THE FUTURE OF PLANETARY CLIMATE MODELING AND WEATHER PREDICTION. A. D. Del Genio[1], S. D. Domagal-Goldman[2], N. Y. Kiang[1], R. K. Kopparapu[2], G. A. Schmidt[1], L. E. Sohl[3], [1]NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025 (anthony.d.delgenio@nasa.gov), [2]NASA Goddard Space Flight Center, Greenbelt, MD 20771, [3]Columbia University, New York, NY 10027.

Introduction: Modeling of planetary climate and weather has followed the development of tools for studying Earth, with lags of a few years. Early Earth climate studies were performed with 1-dimensional radiative-convective models, which were soon followed by similar models for the climates of Mars and Venus and eventually by similar models for exoplanets. 3-dimensional general circulation models (GCMs) became common in Earth science soon after and within several years were applied to the meteorology of Mars, but it was several decades before a GCM was used to simulate extrasolar planets. Recent trends in Earth weather and and climate modeling serve as a useful guide to how modeling of Solar System and exoplanet weather and climate will evolve in the coming decade.

The Next Decade: GCMs are now central to studies of the dynamics and climate of Mars, Venus, Titan, and jovian planet atmospheres. Most of these use atmosphere-only GCMs (AGCMs). For the ancient climates of Solar System terrestrial planets and exoplanets, though, many first-order science questions involve the potential for habitability and thus require GCMs that take surface liquid water into account, usually by coupling the AGCM to an ocean model.

Many previous studies assume a simple, computationally efficient thermodynamic ocean mixed layer whose temperature is determined by surface radiative and turbulent energy exchanges with the overlying atmosphere ([1], [2]). However ocean heat transport is important for planetary habitability and is not fully compensated by atmospheric transport when sea ice is present. Thus, planetary GCMs that couple atmosphere and dynamic ocean models (AOGCMs) have begun to appear ([3], [4]). We expect such models to proliferate in the next decade. This will require increased computational resources, since AOGCMs often take centuries rather than decades of simulated time to equilibrate, depending on the depth of ocean assumed. It will also require fundamental research into the spatial scale of ocean eddies, whose mixing effects are unresolved and thus parameterized for the rapidly rotating Earth but may be resolved for slowly rotating planets. Likewise, many planetary GCM studies have used simplified representations of moist convection that do not account for advances in understanding that are now being implemented in Earth GCMs, nor do they account for subgrid fractional cloud cover that is the primary contributor to cloud feedback in simulations of 21st Century climate change [5].

Over the past two decades, Earth science has increasingly synthesized more diverse Earth system processes into coupled AOGCMs to produce more complex “Earth System Models” (ESMs) that simulate not only the standard climate variables, but also their interaction with atmospheric (and possibly ocean) chemistry and aerosols, with dynamic land ice, and with land and ocean ecosystems. ESMs are much more computationally intensive than climate-only models, but the ability to predict rather than arbitrarily specify atmospheric composition is central to a fundamental understanding of planetary climate and habitability, as demonstrated by 1-D planetary model studies ([6], [7], [8]). We expect 3-D planetary GCMs to increasingly include interactive chemistry going forward. One such model already exists [9]. There has also been one exoplanet GCM study that utilized dynamic land ice [3].

As computational power increases, ESM groups are confronted with the question of how to partition computing resources among finer model resolution, more complex parameterizations, more ESM components, the ability to simulate longer time intervals, and the ability to conduct a larger number of simulations. Similar choices will confront the planetary modeling community in the coming decade. From the parameterization standpoint, three major questions loom:

(1) How accurately must radiative transfer be parameterized? For climates similar to modern Earth’s, efficient parameterizations that treat atmospheric absorption and the stellar spectrum within a limited number of spectral intervals with acceptable accuracy are available. These parameterizations degrade, however, when applied to climates much warmer than Earth’s and to stars much cooler than the Sun [10]. Even the line-by-line models that are the standard for evaluating the accuracy of a radiative transfer model disagree with each other in treatments of poorly understood features such as the water vapor continuum. For more exotic planets such as hot Jupiters, and even for some features of Solar System atmospheres, laboratory work is needed to more accurately define absorption coefficients of gases not found on Earth or for which the properties have not been measured over an adequate range of temperatures and pressures [11].

(2) Earth GCMs have sophisticated treatments of chemistry for modern Earth’s oxidizing atmosphere.

For more reducing environments (Archean Earth, Titan, large planets with H_2 envelopes), choices must be made about things such as the number of hydrocarbon species and reactions that are accounted for. Chemistry modules that take into account a full range of redox states will need to be developed in the future. Likewise, there is a need for laboratory work to provide a greater understanding of the variety of organic aerosols that can form and their radiative properties [12].

(3) What impacts of life on climate and atmospheric chemistry can be explored with confidence with relevance to the search for life on other planets? While GCMs simulate fairly well the impact of ecosystems on surface albedo and conductance, biogeochemical interactions such as the carbon and nitrogen cycles are crudely captured due to limited understanding of how the diversity of life varies in these processes adapted to different environmental niches. Progress in identifying conserved relations between critical biophysical parameters [13] will advance GCM-coupled ecosystem models, whiel discoveries of wider biological diversity (metagenomics [14], biogenic gases [15]) will offer exotic possibilities for exoplanet models.

Looking further ahead: It is now possible for an Earth AGCM to be run at resolutions approaching the scales of individual clouds [16], producing dramatic visual portrayals of weather systems (Fig. 1) for limited periods of time. In 30 years, such "global cloud resolving models" might be run routinely for other planets, the advantage being that such models reduce the number of processes that must be parameterized.

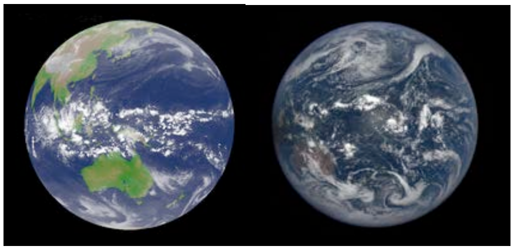

Fig. 1. Which is the satellite image and which is the model? A snapshot of Earth's weather from the NICAM 870 m grid mesh GCM (left) vs. a DSCOVR satellite image of Earth (right).

Uncertainty in GCM parameterizations can be addressed by performing large "perturbed parameter" ensembles (PPEs) of simulations with various combinations of choices of uncertain parameters [17]. One might use the PPE approach to vary external planet parameters over the wide range of conditions that may exist on exoplanets to produce a library of reference simulations for interpreting transmission or direct imaging spectra from future missions. A future challenge is to couple such models to heliospheric magnetohydrodynamics models to capture atmospheric escape processes and their feedback on chemistry and climate.

Weather forecasting on Earth has been revolutionized by data assimilation techniques that incorporate many *in situ* and satellite observations to produce accurate forecasts, as well as global long-term climatologies of atmospheric circulation and thermodynamic structure known as reanalyses. Data assimilation is already performed for Mars GCMs using e.g. TES satellite data [18]. For Earth, even with nothing more than the assimilation of surface pressure from weather stations, it is possible to usefully simulate documented weather events back to the 19th Century with a few hundred such surface meteorology stations [19]. Might Mars be monitored by a similar network of weather stations spanning the planet in 30 years, producing short-term forecasts for visitors or colonists?

Finally, there is a great need for other planets to be observed using new approaches to remote sensing that have been applied to Earth (and vice-versa – techniques such as polarimetry and altimetry were first used to study other planets). Passive microwave remote sensing is now the standard for measuring water vapor on Earth. This is being attempted for the first time on another planet by Juno. For clouds, precipitation, and aerosols, the gold standard is active remote sensing (lidar and radar), which together provide the most sensitive detections and most accurate vertical locations of particulates. Might scanning lidars and radars routinely monitor other planets in 30 years?

References: [1] Shields A. L., et al. (2013) *AsBio, 13,* 715-739. [2] Turbet M., et al. (2016) *arXiv* 1608.06827. [3] Hu Y. and Yang J. (2014) *PNAS, 111,* 629-634. [4] Way, M. J., et al. (2016) *GRL, 43,* 8376-8383. [5] Zelinka M. D., et al. (2016) *GRL, 43,* doi:10.1002/2016GL069917. [6] Domagal-Goldman S. D., et al. (2008), *EPSL, 269,* 29-40. [7] Hu, R., et al. (2012), *ApJ, 761*, 166. [8] Meadows V. S., et al. (2016) *arXiv* 1608.08620. [9] Lefevre F., et al. (2008) *Nature, 454,* 971-975. [10] Yang J., et al. (2016) *Ap.J., 826,* 222. [11] Fortney J J., et al. (2016) *arXiv,* 1602.06305. [12] Trainer M. G., et al. (2012) *AsBio, 12,* 315-326. [13] Osnas J. L. D., et al. (2013) *Science, 340,* 741-744. [14] Garza D. R. and Dutilh B. E. (2015) *Cell. Mol. Life Sci, 72,* 4287-4308. [15] Seager S., et al. (2016) *AsBio, 16,* 465-485. [16] Satoh M., et al. (2014) *Prog. Earth Plan. Sci., 1,* 18. [17] Stainforth D. A., et al. (2005) *Nature, 433,* 403-406. [18] Montabone L., et al. (2011) doi:10.5285/78114093-E2BD-4601-8AE5-3551E62AEF2B. [19] Compo G. P., et al. (2011) *QJRMS, 137*, 1-28.