T. Noda, and K. Oouchi, 2007: A Madden-Julian oscillation event simulated using a global cloud-resolving model. *Science*, **318**, 1763–1765, https://doi.org/10.1126/science.1148443.

Miyakawa, T., Y. N. Takayabu, T. Nasuno, H. Miura, M. Satoh, and M. W. Moncrieff, 2012: Convective momentum transport by rainbands within a Madden–Julian oscillation in a global nonhydrostatic model with explicit deep convective processes. Part I: Methodology and general results. *J. Atmos. Sci.*, **69**, 1317–1338, https://doi.org/10.1175/JAS-D-11-024.1.

Miyamoto, Y., Y. Kajikawa, R. Yoshida, T. Yamaura, H. Yashiro, and H. Tomita, 2013: Deep moist atmospheric convection in a subkilometer global simulation. *Geophys. Res. Lett.*, **40**, 4922–4926, https://doi.org/10.1002/grl.50944.

Mizielinski, M. S., and Coauthors, 2014: High resolution global climate modelling: The UPSCALE project, a large simulation campaign. *Geosci. Model Dev.*, **7**, 563–591, https://doi.org/10.5194/gmdd-7-563-2014.

Murakami, H., and Coauthors, 2015: Simulation and prediction of category 4 and 5 hurricanes in the high-resolution GFDL HiFLOR coupled climate model. *J. Climate*, **28**, 9058–9079, https://doi.org/10.1175/JCLI-D-15-0216.1.

——, G. Villarini, G. A. Vecchi, W. Zhang, and R. G. Gudgel, 2016: Statistical–dynamical seasonal forecast of North Atlantic and U.S. landfalling tropical cyclones using the high-resolution GFDL FLOR coupled model. *Mon. Wea. Rev.*, **144**, 2101–2123, https://doi.org/10.1175/MWR-D-15-0308.1.

Nakano, M., and Coauthors, 2017: Global 7-km mesh nonhydrostatic model intercomparison project for improving typhoon forecast (TYMIP-G7): Experimental design and preliminary results. *Geosci. Model Dev.*, **10**, 1363–1381, https://doi.org/10.5194/gmd-10-1363-2017.

O'Reilly, C. H., and A. Czaja, 2015: The response of the Pacific storm track and atmospheric circulation to Kuroshio Extension variability. *Quart. J. Roy. Meteor. Soc.*, **141**, 52–66, https://doi.org/10.1002/qj.2334.

——, S. Minobe, A. Kuwano-Yoshida, and T. Woollings, 2017: The Gulf Stream influence on wintertime North Atlantic jet variability. *Quart. J. Roy. Meteor. Soc.*, **143**, 173–183, https://doi.org/10.1002/qj.2907.

——, ——, and ——, 2016: The influence of the Gulf Stream on wintertime European blocking. *Climate Dyn.*, **47**, 1545–1567, https://doi.org/10.1007/s00382-015-2919-0.

Ogata, T., S. J. Johnson, R. Schiemann, M.-E. Demory, R. Mizuta, K. Yoshida, and O. Arakawa, 2017: The resolution sensitivity of the Asian summer monsoon and its inter-model comparison between MRI-AGCM and MetUM. *Climate Dyn.*, **49**, 3345–3361, https://doi.org/10.1007/s00382-016-3517-5.

Palmer, T., R. Buizza, F. Doblas-Reyes, T. Jung, M. Leutbecher, G. Shutts, M. Steinheimer, and A. Weisheimer, 2009: Stochastic parametrization and model uncertainty. ECMWF Tech. Memo. 598, 42 pp., www.ecmwf.int/en/elibrary/11577-stochastic-parametrization-and-model-uncertainty.

Pantillon, F., J.-P. Chaboureau, and E. Richard, 2015: Remote impact of North Atlantic hurricanes on the Mediterranean during episodes of intense rainfall in autumn 2012. *Quart. J. Roy. Meteor. Soc.*, **141**, 967–978, https://doi.org/10.1002/qj.2419.

Parfitt, R., A. Czaja, S. Minobe, and A. Kuwano-Yoshida, 2016: The atmospheric frontal response to SST perturbations in the Gulf Stream region. *Geophys. Res. Lett.*, **43**, 2299–2306, https://doi.org/10.1002/2016GL067723.

Piazza, M., L. Terray, J. Boé, E. Maisonnave, and E. Sanchez-Gomez, 2016: Influence of small-scale North Atlantic sea surface temperature patterns on the marine boundary layer and free troposphere: A study using the atmospheric ARPEGE model. *Climate Dyn.*, **46**, 1699–1717, https://doi.org/10.1007/s00382-015-2669-z.

Pope, V. D., and R. A. Stratton, 2002: The processes governing horizontal resolution sensitivity in a climate model. *Climate Dyn.*, **19**, 211–236, https://doi.org/10.1007/s00382-001-0222-8.

Puy, M., and Coauthors, 2017: Influence of westerly wind events stochasticity on El Niño amplitude: The case of 2014 vs. 2015. *Climate Dyn.*, https://doi.org/10.1007/s00382-017-3938-9.

Ringler, T., M. Petersen, R. L. Higdon, D. Jacobsen, P. W. Jones, and M. Maltrud, 2013: A multi-resolution approach to global ocean modeling. *Ocean Modell.*, **69**, 211–232, https://doi.org/10.1016/j.ocemod.2013.04.010.

Roberts, M. J., and Coauthors, 2015: Tropical cyclones in the UPSCALE ensemble of high-resolution global climate models. *J. Climate*, **28**, 574–596, https://doi.org/10.1175/JCLI-D-14-00131.1.

——, H. T. Hewitt, P. Hyder, D. Ferreira, S. A. Josey, M. Mizielinski, and A. Shelly, 2016: Impact of ocean resolution on coupled air-sea fluxes and large-scale climate. *Geophys. Res. Lett.*, **43**, 10 430–10 438, https://doi.org/10.1002/2016GL070559.

Rodwell, M. J., D. S. Richardson, T. D. Hewson, and T. Haiden, 2010: A new equitable score suitable for verifying precipitation in numerical weather prediction. *Quart. J. Roy. Meteor. Soc.*, **136**, 1344–1363, https://doi.org/10.1002/qj.656.

Saba, V. S., and Coauthors, 2016: Enhanced warming of the northwest Atlantic Ocean under climate change. *J. Geophys. Res. Oceans*, **121**, 118–132, https://doi.org/10.1002/2015JC011346.

Satoh, M., T. Matsuno, H. Tomita, H. Miura, T. Nasuno, and S. Iga, 2008: Nonhydrostatic Icosahedral Atmospheric Model (NICAM) for global cloud resolving simulations. *J. Comput. Phys.*, **227**, 3486–3514, https://doi.org/10.1016/j.jcp.2007.02.006.

——, and Coauthors, 2014: The Non-Hydrostatic Icosahedral Atmospheric Model: Description and development. *Prog. Earth Planet. Sci.*, **1**, 18, https://doi.org/10.1186/s40645-014-0018-1.

Scaife, A. A., and Coauthors, 2011: Improved Atlantic winter blocking in a climate model. *Geophys. Res. Lett.*, **38**, L23703, https://doi.org/10.1029/2011GL049573.

Scher, S., R. J. Haarsma, H. de Vries, S. S. Drijfhout, and A. J. van Delden, 2017: Resolution dependence of extreme precipitation and deep convection over the

Gulf Stream. *J. Adv. Model. Earth Syst.*, **9**, 1186–1194, https://doi.org/10.1002/2016MS000903.

Schiemann, R., and Coauthors, 2017: The resolution sensitivity of Northern Hemisphere blocking in four 25-km atmospheric global circulation models. *J. Climate*, **30**, 337–358, https://doi.org/10.1175/JCLI-D-16-0100.1.

Schneider, T., J. Teixeira, C. S. Bretherton, F. Brient, K. G. Pressel, C. Schär, and A. P. Siebesma, 2017: Climate goals and computing the future of clouds. *Nat. Climate Change*, **7**, 3–5, https://doi.org/10.1038/nclimate3190.

Schneider, U., T. Fuchs, A. Meyer-Christoffer and B. Rudolf, 2008: Global precipitation analysis products of the GPCC. Global Precipitation Climatology Centre Tech. Rep., 12 pp.

Scoccimarro, E., 2016: Modeling tropical cyclones in a changing climate. *Oxford Research Encyclopedia of Natural Hazard Science*, S. L. Cutter, Ed., Oxford University Press, https://doi.org/10.1093/acrefore/9780199389407.013.22.

——, S. Gualdi, and A. Navarra, 2012: Tropical cyclone effects on Arctic Sea ice variability. *Geophys. Res. Lett.*, **39**, L17704, https://doi.org/10.1029/2012GL052987.

——, ——, G. Villarini, G. Vecchi, M. Zhao, K. Walsh, and A. Navarra, 2014: Intense precipitation events associated with landfalling tropical cyclones in response to a warmer climate and increased CO_2. *J. Climate*, **27**, 4642–4654, https://doi.org/10.1175/JCLI-D-14-00065.1.

——, P. G. Fogli, K. Reed, S. Gualdi, S. Masina, and A. Navarra, 2017: Tropical cyclone interaction with the ocean: The role of high-frequency (subdaily) coupled processes. *J. Climate*, **30**, 145–162, https://doi.org/10.1175/JCLI-D-16-0292.1.

Sein, D. V., S. Danilov, A. Biastoch, J. V. Durgadoo, D. Sidorenko, S. Harig, and Q. Wang, 2016: Designing variable ocean model resolution based on the observed ocean variability. *J. Adv. Model. Earth Syst.*, **8**, 904–916, https://doi.org/10.1002/2016MS000650.

Senior, C. A., and Coauthors, 2009: Synergies between numerical weather prediction and general circulation climate models. *The Development of Atmospheric General Circulation Models*, L. Donner, W. Schubert, and R. Somerville, Eds., Cambridge University Press, 76–116.

Skamarock, W. C., J. B. Klemp, M. G. Duda, L. Fowler, S.-H. Park, and T. D. Ringler, 2012: A multi-scale nonhydrostatic atmospheric model using centroidal Voronoi tesselations and C-grid staggering. *Mon. Wea. Rev.*, **140**, 3090–3105, https://doi.org/10.1175/MWR-D-11-00215.1.

Slingo, J. M., K. R. Sperber, J.-J. Morcrette, and G. L. Potter, 1992: Analysis of the temporal behavior of convection in the tropics of the European Centre for Medium-Range Weather Forecasts model. *J. Geophys. Res.*, **97**, 182119–182135, https://doi.org/10.1029/92JD01408.

Small, R. J., and Coauthors, 2008: Air-sea interaction over ocean fronts and eddies. *Dyn. Atmos. Oceans*, **45**, 274–319, https://doi.org/10.1016/j.dynatmoce.2008.01.001.

——, and Coauthors, 2014a: A new synoptic-scale resolving global climate simulation using the Community Earth System Model. *J. Adv. Model. Earth Syst.*, **6**, 1065–1094, https://doi.org/10.1002/2014MS000363.

——, R. A. Tomas, and F. O. Bryan, 2014b: Storm track response to ocean fronts in a global high-resolution climate model. *Climate Dyn.*, **43**, 805–828, https://doi.org/10.1007/s00382-013-1980-9.

Smirnov, D., M. Newman, M. A. Alexander, Y.-O. Kwon, and C. Frankignoul, 2015: Investigating the local atmospheric response to a realistic shift in the Oyashio sea surface temperature front. *J. Climate*, **28**, 1126–1147, https://doi.org/10.1175/JCLI-D-14-00285.1.

Stephens, G. L., and Coauthors, 2012: An update on Earth's energy balance in light of the latest global observations. *Nat. Geosci.*, **5**, 691–696, https://doi.org/10.1038/ngeo1580.

Stock, C. A., and Coauthors, 2011: On the use of IPCC-class models to assess the impact of climate on living marine resources. *Prog. Oceanogr.*, **88**, 1–27, https://doi.org/10.1016/j.pocean.2010.09.001.

Taylor, C. M., R. A. M. de Jeu, F. Guichard, P. P. Harris, and W. A. Dorigo, 2012: Afternoon rain more likely over drier soils. *Nature*, **489**, 423–426, https://doi.org/10.1038/nature11377.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experimental design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1.

Terai, C. R., P. M. Caldwell, S. A. Klein, Q. Tang, and M. L. Branstetter, 2018: The atmospheric hydrologic cycle in the ACME v0.3 model. *Climate Dyn.*, **50**, 3251–3279, https://doi.org/10.1007/s00382-017-3803-x.

Tokinaga, H., Y. Tanimoto, S.-P. Xie, T. Sampe, H. Tomita, and H. Ichikawa, 2009: Ocean frontal effects on the vertical development of clouds over the western North Pacific: In situ and satellite observations. *J. Climate*, **22**, 4241–4260, https://doi.org/10.1175/2009JCLI2763.1.

Trenberth, K. E., J. T. Fasullo, and J. Kiehl, 2009: Earth's global energy budget. *Bull. Amer. Meteor. Soc.*, **90**, 311–324, https://doi.org/10.1175/2008BAMS2634.1.

——, ——, and J. Mackaro, 2011: Atmospheric moisture transports from ocean to land and global energy flows in reanalyses. *J. Climate*, **24**, 4907–4924, https://doi.org/10.1175/2011JCLI4171.1.

Vellinga, M., M. Roberts, P. L. Vidale, M. S. Mizielinski, M.-E. Demory, R. Schiemann, J. Strachan, and C. Bain, 2016: Sahel decadal rainfall variability and the role of model horizontal resolution. *Geophys. Res. Lett.*, **42**, 326–333, https://doi.org/10.1002/2015GL066690.

Walsh, K., S. Lavender, E. Scoccimarro, and H. Murakami, 2013: Resolution dependence of tropical cyclone formation in CMIP3 and finer resolution models. *Climate Dyn.*, **40**, 585–599, https://doi.org/10.1007/s00382-012-1298-z.

——, and Coauthors, 2015: Hurricanes and climate: The U.S. CLIVAR working group on hurricanes. *Bull. Amer. Meteor. Soc.*, **96**, 997–1017, https://doi.org/10.1175/BAMS-D-13-00242.1.

Walters, D., and Coauthors, 2017: The Met Office Unified Model Global Atmosphere 6.0/6.1 and JULES Global Land 6.0/6.1 configurations. *Geosci. Model Dev.*, **10**, 1487–1520, https://doi.org/10.5194/gmd-10-1487-2017.

Wang, Q., S. Danilov, and J. Schröter, 2008: Finite element ocean circulation model based on triangular prismatic elements, with application in studying the effect of topography representation. *J. Geophys. Res.*, **113**, C05015, https://doi.org/10.1029/2008JE003126.

——, ——, D. Sidorenko, R. Timmermann, C. Wekerle, X. Wang, T. Jung, and J. Schröter, 2014: The finite element sea ice-ocean model (FESOM) v.1.4: Formulation of an ocean general circulation model. *Geosci. Model Dev.*, **7**, 663–693, https://doi.org/10.5194/gmd-7-663-2014.

Watanabe, M., H. Shiogama, Y. Imada, M. Mori, M. Ishii, and M. Kimoto, 2013: Event attribution of the August 2010 Russian heat wave. *SOLA*, **9**, 65–68, https://doi.org/10.2151/sola.2013-015.

Watson, P. A. G., J. Berner, S. Corti, P. Davini, J. von Hardenberg, C. Sanchez, A. Weisheimer, and T. N. Palmer, 2017: The impact of stochastic physics on tropical rainfall variability in global climate models on daily to weekly time scales. *J. Geophys. Res. Atmos.*, **122**, 5738–5762, https://doi.org/10.1002/2016JD026386.

Wedi, N. P., 2014: Increasing horizontal resolution in numerical weather prediction and climate simulations: illusion or panacea? *Philos. Trans. Roy. Soc. London*, **372A**, 20130289, https://doi.org/10.1098/rsta.2013.0289.

Wehner, M. F., and Coauthors, 2014: The effect of horizontal resolution on simulation quality in the Community Atmospheric Model, CAM5.1. *J. Adv. Model. Earth Syst.*, **6**, 980–997, https://doi.org/10.1002/2013MS000276.

——, Prabhat, K. A. Reed, D. Stone, W. D. Collins, and J. T. Bacmeister, 2015: Resolution dependence of future tropical cyclone projections of CAM5.1 in the U.S. CLIVAR Hurricane Working Group idealized configurations. *J. Climate*, **28**, 3905–3925, https://doi.org/10.1175/JCLI-D-14-00311.1.

Wild, M., D. Folini, C. Schär, N. Loeb, E. G. Dutton, and G. König-Langlo, 2013: The global energy balance from a surface perspective. *Climate Dyn.*, **40**, 3107–3134, https://doi.org/10.1007/s00382-012-1569-8.

——, and Coauthors, 2015: The energy balance over land and oceans: an assessment based on direct observations and CMIP5 climate models. *Climate Dyn.*, **44**, 3393–3429, https://doi.org/10.1007/s00382-014-2430-z.

Williams, P. D., 2012: Climatic impacts of stochastic fluctuations in air–sea fluxes. *Geophys. Res. Lett.*, **39**, L10705, https://doi.org/10.1029/2012GL051813.

Willison, J., W. A. Robinson, and G. M. Lackmann, 2013: The importance of resolving mesoscale latent heating in the North Atlantic storm track. *J. Atmos. Sci.*, **70**, 2234–2250, https://doi.org/10.1175/JAS-D-12-0226.1.

Xie, S.-P., 2004: Satellite observations of cool ocean–atmosphere interaction. *Bull. Amer. Meteor. Soc.*, **85**, 195–208, https://doi.org/10.1175/BAMS-85-2-195.

——, J. Hafner, Y. Tanimoto, W. T. Liu, H. Tokinaga, and H. Xu, 2002: Bathymetric effect on the winter sea surface temperature and climate of the Yellow and East China Seas. *Geophys. Res. Lett.*, **29**, 2228, https://doi.org/10.1029/2002GL015884.

Yamada, Y., M. Satoh, M. Sugi, C. Kodama, A. T. Noda, M. Nakano, and T. Nasuno, 2017: Response of tropical cyclone activity and structure to global warming in a high-resolution global nonhydrostatic model. *J. Climate*, **30**, 9703–9724, https://doi.org/10.1175/JCLI-D-17-0068.1.

Zappa, G., L. C. Shaffrey, and K. I. Hodges, 2013: The ability of CMIP5 models to simulate North Atlantic extratropical cyclones. *J. Climate*, **26**, 5379–5396, https://doi.org/10.1175/JCLI-D-12-00501.1.

Zarzycki, C. M., M. N. Levy, C. Jablonowski, J. R. Overfelt, M. A. Taylor, and P. A. Ullrich, 2014: Aquaplanet experiments using CAM's variable-resolution dynamical core. *J. Climate*, **27**, 5481–5503, https://doi.org/10.1175/JCLI-D-14-00004.1.

Zhao, M., I. M. Held, S.-J. Lin, and G. A. Vecchi, 2009: Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50-km resolution GCM. *J. Climate*, **22**, 6653–6678, https://doi.org/10.1175/2009JCLI3049.1.

METEOROLOGY GLOSSARY
AMERICAN METEOROLOGICAL SOCIETY
glossary *of* meteorology

SEARCH ☐ Go Search

Navigation
Main page
Glossary History
Modify this term
Suggest a new term
Random page
Help

Page

A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

(Redirected from Dust devils)

dust devil

A well-developed dust whirl; a small but vigorous whirlwind, usually of short duration, rendered visible by dust, sand, and debris picked up from the ground.

Dust devils occasionally are strong enough to cause minor damage (up to F1 on the Fujita scale). Diameters range from about 3 m to greater than 30 m; their average height is about 200 m, but a few have been observed as high as 1 km or more. They have been observed to rotate anticyclonically as well as cyclonically. Although the vertical velocity is predominantly upward, the flow along the axis of large dust devils may be downward. Large dust devils may also contain secondary vortices. Dust devils are best developed on a hot, calm afternoon with clear skies, in a dry region when intense surface heating causes a very steep lapse rate of temperature in the lowest 100 m of the atmosphere.

Categories: Term | Terms D