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INVITED COMMENTARY

Hyper-resolution global hydrological modelling: what is next? "Everywhere and locally relevant"

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Background

Between 15 and 17 March 2010, a workshop was held at Princeton University entitled 'Meeting a Grand Challenge to Hydrology: The Global Monitoring of Earth's Terrestrial Water'. The goal of this workshop was to assess the need for developing hyper-resolution (0.1–1 km) global hydrology and land surface models and to make an inventory on what obstacles need to be overcome to make hyper-resolution models a reality. The primary output from this workshop was a position paper formulating a number of science questions that would benefit from hyper-resolution modelling and key challenges to overcome to make this possible (see Wood *et al.*, 2011).

Since the Princeton workshop and the paper, several groups have been working on making high-resolution 'Locally Relevant Hydrological Models Everywhere' a reality. For instance, WaterGAP (Döll *et al.*, 2003) now runs at 5 min globally (Flörke *et al.*, 2013) as does PRC-GLOBWB (Van Beek *et al.*, 2011), whereas LISFLOOD (De Roo *et al.*, 2000; Van Der Knijff *et al.*, 2010) runs at 6 min globally. Using a modular python-based framework, NOAH-MP (Niu *et al.*, 2011) is being coupled to Dynamic TOPMODEL (Beven and Freer, 2001) for 30-m continental simulations. At the same time, the Land Information System software has been developed to support high-performance land surface modelling and data assimilation with horizontal resolutions down to 1 km (Peters-Lidard *et al.*, 2007). Parallel to these efforts is the community of models configured to be as physically based as possible (e.g. three-dimensional variably saturated coupled to shallow water equations for surface runoff) using high-performance computing technology to scale up from catchments to basins to continents (Kollet and Maxwell, 2006; Camporese *et al.*, 2010;

Brunner and Simmons, 2012; Maxwell, 2013). With global hydrological models ever increasing their resolution and physically based catchment models their domains, the two approaches are bound to meet in the middle in the near future. Aside from hydrology, but relevant to the present initiative, are ongoing efforts to improve the hydrology in land surface models (Milly and Shmakin, 2002; Balsamo *et al*., 2009; Milly *et al*., 2014) and dynamic vegetation models (Rost *et al*., 2008; Biemans *et al*., 2011), some of which act as land components in earth system models (Oleson *et al*., 2004; Best *et al*., 2011; Guimberteau *et al*., 2012). Table I provides a (non-exhaustive) overview of the various large-scale models from the different communities and their properties.

Undoubtedly, all these efforts face similar problems: which processes are best explicitly modelled and which are better parameterized? How to cope with the computer processing costs that increase exponentially with resolution; not only from finer resolution grids but also because many processes previously parameterized at the lower resolution now have to be addressed in a spatially explicit manner? How to best utilize increasingly powerful computing resources including parallel computers? How to obtain and process the data required to feed the huge parameterization needs of these models? How, if at all, to calibrate such models, validate their simulation results and perform uncertainty analyses on them?

Because many of the groups are at the moment trying to find solutions to these problems independently, we organized a follow-up workshop in Utrecht to exchange experiences and learn from each other. The main outcome of the workshop was the foundation of the open HyperHydro network. Here, we present the objectives of and the rationale behind this initiative, the scientific questions that it will attempt to answer and the major obstacles we need to work on.

The Objective, the Rationale and the Science

The HyperHydro initiative is an open network of scientists with the objective of simulating large-scale terrestrial hydrology and water resources at hyper-resolution with acceptable accuracy. By using the term ‘open network’, we intend that scientists are free to join and co-operate and that participation in its activities is voluntary: Participants use their own time and resources to participate in the network’s activities. There are a number of reasons that motivate this initiative:

Science

There are science questions related to global environmental change that require hyper-resolution descriptions of terrestrial water resources (see also Wood *et al*., 2011). We will mention four of these: (1) In global biogeochemical cycling, a proper description of the fate and export of, e.g. N, P, C, and Si requires a very detailed representation of streams, ponds, lakes, reservoirs, floodplains and wetlands because much of the retention on land can be concentrated in the smallest of water bodies (Bouwman *et al*., 2013). (2) Related to this, reconciling rates of soil erosion to observed riverine sediment export rates is impossible at the present time because of an insufficient description of along-river sediment transport, which in turn is largely related to not resolving important small scale processes such as sediment trapping, river bank erosion and bedload transport (Walling, 2009; Wisser *et al*., 2013); (3) Recently, several groups have been working on the assessment of global flood hazard and risk (Pappenberger *et al*., 2012; Hirabayashi *et al*., 2013; Winsemius *et al*., 2013). These approaches thus far only consider the probability of flooding based on simplified hydrodynamics or downscaled volumes of overbank discharge. However, flood risk also needs flow velocities, time to flooding and flood duration times to convert hazard into risk. This in turn requires very detailed (<100 m) resolution hydrodynamic modelling including the effects of flood defence structures. (4) The non-uniqueness of parameters and process descriptions in hydrological models (Beven and Binley, 1992) and the fact that different processes are active at different time scales in different catchments making each catchment unique (Beven, 2000), calls for generally applicable hydrological models with better process understanding that provide acceptable predictions in ungauged catchments (PUB, Hrachowitz *et al*., 2014). Many of the approaches suggested in PUB, such as regionalization methods and similarity frameworks, and its successor Panta Rhei (Montanari *et al*., 2013), e.g. optimality and catchment co-evolution, would be greatly helped if we had ‘hydrological and water resources models of everywhere’ at a locally relevant resolution. These models and their output could then be explored for scale dependent first order controls on runoff, evaporation, groundwater recharge and others.

Opportunity

Not always popular with hydrologists but no less an important reason to pursue hyper-resolution models is the phrase ‘Because we can!’. On the one hand, there have been enormous advances in global data availability, such as (a) low-resolution hydrologic states from remote sensing: soil moisture (de Jeu *et al*., 2008), evaporation (Sheffield *et al*., 2006; Miralles *et al*., 2011), total terrestrial water storage (Swenson *et al*., 2006; Famiglietti and Rodell, 2013), lake and reservoir levels (Swenson and Wahr, 2009; Gao *et al*., 2012); (b) high-

Table I. A (non-exhaustive) overview of the various large-scale models from the different communities and their properties

Model name	Class of model (six types)[a] :	Domain	Resolution (space and time)	Discretization type (grid, polygon or sub-catchment)	Soil and groundwater dynamics	Routing	Human water use/ Reservoirs	Surface energy balance	Vegetation	Carbon cycling	reference	Institutes	url
Mac-PDM	GHM	Globe	0.5°; daily	Grid	Vertical soil	Basin aggregation of runoff	No/No	No	Fixed	No	Gosling and Arnell (2011)	University of Reading (UK) University of Nottingham (UK)	
WBMPlus	GHM	Globe	0.5°; daily	Grid	Vertical soil, groundwater reservoir	1 D Muskingum–Cunge over channel network	Yes/Yes	No	Fixed, climatology of phenology, irrigated area change		Wisser *et al.* (2010)	University of New Hampshire (USA) City University of New York (USA)	www.wsag.unh.edu/wbm.html
WaterGAP	GHM	Globe	0.5°; 5′; daily	Grid	Vertical soil, groundwater reservoir	1D Kinematic wave + Manning channel network	Yes/Yes	No	Fixed, climatology of phenology, irrigated area change	No	Döll *et al.* (2003), Müller Schmied *et al.* (2014).	Kassel University (Germany) Goethe University Frankfurt (Germany)	www.watergap.de
H08	GHM	Globe	1.0°; daily (3 h for energy balance)	Grid	Vertical soil	Accumulation along 1.0° channel network	Yes/Yes	Yes	Simple crop growth model	No	Hanasaki *et al.* (2008)	Institute for Environmental Studies (Japan)	http://h08.nies.go.jp/h08/index.html
PCR-GLOBWB	GHM	Globe	0.5°; 5′; daily	Grid	Vertical soil, groundwater reservoir or lateral groundwater (optional)	Kinematic wave + Manning channel network, approximate floodplain inundation	Yes/Yes	No	Fixed, climatology of phenology, irrigated area change	No	Van Beek *et al.* (2011), Wada *et al.* (2014)	Utrecht University (Netherlands) Deltares (Netherlands)	www.globalhydrology.nl
VIC	LSM/GHM	Globe	0.5°; daily (3 h for energy balance)	Grid	Vertical soil, groundwater-like reservoir	Unit Hydrograph per cell + linearized St. Venant over channel network.	No/No	Yes	Fixed, climatology of phenology	No	Gao *et al.* (2009)	Princeton University (USA) University of Washington (USA)	http://www.hydro.washington.edu/Lettenmaier/Models/VIC/index.shtml
MATSIRU	LSM/GHM	Globe	1.0°; daily daily (6 h for energy balance)	Grid	Vertical soil, groundwater reservoir	CAMA Flood: 1D Diffusive wave + Manning for	Yes/Yes	Yes	Simple crop growth model	No	Koirala *et al.* (2014)	IIS, University of Tokyo (Japan)	

						friction slope channel network, floodplain inundation.							
LaD	**LSM**	**Globe**	**1.0°; daily**	**Grid**	**Vertical soil, groundwater reservoir**	**Basin aggregation of runoff**	**No/No**	**Yes**	**Constant**	**No**	**Milly and Shmakin (2002)**	**NOAH Geophysical Fluids Dynamics Laboratory (USA)**	**http://www.gfdl.noaa.gov/land-model**
LM3 (part of ESM2)	**LESM**	**Globe**	**daily (sub-daily for energy balance) 1.0°; daily daily (sub-daily for energy balance)**	**Grid**	**Vertical soil, groundwater reservoir and topography-based groundwater dynamics**	**Non-linear storage – outflow relationship per cell along the channel network**	**No/No**	**Yes**	**Dynamic**	**Yes**	**Milly *et al.* (2014)**		
HTESSEL	**LSM/LESM**	**Globe**	**Variable, 0.25–1.0° globally; 3 hourly time steps.**	**Grid**	**Vertical soil**	**Basin aggregation of runoff**	**No/No**	**Yes**	**Constant**	**Optional: coupling with LPJGeuss is possible**	**Balsamo *et al.* (2009)**	**European Centre for Medium Range Weather Forecasting (UK)**	
LPJml	**DVM**	**Globe**	**0.5°; daily**	**Grid**	**Vertical soil**	**Linear reservoir per cell along the channel network**	**Yes/Yes***	**No**	**Dynamic + phenology + plant physiology**	**Yes**	**Rost *et al.* (2008), Biemans *et al.* (2011)**	**PIK- Potsdam Institute for Climate Research (Germany)**	**www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml**
JULES	**LSM/LESM**	**Globe**	**0.5°; 3 hourly time steps.**	**Grid**	**Vertical soil**	**Routing over 1° grid using an advection scheme.**	**Yes (irrigation only)/Yes**	**Yes**	**Dynamic + phenology + plant physiology**	**Yes**	**Best *et al.* (2011)**	**Centre for Ecology and Hydrology (UK) Met Office Hadley Centre (UK) University of Exeter (UK)**	**https://jules.jchmr.org**
ORCHIDEE	**LSM/LESM**	**Globe**	**0.5°; half hourly time steps.**	**Grid**	**Vertical soil**	**No built-in routing; but has been used with routing schemes.**	**Yes (irrigation only)/No**	**Yes**	**Dynamic + phenology + plant physiology**	**Yes**	**Guimberteau *et al.* (2012)**	**Institut Pierre Simon Laplace (France) Laboratoire des Sciences du Climat et de l'Environment (France)**	**http://labex.ipsl.fr/orchidee/**
CLM	**LESM**	**Globe**	**Variable, standard 0.9° by 1.25° LAT-LON; 6 hourly**	**Grid**	**Vertical soil, groundwater reservoir.**	**Linear reservoir per cell along the channel network**	**No/No**	**Yes**	**Dynamic + phenology + plant physiology**	**Yes**	**Lawrence *et al.* (2011).**	**National Center for Atmospheric Research (USA)**	**http://www.cesm.ucar.edu/models/clm/**

(*Continues*)

Table I. (Continued)

Model name	Class of model (six types)^a :	Domain	Resolution (space and time)	Discretization type (grid, polygon or sub-catchment)	Soil and groundwater dynamics	Routing	Human water use/ Reservoirs	Surface energy balance	Vegetation	Carbon cycling	reference	Institutes	url
WRF-Hydro	LESM/DVM	Variable	Variable, (sub-) hourly time steps	Finite difference	Vertical soil, groundwater reservoir or lateral groundwater (optional)	2D-diffusion wave over topography	No/Yes	Yes	Dynamic phenology depending on LSM selection	No	Gochis *et al.* (2013)	National Center for Atmospheric Research (USA)	http://www.ral.ucar.edu/projects/wrf_hydro/
Lisflood	RHM	Europe, Africa	Europe (5 km), Global (0.1 degrees)	grid	Vertical soil, groundwater reservoir	Kinematic wave + Manning over channel network	Yes/Yes	No	LAI observed / LAI climatology for scenarios	No	Van der Knijff *et al.* (2010)	EC-JRC at Ispra (Italy)	http://floods.jrc.ec.europa.eu/lisflood-model.html
E-Hype	RHM	Europe	Median catchment size 215 km^2 (15 × 15 km); daily time step	Sub-catchments	Vertical soil, groundwater reservoir	Variable velocity (translation) + linear reservoir (attenuation) along a channel network	Yes/no	No	Partly Fixed, partly with seasonal climatology of crop cover.	No	Lindström *et al.* (2010)	SMHI – Swedish Meteorological and Hydrological Institute (Sweden)	http://hype.sourceforge.net/
mHM	RHM	Europe	1-24 km (Europe) 1/8° (USA) 1° (Africa, Asia, Lat-Ame), hourly-daily	Grid	Vertical soil. Groundwater reservoir.	1D Muskingum–Cunge over channel network.	No/No	No	LAI-observed. Dynamic phenology (option)	No	Samaniego *et al.* (2010), Kumar *et al.* (2013)	Helmholtz Centre for Environmental Research – UFZ	http://www.ufz.de/index.php?en=31389
RAPID	RHM (fast routing module)	Basins	Median catchment size 3 km^2; 3-hourly time steps (outputs, routing at 15 min)	Sub-catchments	No	1D Muskingum–Cunge over channel network	No/No	No	No	No	David *et al.* (2011)	University of Texas at Austin University of California Center for Hydrologic Modeling. Jet Propulsion Laboratory (USA)	http://rapid-hub.org.

(Continues)

Table I. (Continued)

Model name	Class of model (six types)[a] :	Domain	Resolution (space and time)	Discretization type (grid, polygon or sub-catchment)	Soil and groundwater dynamics	Routing	Human water use/ Reservoirs	Surface energy balance	Vegetation	Carbon cycling	reference	Institutes	url
HydroGeoSphere	FI-PDE	Sub-watershed to Basin to Continental (3D)	Dynamically variable, fully implicit	Control-Volume Finite Element, unstructured mesh or structured finite difference	3D-Richards Equation	2D-diffusion wave over topography	Yes/Yes	Yes	Variable	No	Brunner and Simmons (2012); Hwang *et al.* (2014)	University of Waterloo (Canada) University of Laval (Canada) Aquanty (Canada)	www.aquanty.com
ParFlow	FI-PDE	US, Basins Euro-Cordex	Variable, (sub-) hourly time steps	Finite difference	3D-Richards Equation	2D-kinematic wave over topography	No/No	Yes, when coupled to Community Land Model	Fixed	No	Kollet and Maxwell (2006), Shrestha *et al.* (2014).	Lawrence Livermore National lab (USA) Colorado School of Mines (USA) Centre for High-Performance Scientific Computing in Terrestrial Systems, Geoverbund ABC/J	http://computation.llnl.gov/casc/parflow/parflow_home.html
CATHY	FI-PDE	Basins	Variable, (sub-) hourly time steps	Finite elements (subsurface flow), finite difference (surface water flow)	3D-Richards Equation	2D-diffusion wave over topography	No/No	No	Fixed	No	Camporese *et al.* (2010)	University of Padua (Italy) University of Quebec (Canada)	

[a] GHM, global hydrological model (conceptual bucket type; often human impacts); RHM, regional hydrological model (conceptual bucket type; often human impacts); LSM, land surface model (used in climate or numerical weather prediction models; energy balance); DVM, dynamic vegetation model (water, vegetation, carbon); LESM, Land models used in earth system models (water, energy, carbon); FI-PDE, fully implicit partial differential equations

resolution parameter fields: global land cover at 1 km (GLCC), global soils and soil properties at 1 km (http://soilgrids.org), global surface lithology at 1 km (Hartmann and Moosdorf, 2012), surface elevation and global river networks at 15 arc-second (500 m) (Lehner *et al.*, 2008) and 3 arc-second (100 m). (c) Global online databases of field observations: discharge (GRDC, MOPEX, EWA-FRIEND), evaporation and carbon fluxes (FLUXNET), soil moisture (ISMN (Dorigo *et al.*, 2011)); (d) low-resolution forcing datasets of meteorological forcing (WFD (Weedon *et al.*, 2011); CRU TS3.21 (Harris *et al.*, 2014); ERA-INTERIM (Dee *et al.*, 2011), MERRA (Rienecker *et al.*, 2011)). On the other hand, advances in computational capabilities and data storage have exceeded petaflop and petabyte capabilities, making it possible to model large domains at very high resolution. At the same time, new solvers and simulation platforms are being developed that take advantage of these new computational possibilities and can efficiently handle very large problems. The earth system modelling and climate modelling community will certainly grasp the opportunity. It is imperative that hydrologists are central to this effort in order to safeguard the sound incorporation of hydrologic principles at hyper-resolutions.

Society

Most developed countries have dedicated hydrological models to support water resources management and planning under conditions of environmental change, or for operational forecasting and early warning. However, in many developing countries, such models are not yet available or are poorly constrained because of the lack of local data. For these developing countries, access to information about water resources that is timely and locally relevant can be a great asset (GEOSS, 2009). The issue here is an ethical argument on the equity of information (Lievrouw and Farb, 2003). One could discuss whether detailed information on water resources status is really of use to local water managers, or the local population in general, given that one needs to be a specialist to be able to interpret these data and because it arises from technological push rather than stakeholder pull. However, we believe that adoption of new technology is always likely to be slow unless it is made freely available and presented in the right manner. Similarly, the potential future applications of new technology are often unpredictable ,and as a result, the development of new capabilities to model the global water cycle may produce additional, currently unrecognized benefits. In any case, river basin managers often consider 1–5 km resolution models more useful than 0.5° models. Obviously, how and in what form to make this information available needs further thought.

Obstacles and Challenges

The goal to provide locally relevant hydrological information globally is far from trivial and poses a series of significant challenges (see also Wood *et al.*, 2011). To name a few:

Scale separation and scale-related breakdown of concepts and assumptions

When moving from the common resolution of 0.5° (order of 50 km at the equator) down to 1 km and smaller, many concepts that have been designed to resolve small-scale processes at the sub-grid scale break down. One could even talk about the ‘loss of the sub-grid paradigm’. First, simple cell fractionation has to be replaced by explicit dynamics. For instance, surface runoff at 0.5° can be conceptualized as the fraction of saturated soil assuming a univariate spatial frequency distribution of sub-grid surface elevation or associated with a distribution of soil storage within a cell (Moore, 1985; Blyth *et al.*, 2004). However, when moving to higher resolutions, the explicit spatial juxtaposing of saturated soils with time has to be accounted for, e.g. by using concepts related to the topographic index (Beven and Freer, 2001). Second, very much related to the reasons above, is the breaking up of connections between compartments of the hydrological system. In 0.5° models, water stress assessments are based on the assumption that water demand is satisfied by available surface water and groundwater within the same grid cell. This assumption works well because most regional water redistribution works fit within a 50 × 50 km area around the location where water is consumed. However, at resolutions of 10 km and finer, inter-cell redistribution of water from abstraction points to hotspots of water consumption, or from lateral groundwater flow, need to be taken into account (Krakauer *et al.*, 2014). Third, assumptions about dominant physics break down. For example, consider the way we model heat and water fluxes between the land and atmosphere. It is generally assumed that sensible and latent heat fluxes are proportional to the vertical gradient of potential temperature and specific humidity. This only holds true if vertical gradients are much larger than horizontal gradients (Holtslag and Ek, 2008), for example, when using average fluxes over large horizontal domains. However, for spatial resolutions approaching 100 m and below, horizontal advection becomes important, and new theories to correctly model land-atmosphere heat and moisture exchange are needed. Finally, and this is indeed a great challenge, in an ideal world we would have sub-grid concepts and parameterizations that change consistently with scale as described in, e.g. Blöschl and Sivapalan (1995) and Bierkens *et al.* (2000).

Lack of information and epistemic uncertainty

In a comment on the paper of Wood *et al.* (2011), Beven and Cloke (2012) rightly point out that moving to higher resolutions will pose huge challenge as epistemic uncertainties will become very large because of lack of process and parameter knowledge at such high resolutions. Indeed, there is much we do not know about the global land surface properties at these resolutions that need to be added. For instance, relating local water demand and water abstraction at high resolution requires knowledge of local water redistribution systems that is not available globally. Although the number of high-resolution datasets on topography, land use, geology, soil properties and others, is increasing, these data are also the products of remote sensing, land surface models, statistical downscaling techniques or combinations thereof and thus full of inaccuracies. Finally, several studies (e.g. Döll and Fiedler, 2008; Biemans *et al.*, 2009) have shown that precipitation that is used to force global hydrological models contributes to a large part of the uncertainty in model output. High-resolution meteorological datasets of sufficient accuracy are thus greatly needed. This does not mean that current lack of information and related uncertainty should deter us from attempting hyper-resolution modelling. First, the number and quality of high-resolution datasets are increasing, and they are expected to increase even further as new missions with better sensors are launched. Second, our globalized digital world makes local datasets universally accessible, enabling better ground-truthing of these datasets. Third, because many of the envisioned hyper-resolution models will have global coverage, multi-model predictions of parameters and variables are available for all locations in the world. A comparison of multiple model results and their fit to observations will reveal pathways for improvement of both process description and their parameterizations. Moreover, multi-model ensemble simulations would provide an approximation of predictive uncertainty, arising from both model structure and forcing datasets.

Computational challenges

Obviously, hyper-resolution global modelling results in large computational demands in terms of CPU time and storage requirements (Kollet *et al.*, 2010; Maxwell, 2013). Just increasing the spatial resolution by a factor of 10 increases calculation and storage requirements by a factor of 100. Moreover, as stated before, when increasing resolution, many processes that use simple sub-grid parameterizations may need to be replaced by explicit process dynamics further increasing computational efforts. Finally, running hyper resolution models real-time in an operational setting, and incorporating incoming observations using data-assimilation schemes, will further increase the computational demand. Fortunately rapid developments in both hardware and software architecture support these increased computational challenges. Powerful PCs with multi-core and multi-thread CPUs or small linux clusters are commonplace with many hydrology groups. Fibre-optic cable networks are present on many universities as well as large quantities of idle desktops making grid computing a possibility. Moreover, massively parallel computing facilities involving many hundreds of thousands of cores can be found in the larger research centres, with the largest having >10 petaflop performance and expecting to reach exaflop ability in 2020. This tremendous computational power can only be exploited if the computations behind a model can be performed in parallel. Here, domain decomposition methods can be used (e.g. using a hierarchical structure based on continents, basins, catchments, sub-catchments, etc.). If the code can be adequately restructured, parallel processing software such as Open MPI allows information to travel between different computers (nodes) and OpenMP to allow further breakup of operations to different cores (processors). Alternatively, smart robust numerical methods need to be developed that solve the equations relying on only a limited number of cores. Note, however, that efficient numerical methods are also needed in the case of massive parallel computing if one requires a good scaling to a large numbers of cores.[1]

The Hyperhydro Network (www.hyperhydro.org)

The HyperHydro network is open to the broader scientific community for anyone who wants to cooperate in activities furthering the development of hyper-resolution models. The governance structure is quite informal, with a post box and a website hosted at Utrecht University and three working groups (WG) loosely organized around the sets of challenges laid out above. These groups are:

WG1 Test beds

The objective of this working group is to set up a test bed for comparing different large-scale models at different resolutions. Data-sets will be provided for different domains resolutions: Global at 5 min; CONUS and CORDEX Europe at 1 km; the Rhine-Meuse, Illinois and California at 100 m. Starting with the smallest domains, the WG will run a collection of different models on the same datasets (forcing, soil,

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[1] In parallel computing, 'good scaling' means that the computation times keep decreasing significantly when more processors are used.

geology, etc., output data) for decreasing resolution. This enables the assessment of model uncertainty (by model inter comparison) and model bias (by model-data comparison) but also the effects of resolution on model uncertainty and bias. The WG will set up the data and simulation protocols for participating groups to perform their analyses. The ultimate goal is to improve model conceptualizations and parameterizations and make these robust under change of model resolution.

WG2 Common framework

Members of this group together work on computational challenges, including parallel computing and model component coupling. This will take the form of collecting information on and developing tools for solving computational issues (e.g. parallelization), developing a common framework for coupling modules based on existing couplers and standards and setting up a common platform for generating comparison statistics (as related to the work by WG1).

WG3 Parameter and concepts

The goal of WG3 is to develop concepts and possible solutions on how to deliver the information needed to achieve hyper-resolution (<1 km) globally. Their work will consist of compiling an overview of useful high-resolution global datasets that can be used in parameterizing global hyper-resolution models, creating new high-resolution datasets using auxiliary information, devising new model concepts to replace sub-grid parameterizations with computationally frugal, spatially explicit physics and to create new hyper-resolution global forcing data of sufficient accuracy.

HyperHydro will set up regular meetings at international conferences and symposia to discuss progress and set targets. Working group leads will be responsible for its impetus and progress, and we expect that results of working group activities will be reported through peer-reviewed publications. We invite all those who are interested to look on the website www.hyperhydro.org for current activities and past results and urge those who want to be on the mailing list or actively participate in one of the working groups to send an email to the lead author.

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ERA-Interim daily meteorological forcing from ECMRWF re-analysis. http://data-portal.ecmwf.int/data/d/interim_daily/

EWA-Friend European catchment data. http://www.bafg.de/GRDC/EN/04_spcldtbss/42_EWA/ewa_node.html

FLUXNET: Water vapour, energy and CO_2 land-atmosphere fluxes from towers. http://fluxnet.ornl.gov/obtain-data

GLCC land cover data. http://landcover.usgs.gov/landcoverdata.php

GRDC global runoff data. http://www.bafg.de/GRDC/EN/Home/homepage_node.html

ISMN global network of soil moisture data. https://ismn.geo.tuwien.ac.at/ismn/

MERRA daily meteorological forcing from the NASA Goddard Earth Observing System Data Assimilation System Version 5. http://gmao.gsfc.nasa.gov/research/merra/

MOPEX US catchment data. ftp://hydrology.nws.noaa.gov/pub/gcip/mopex/US_Data/