Added Value and the Future of Regional Downscaling

Added Value of Downscaling

- *Does the application of downscaling to GCM output increase the value of these predictions/projections?*
- Added value may have different meanings for researchers and end users.
- From the perspective of climate scientists, added value is simply the idea that performing downscaling
  - produces more accurate predictions when evaluated against observations;
  - introduces new information to a downscaled variable that is not resolved in a GCM or resolves a phenomenon not well represented in a GCM.
- From the perspective of users, added value may lie in the customization, translation, and/or localization of information.
  - Downscaling at a high-resolution grid or individual weather stations may help a city or a region with spatial diversity better estimate the predicted/projected impacts.
  - Downscaling of daily/sub-daily precipitation helps a hydraulic engineer incorporate climate projections into the design and construction of key infrastructure.

Different aspects of added value

- Different aspects of added value
  - Precision, Accuracy and Uncertainty
- Precision is not equivalent to accuracy. Increased accuracy means added value, but higher precision does not always lead to added value.
  - For example, higher-resolution temporal information can be obtained from simple interpolation, but the information would only be accurate at the same temporal scale as the original data and may not provide added value for some applications.
- Increasing uncertainty may still represent added value.
  - For example, RCM may reveal new uncertainty as some physical processes are better resolved. A risk envelope wider than previously thought is important information for decision makers to take into account.

Added Value: Dynamical vs. Statistical Downscaling

- Dynamical Downscaling:
  - The added value in dynamical downscaling is typically associated with finer scale phenomena and conditions where higher-resolution forcing comes into play.
- Statistical Downscaling
  - Evaluating the performance of statistical downscaling using an independent validation dataset is a common approach. A good model should be able to replicate observed climate conditions in the independent validation period.
  - The perfect model approach: Dixon et al. (2016) used high-resolution (25 km) GCM output as “observations” for both past and future periods and coarsened (200 km) versions of the same fields as “models.” They defined “added value” as occurring if the mean absolute error of the downscaled output is less than the mean absolute error of the coarse-resolution “models” when evaluated against the high-resolution “observations”.
- Added value can vary by location, variable, and the time of year.
  - For example, a simple mean/variance bias correction method may provide added value for temperature prediction but not for precipitation prediction.

Future Directions for Regional Climate Prediction

- Statistical downscaling:
  - increasing availability of long-term, high-resolution observations that can be used to train/validate a statistical model
  - more advanced statistical methods, including ML
  - downscaling within probabilistic frameworks to better represent natural variability.
  - better transition of uncertainties into practical guidance about risk assessment and decision making
- Regional modeling:
  - Higher model resolution
  - Regional Earth System Models (RESMs) are in development to include more interactive components (as shown in the figure)
- Global cloud resolving models

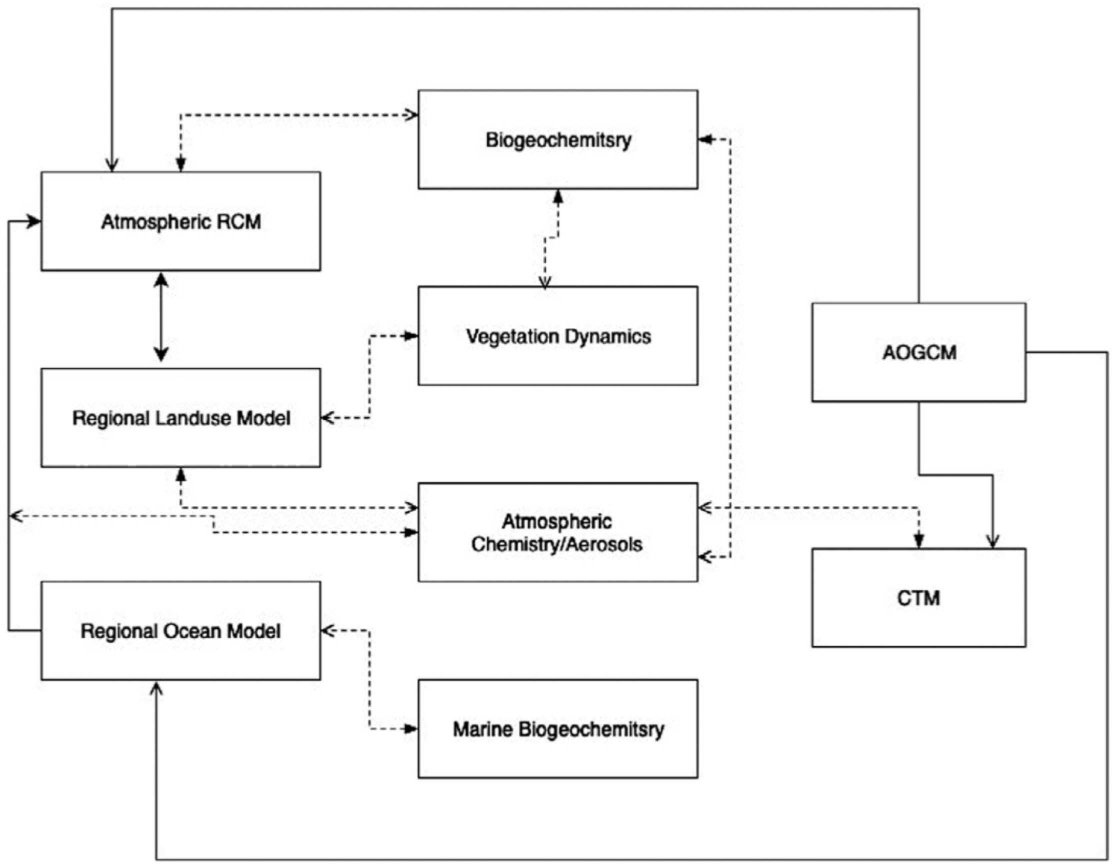
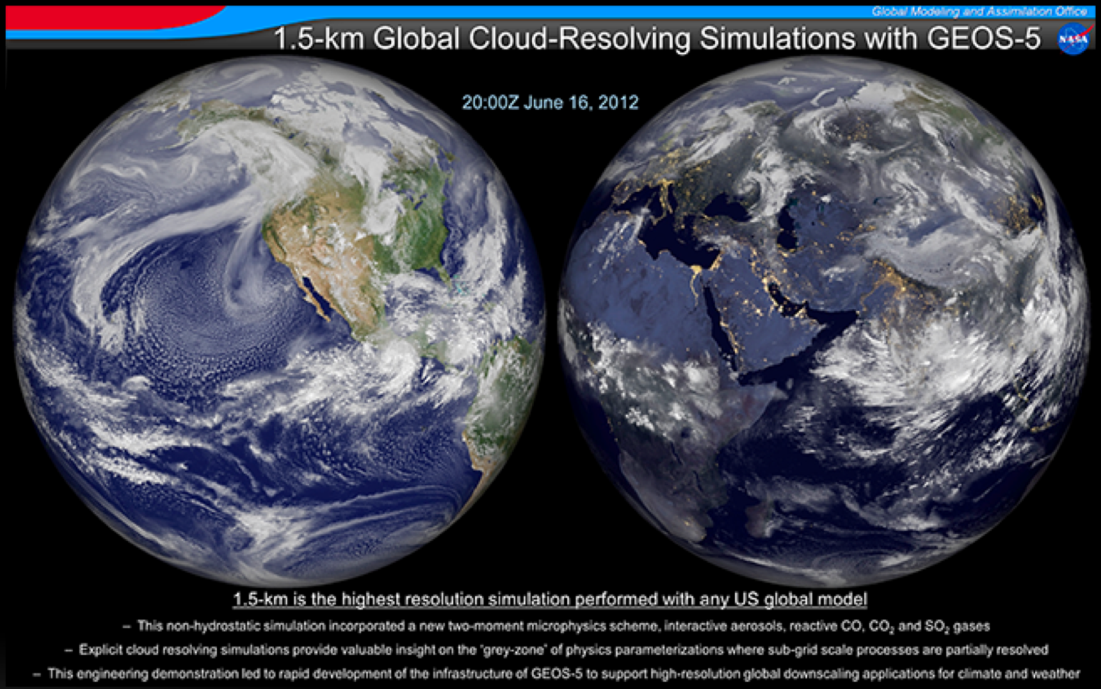


Figure 9.1 Depiction of a coupled RESM framework and the interactions across its different components and global climate model drivers (CTM: chemical transport model). Arrows indicate the flow of information. Solid line: interaction with driving global models; broken lines: interaction inside the RESM.
Source: Based on Giorgi and Gao (2018)

From Kotamarthi et al. 2021

Global Cloud-Resolving Models

- Global cloud-resolving models (GCRMs) are a new category of atmospheric global models that solve the nonhydrostatic equations on kilometer-scale global meshes without using cumulus parameterization.
- GCRMs are also known as cloud system-resolving models, global storm-resolving models, and convection-permitting models
- The first GCRM was constructed in 2004. Some believe that GCRMs will become a mainstream tool for climate research with exascale computing.
  - *"Exascale computing refers to computing systems capable of at least one exaflop or a billion billion calculations per second (10^{18}). That is 50 times faster than the most powerful supercomputers being used today and represents a thousand-fold increase over the first petascale computer that came into operation in 2008."* (https://www.lanl.gov/projects/exascale-computing-project)



https://gmao.gsfc.nasa.gov/research/science_snapshots/1.5km_cloud_simulation.php

GCRMs in an Intercomparison Project

Table 2 Configuration of GCRMs used in DYAMOND

	Grid	Time integration scheme	dx [km]	Lev	Top [km]	References
NICAM	ICO, A-grid [2]	Fully compressible, split-explicit, vertically implicit	3.5	78	50	[3, 4]
ICON	ICO [5]	Fully compressible, split-explicit, vertically implicit	2.5	90	75	[6]
MPAS	Voronoi, C-grid [7]	Fully compressible, split-explicit, vertically implicit	3.8	75	40	[7, 8]
FV3	Cube, C-D staggering for optimal PV advection [9]	Fully compressible, forward-in-time finite-volume scheme, vertically Lagrangian	3.3	79	39	[10, 11]
GEOS-5	Same as FV3	Same as FV3	3.3	132	80	[9, 12]
SAM	Lat-Lon, C-grid [13]	Anelastic	4.3	74	37	[41]
IFS-ST	Octo, spectral [14]	Semi-implicit semi-Lagrangian	4.8	137	80	[14, 15]

ICO icosahedral grid, *Voronoi* Voronoi tessellation, *Cube* cubed sphere, *Lat-Lon* latitude-longitude grids, *Octo* cubic octahedral reduced grid, *dx* the horizontal grid size is defined by a square of the largest area of a grid cell, *Lev* number of vertical levels, *Top* model top

- the Nonhydrostatic Icosahedral Atmospheric Model (NICAM) in Japan,
- ICOsahedral Nonhydrostatic (ICON) in Germany,
- the Model for Prediction Across Scales (MPAS) in the USA,
- Finite-Volume Dynamical Core on the Cubed Sphere (FV3) in the USA
- the Goddard Earth Observing System Model, Version 5 (GEOS-5) in the USA
- the Integrated Forecast System (IFS) by the European Centre for Medium-Range Weather Forecasts (ECMWF)

Advantages of GCRMs

- Representation of the global mesoscale:
  - Organized convection or mesoscale storms can be better represented.
- Multiscale interaction of convection:
  - GCRMs simulate the multiscale structure of convective systems from individual deep convection, cloud clusters, and large-scale organized convective systems.
- Turbulence and gravity waves:
  - Kilometer-scale disturbances, such as topographic effects and ensuing wave excitation, and their effects on larger-scale circulations are captured globally.
- Nature runs as a source of empiricism
  - Nature runs with GCRMs function as natural laboratories for developing and testing algorithms in three-dimensional and time continuous space—something that is not always possible with observations

A nature run is a free-running numerical model simulation with minimal knowledge of any realistic atmospheric state but with a realistic climatology consisting of realistic weather patterns (McCarty et al. 2012)

Challenges related to GCRM

- Expensive to run a GCRM and to store and process the output.
- *Do we still need to be concerned about uncertainties related to model physics?*
  - Many physical processes (such as microphysics and boundary eddies) still need to be parameterized in GCRMs.
  - No consensus has emerged as to the resolution at which a model can be considered cloud-resolving.
- *Do GCRMs resolve all clouds?*
  - Clouds in the real atmosphere exist with different size, phase and structure.
  - GCRMs resolve the statistics of clouds or mesoscale dynamics of precipitating storm systems instead of the evolution of individual clouds (i.e., cloud system-resolving models, global storm-resolving models, and convection-permitting models).
- Coupling with ocean and land
- Ensemble size vs. model resolution?
  - It may depend on the phenomenon of interest (e.g., the NAO vs. tropical cyclones)
- *Will regional climate models become obsolete?*

References

- Satoh, M., Stevens, B., Judt, F. *et al.* Global Cloud-Resolving Models. *Curr Clim Change Rep* **5,** 172–184 (2019). https://doi.org/10.1007/s40641-019-00131-0
- Kotamarthi, R., Hayhoe, K., Mearns, L., Wuebbles, D., Jacobs, J., & Jurado, J. (2021). Downscaling Techniques for High-Resolution Climate Projections: From Global Change to Local Impacts. Cambridge: Cambridge University Press. doi:10.1017/9781108601269. Chapters 6 and 9.