ANTHONY DEL GENIO: CLIMATES OF PLANETS NEAR AND FAR

Anthony D. Del Genio
NASA Goddard Institute for Space Studies
New York, NY 10025
Email: anthony.d.delgenio@nasa.gov
ORCID : 0000-0001-7450-1359

Submitted to *Perspectives of Earth and Space Scientists*
June 6, 2019

Plain language summary: This essay describes a career that has spanned one of the most momentous periods in science history, a time when humankind first ventured into space, visited every planet in the Solar System, discovered thousands of planets orbiting other stars, and during this whole time, began to unintentionally transform the climate of our own planet. The author had the opportunity to do research in all these areas – after failing an early graduate school exam – and grew as a scientist along the way as the direct result of working across disciplines, with the help of many colleagues whose talents complemented and often exceeded his own.

Key points:

- The path of a scientific career can be serendipitous – and that's a good thing.
- Science today is mostly a team effort rather than a sole pursuit.
- Cross-discipline thinking is beneficial to a rewarding scientific career.

1 A “Rocky” Beginning

This should have been an essay about the career of a planetary geophysicist. As an undergraduate engineering student in the early 1970s looking to switch fields, my Cornell advisor, AGU Fellow Joe Burns, served as an example of how my education could lead to a career in planetary sciences. This was an exciting time in the history of science, not long after the first NASA missions to Venus and Mars. Joe helped me put together a course plan that would position me well for graduate school in this field. AGU Fellow Joe Veverka mentored me in an independent study counting craters in early Mariner Mars images that were showing the face of another planet to us in detail for the first time.

I arrived at UCLA for graduate school in 1973 to work with geophysicist and AGU Fellow Jerry Schubert, fascinated by what was being learned about the dynamic interiors of Earth and other planets. My career path seemed set. Then at the end of my first year, I took the department-wide comprehensive exam. I was confident about the geophysics section of the exam – I knew my mantle convection, sea floor spreading, magnetic field reversals, gravity field harmonics. Unfortunately that year the geophysics exam was all seismology, written by AGU Fellow Leon Knopoff. The angry red slashes through most of what I wrote told a different story about my understanding of geophysics. I had done well in the planetary atmospheres and geophysical fluid dynamics sections of the exams, though, and Jerry gently suggested (managing to hold back laughter) that I might want to consider pursuing research in those areas instead.

Mariner 10 had just flown by Venus the previous November, sending back the first detailed images of another planet’s atmosphere. Jerry had just begun a collaboration with astronomer Mike Belton to analyze the mysterious dark ultraviolet (UV) features in those images. Together they guided me through my first trip through the terror of the peer review process, leading to my first paper (*Belton et al*., 1976), which suggested that the major UV features on Venus were produced by a planetary-scale Kelvin wave. This began my career as a planetary atmospheric scientist.

In the course of that research, I realized that I needed to know much more about atmospheric dynamics than is covered by planetary science courses. UCLA has a world-class atmospheric science department, and I was able to take courses from several giants of the field, Akio Arakawa and Michio Yanai, and to meet atmospheric science grad students such as future AGU Fellow David Randall. At this time cumulus parameterization in 3-D atmospheric general circulation models (GCMs) was just beginning to receive serious attention. I'd like to say that I recognized my great fortune in being able to interact with and learn from these people who were so instrumental in advancing our understanding of moist convection, but in truth I was clueless at the time about the significance of what they were doing. I did however get my first taste of terrestrial meteorology and used it to write my Ph. D. dissertation on how the compositional stratification of the thermosphere affects the characteristics of gravity waves, guided by Jerry Schubert and Joe M. Straus (e.g., *Del Genio et al.*, 1979).

2 An Eventful Summer

During my graduate school tenure, the NASA Goddard Institute for Space Studies (GISS) had been selected to put a photopolarimeter on the upcoming Pioneer Venus Orbiter mission. The Principal Investigator, AGU Fellow Jim Hansen, was seeking young scientists to eventually work on data analysis for the mission. I was still two years from my Ph.D., but Jerry put me in touch with Jim, who invited me to spend the summer of 1976 at GISS. This was a chance to learn from scientists who were at the forefront of using polarimetry to deduce the properties of particulates in planetary atmospheres, not only Jim, but also David Coffeen, Larry Travis, and Kiyoshi Kawabata.

At that time Jim had also begun applying his knowledge of radiative transfer to the problem of terrestrial anthropogenic climate change and was leading a project to develop a GCM specifically for use in projecting future climate warming. That summer Jim asked me if I had any interest in moist convection. With confidence (and naïveté), I replied that I had taken Arakawa's course and could certainly develop a good cumulus parameterization for the GISS GCM. Years later, at a conference on cumulus parameterization, I presented the ideas of my long-time collaborator and co-author Mao-Sung Yao and myself (*Del Genio and Yao*, 1993), describing a scheme intended to capture the essentials of moist convection efficiently enough to simulate long-term climate change. After my talk, an audience member stated that he didn't think we should even be running GCM climate change simulations until the cumulus parameterization problem was solved. My response was to ask how long that might take, and would the climate already have warmed by then?

I am still trying to develop a good cumulus parameterization, and the climate has indeed already warmed. But today I'd answer that comment by saying that any attempt we make to model the Earth system is merely an opening gambit. Earth responds by telling us (if we devote the resources to observe it) that we got some things right but there is still more work to do. This iterative process, which balances the hubris required for scientists to believe we can understand a system as complex as the Earth with the humility required to accept that we never have all the answers and the motivation to dig deeper, is essential to scientific progress. The good news is that over time our models, though imperfect, become increasingly useful tools (*Schmidt*, 2009). In fact, the past decade has seen impressive progress in cumulus parameterization (*Rio et al.*, 2019). The beauty of science, if we are patient, is that nature reveals its secrets little by little, slowly enough to keep us pressing forward for more, but fast enough for us not to despair.

As members of the GISS GCM development team, first led by Jim and later by AGU Fellow Gavin Schmidt, Yao and I have been able to add new pieces of the physics of convection to our parameterization over time (e.g., *Del Genio et al.*, 2015), as well as implementing the GCM's first version of a prognostic scheme for cloud water and ice (*Del Genio et al.*, 1996). As I prepare to depart the scene my colleagues Andy Ackerman, Ye Cheng, Greg Elsaesser, Ann Fridlind, and Max Kelley are now upgrading many aspects of the cloud, convection, and turbulence parameterizations in the GCM to produce an increasingly capable tool for exploring cloud and convection feedbacks, though more will always need to be done.

A NASA conference proceedings that illustrates the necessary tension between knowledge and its continual pursuit was given to me during that 1976 summer at GISS. The conference was held to discuss understanding of Venus' atmosphere post-Mariner 10 and pre-Pioneer Venus, and the proceedings captured the post-presentation Q&A. After planetary atmospheric dynamicist Peter Stone spoke about his theory for Venus' deep circulation, discussion ensued between the speaker and Al Seiff, Mike Belton, and Seymour Hess about Stone's prediction of a 0.1°C equator-pole temperature contrast (*Stone*, 1975):

DR. SEIFF: What happens if, on Pioneer Venus, we find temperature contrasts of the order of a few degrees?

DR. STONE: Why, I'd be disappointed.

DR. SEIFF: Disappointed?

DR. STONE: Yes, because obviously a different mechanism must be invoked to explain that.

DR. BELTON: Don't you think you would be excited?

DR. HESS: First, disappointed. Then excited.

DR. STONE: Yes. I am speaking as a theoretician here.

Temperature contrasts on Venus did turn out to be small, but not quite as small as Stone had predicted due to the near-cyclostrophic wind balance associated with Venus' superrotation at depth, which at that time had not yet been confirmed to exist. Pioneer Venus demonstrated that the superrotation – an atmosphere circulating 60 times as fast as the rotating solid surface beneath it - that had been inferred from ground-based observations of the movement of dark UV features across Venus' disk was real rather than an artifact caused by the phase speeds of propagating waves. Nonetheless, when I returned to GISS for good as a postdoc, frequent collaborator and AGU Fellow Bill Rossow and I showed that the Kelvin wave I had earlier proposed to explain the morphology of the UV markings did exist, with a small but detectable phase speed relative to the superrotation (*Del Genio and Rossow*, 1990).

3 Earth Remote Sensing, Climate Change, and Teaching

In retrospect, working on subjects such as cumulus parameterization, or anything having to do with clouds and their role in climate, in the 1970s was audacious given the paucity of data at that time. AGU Fellows Joanne Simpson, Ed Zipser, and Bob Houze had made fundamental inferences about deep convection from a few tropical field experiments (e.g., *Simpson and Wiggert,* 1969; *Zipser,* 1977; *Houze,* 1977), but little was known about its systematic global behavior, especially over ocean. Almost as little was known about clouds, except their correlation with the dominant features of the general circulation, until the first atlases of cloud types from surface observer records were published (*Hahn et al.*, 1982, 1984).

My Earth science career, though, began at the start of the golden age of Earth remote sensing. During my early years developing GCMs, it became obvious that not only moist convection, but clouds of all kinds were dominating the uncertainty in projections of future climate change (*Cess et al.*, 1990). The *Cess et al.* GCM intercomparisons were revealing of the psychology of the modeling community. Although they consisted of idealized experiments to estimate the spread in cloud feedbacks among GCMs, with no data component for validation, the modelers on the low and high ends of the feedback distribution nonetheless tended to present their results apologetically, as if they were incorrect because they didn't agree with the consensus. Half a decade later, when the experiment was repeated, the distribution had magically narrowed. This time a seasonal component that could be validated by the ERBE satellite radiation budget dataset was included. A subset of the models (including ours) agreed well with the ERBE cloud forcing data…until they were separated into longwave and shortwave components, which disagreed markedly among the models. Cloud feedback would apparently not yield its secrets easily.

Luckily, starting in the 1980s, a number of remote sensing projects focused on convection and clouds came to fruition. Among those I have been involved in are the International Satellite Cloud Climatology Project (ISCCP), a gargantuan effort by Bill Rossow and co-workers to use the world's operational weather satellites to derive a long term climatology of cloud occurrence and optical properties (*Schiffer and Rossow*, 1983); the Tropical Rainfall Measuring Mission (TRMM), and its follow-on the Global Precipitation Measurement Mission (GPM), which have provided the first direct information about precipitation over the oceans and at high latitudes from space (*Simpson et al.*, 1988; *Hou et al.*, 2014); the Atmospheric Radiation Measurement (ARM) and Atmospheric System Research (ASR) Programs (*Stokes*, 2016), which pioneered the deployment of large suites of surface remote sensing instruments in virtually every important climate regime in the world; and the CloudSat cloud radar (*Stephens et al.*, 2002) and CALIPSO cloud-aerosol lidar (*Winker and Pelon*, 2003) A-Train missions, which have given us the first planet-wide view of the complete vertical structure of clouds.

These missions sculpted my understanding of convection and clouds. They also influenced my philosophy of how to use remote sensing data in the service of GCM evaluation and improvement. The most common use of global data by modelers is to find differences between the observed latitude-longitude climatology of some geophysical parameter and its simulation by the model. Awareness of these mean state biases is important, but they only tell us *that* the model is wrong, not *why* it is wrong. Unfortunately, mean state biases have been the basis of most metrics of GCM evaluation in formal intercomparisons. Not surprisingly, they have not been very useful in reducing the uncertainty in climate change projections (e.g., *Flato et al.*, 2013) because they do not isolate the physical processes that cause the climate to change.

In my research, I have strived to go beyond mean state biases to get a step closer to what is going on at the process level that might point me toward specific parameterization improvements, e.g., by mapping clouds into dynamical, radiative, or lifecycle composites of many events. This requires labor-intensive analysis of large datasets at the “Level 2” (orbit) stage and more detailed higher-frequency analyses of GCM outputs than is typical, which is why it is not done more often. It would not have been possible for me to usefully exploit these datasets without the many highly-skilled collaborators, postdocs, and graduate students I have worked with at GISS.

Examples of this include: Rong Fu and Bill Rossow on deep convective clouds and their interaction with sea surface temperature and convergence (*Fu et al.*, 1990, 1994); AGU Fellow Andy Lacis and Reto Ruedy on water vapor feedback (*Del Genio et al.*, 1991); Ron Miller on the natural variability of tropical climate (*Miller and Del Genio*, 1994); Aiguo Dai and AGU Fellow Inez Fung on long-term patterns of precipitation change (*Dai et al.*, 1997); Bing Ye and Ken Lo on climate changes in convective available potential energy (*Ye et al.*, 1998); George Tselioudis and Audrey Wolf on low cloud optical thickness feedbacks (*Tselioudis et al.*, 1998; *Del Genio and*

Wolf, 2000); Samantha Smith on the internal structure of cirrus clouds (*Smith and Del Genio*, 2002); Bill Kovari and Jeff Jonas on mesoscale convective systems and detrainment-precipitation partitioning (*Del Genio and Kovari*, 2002; *Del Genio et al.*, 2005); Surabi Menon and Dorothy Koch on aerosol indirect and semi-direct effects (*Menon et al.*, 2002; *Koch and Del Genio*, 2010); Jonathan Chen and Barbara Carlson on tropical overturning and decadal variability (*Chen et al.*, 2002, 2008); Mike Jensen on mid-troposphere humidity and the depth of congestus clouds (*Jensen and Del Genio*, 2006); Mike Bauer on the identification and tracking of extratropical cyclones (*Bauer and Del Genio*, 2006); Catherine Naud and Jimmy Booth on the clouds in extratropical cyclones (*Naud et al.*, 2010; *Booth et al.*, 2013); Joanna Futyan on the lifecycles of tropical convective storms and the lightning they produce (*Futyan and Del Genio*, 2007a,b); Jingbo Wu on updrafts and entrainment in the transition from shallow to deep convection (*Wu et al.*, 2009; *Del Genio and Wu*, 2010); Yonghua Chen on the lifecycle of convective clouds and radiative heating in the Madden-Julian Oscillation (MJO; *Chen and Del Genio*, 2009; *Del Genio and Chen*, 2015); Kirstie Stramler on the bimodal “radiatively clear” and “opaquely cloudy” behavior of Arctic clouds (*Stramler et al.*, 2011); Aga Mrowiec on updrafts and downdrafts in mesoscale convective systems (*Mrowiec et al.*, 2012); Greg Elsaesser on the parameterization of convective ice particle size distributions and fall speeds (*Elsaesser et al.*, 2017), as well as in-progress work on the onset and lifecycle of organized convection; and Greg Cesana on discriminating cumulus from stratocumulus clouds in satellite data and constraining their cloud feedbacks (*Cesana et al.*, 2019a,b). I have also had fruitful collaborations with Columbia colleagues, most notably Daehyun Kim and Adam Sobel, to understand the physics required to allow the GCM to simulate the MJO (*Del Genio et al.*, 2012, 2015; *Kim et al.*, 2012).

During the 1976 summer I spent at GISS, anthropogenic climate warming was not on the minds of many people, but once the basic radiative transfer physics had shown that increasing CO_2 was a major concern in work by Hansen, Lacis and others, it seemed only a matter of time before the warming became obvious. On June 23, 1988, months before my first paper on cumulus parameterization was published, Jim Hansen testified before Congress that anthropogenic warming had already been detected. Jim, my GISS colleague and AGU Fellow David Rind, and I had attended a NASA meeting in Washington, DC that day at which modest new funding for climate change research was being discussed, and Jim sent David (*Nightline*) and me (*The MacNeil-Lehrer Report*) to discuss the evidence for anthropogenic climate change on national TV. The initial interview went well enough, but I was unprepared for the meteorologist interviewed next who (incorrectly) dismissed Hansen's findings as natural meteorological variability that said nothing about the existence of any climate change. Almost four decades after Hansen and colleagues made their first prediction of the rate of CO_2-induced climate warming (*Hansen et al.*, 1981), their projection has turned out to be impressively accurate. How often can that be said about any prediction of the future in any walk of life? Under our current director, Gavin Schmidt, GISS has continued to be active in communicating to the public about climate change.

During the 1980s, I became involved with Columbia University, teaching an introductory graduate level survey course in atmospheric science and later advising graduate students. There is nothing that makes one's tenuous grasp of scientific first principles more obvious than having to create a set of coherent lectures and then fielding the daily questions of students who see you as the expert when in some areas you are barely a step ahead of them. This was especially true of the radiative transfer section of my course, for which I periodically had to consult Larry Travis and Andy Lacis to explain things to me first. I highly recommend teaching for that reason, but also because it is an opportunity to meet nascent scientists who often become major contributors to their fields. The only downside is that the election of former students who passed through my course as AGU Fellows is a stark reminder of my advancing age.

4 Back to Planetary Science

My Columbia teaching made me begin to think about science in a more unified fashion – for example, that thunderstorms, North Atlantic Deep Water formation, and mantle convection were merely different manifestations of the same phenomenon in different fluids. It also forced me for the first time to confront the fact that I now had two separate careers, one as a planetary scientist and the other as an Earth climate scientist. In my lectures and homework assignments, I found myself trying to illustrate the same concepts with examples from both fields.

At some point this began to influence my thinking about my own research. I realized that (with help from colleagues Bob Suozzo, Wei Zhou, and Tim Eichler), the GISS GCM could be adapted to ask general questions about the dynamics of planetary atmospheres. We showed how the dynamical regime changes as the size of baroclinic eddies approaches the size of the planet, and we demonstrated the conditions required to maintain superrotation on a slowly rotating planet (*Del Genio and Suozzo,* 1987; *Del Genio et al.*, 1993). Using our cumulus parameterization as a 1-D climate model, we showed that Jupiter's dry (in H_2O) atmosphere at the visible cloud level was consistent with "supersolar" water vapor at depth, and that water convection in a low molecular weight H_2-He atmosphere would experience buoyancy effects more like those created by salinity in Earth's oceans than by water vapor in Earth's atmosphere (*Del Genio and McGrattan*, 1990). My GISS colleague Mike Allison and I distilled our own and earlier ideas into a 2-D dynamical regime classification (*Allison et al.*, 1995) that grouped planets by the effect of rotation and the relative horizontal and vertical contrasts of temperature on their dynamics. Sadly, we only had half a dozen planets to work with…or so I thought at the time.

Nonetheless, as my involvement in Earth climate research and satellite/surface remote sensing missions increased and Pioneer Venus drew to a close, my planetary science career seemed to be ending. Then I was selected to the imaging team for the Cassini Saturn Orbiter mission. I was privileged to have been part of one of the greatest planetary science endeavors NASA has ever undertaken. Imaging team leader Carolyn Porco worked tirelessly to represent the team's interests in a complex mission that needed to allocate resources to observe not only Saturn's and Titan's atmosphere, but also Saturn's rings, satellites, and magnetosphere as well as Titan's newly revealed surface. Just as important was Carolyn's devotion to communicating Cassini imaging science to the public and her instinct for iconic images such the Voyager 1 "Pale Blue Dot" image of Earth from beyond Neptune which she co-conceived with Carl Sagan, and Cassini's rendition, "The Day the Earth Smiled," for which she invited the public to participate in the imaging of Earth from Saturn (https://www.bbc.com/news/science-environment-22968105). These distant images of our planet carry even greater significance, now that we know of almost 4,000 planets orbiting other stars.

John Barbara, Joe Ferrier and I used Cassini Saturn images to show that eddies drive the eastward and westward jets on Saturn and that the mean meridional overturning circulation on Saturn is more like Earth's Ferrel cell than its Hadley cell (*Del Genio et al.*, 2007; *Del Genio and Barbara*, 2012). My postdoc Ulyana Dyudina related nightside lightning on Jupiter to apparent storm clouds on the dayside and later made the first optical detection of lightning on Saturn (*Dyudina et al.*, 2004, 2007). Titan was initially a disappointment, a seeming desert rather than home to extensive seas of liquid methane as had been speculated before the mission. Eventually, though, images showed evidence of methane-ethane lakes at high latitudes (*Porco et al.*, 2005), and John and I were able to detect tropospheric methane convective clouds and map the seasonal progression of Titan's Hadley cell-like meridional circulation, along with Cassini imaging colleagues Zibi Turtle, Alfred McEwen, and Jason Perry (e.g., *Turtle et al.*, 2018). Cassini was also an opportunity to re-unite with my undergraduate mentors Joe Burns and Joe Veverka, and a chance to get to know new colleagues such as André Brahic, a wonderful scientist and person who showed me the correct way to pour red vs. white wine. My only regret was missing the team meeting in London that featured an Abbey Road re-shoot (http://carolynporco.com/about/photos/2001-carolyn-porco-cassini-imaging-team-beatles-abbey-road.html).

5 Unexpectedly, to the Stars

At the 1984 Division for Planetary Sciences meeting in Kailua-Kona, Hawaii, Voyager imaging scientist Reta Beebe introduced me to Clyde Tombaugh, the discoverer of Pluto. This was one of the great thrills of my professional life – a once-in-a-lifetime chance to meet someone who had discovered a planet. Of course, I was wrong on two fronts: Pluto is no longer a planet (which I hope is a temporary state of affairs – to a climate scientist, any relatively spherical object that can retain a non-negligible atmosphere qualifies as a planet, even Titan), and little did I know then that I would later meet many people who had discovered planets. I had long been fascinated by the idea of life elsewhere in the universe - initially after being introduced to the Drake equation (a probabilistic equation for the number of technologically developed civilizations in the universe) by Shklovskii and Sagan's *Intelligent Life in the Universe* (*Shklovskii and Sagan*, 1966) and later by Stephen Dole's *Habitable Planets for Man* (*Dole*, 1964). I regarded these only as amusing thought experiments, though, so I took little notice when *Wolszczan and Frail* (1992) announced the first confirmed detection of planets orbiting a pulsar – not candidates for life by any means. Exoplanet detections accelerated through the 1990s and 2000s, though, and with the advent of the Kepler mission and observations by ground-based telescopes, we entered the age of actual, rather than imagined, "rocky" exoplanets with solid surfaces orbiting main sequence stars. To my great surprise, the question of whether we might some day discover life elsewhere had become real.

My GISS colleague Nancy Kiang and Goddard Greenbelt colleague Shawn Domagal-Goldman were already thinking about this as members of the Virtual Planetary Laboratory team that had been considering spectral signatures of life on other planets ("biosignatures") for some time. They sensed that the time might be right for 3-D climate models to be applied to the emerging problem of exoplanet habitability. They secured a bit of internal funding from Goddard to put together a small team, including me, to begin to generalize the GISS GCM to simulate planets other than Earth. (Columbia Astronomy colleagues Caleb Scharf and Kristen Menou and several of us at GISS had been unsuccessful at securing funding for this a decade earlier despite good reviews of our proposals.) In 2013 our group submitted a major proposal to NASA that included planetary scientists, astrophysicists, paleoclimate scientists, and several hybrid Earth climate-planetary scientists (e.g., me) to address questions about the characteristics that might make a planet conducive to life.

As luck would have it, NASA Astrobiology Program Manager Mary Voytek had been thinking for several years about new ways to break down the "stovepipes" that separated research in NASA's Astrophysics, Planetary Science, Heliophysics, and Earth Science Divisions. Our proposal was selected, and Mary made us a founding member of a "research coordination network" (a concept borrowed from the National Science Foundation) that was given the name the Nexus for Exoplanet System Science (NExSS; https://nexss.info). Totaling 18 teams in its first iteration, and now up to 34, NExSS' mandate is to bring together researchers in the 4 NASA science divisions to accelerate progress in the search for life elsewhere. In addition, I was asked, along with astrophysicists Natalie Batalha, the Kepler project scientist, and Dawn Gelino, now Deputy Director of the NASA Exoplanet Science Institute, to serve as co-leads of NExSS, along with Shawn and NASA management postdoctoral fellow Andrew Rushby (named by Mary the "Jedi Council"). (Vikki Meadows, PI of the Virtual Planetary Laboratory, has recently joined the Jedi.) My double life as an Earth scientist and a planetary scientist had suddenly become marketable.

What can an Earth scientist tell an astrophysicist that would be useful? Exoplanet astronomers are continually searching for an "Earth twin" – a planet similar to ours that would be a good candidate to host life. The real question though is how different a planet can be from Earth and still maintain liquid water on its surface, where it, and the life that it might support, could be detected from light-years away. Put another way: What determines the surface temperature of a planet whose atmosphere contains different amounts of greenhouse gases, receives a different amount of sunlight, etc., than present-day Earth does? This is actually the same question of forcings and feedbacks that I have studied for decades to understand 21st Century anthropogenic climate change, but taken to extremes. Not surprisingly, then, what are some of the biggest uncertainties in assessing exoplanet habitability? Cloud (and water vapor and lapse rate and sea ice) feedbacks!

Led by my GISS colleague Mike Way and with contributions from many others in the GISS Earth GCM group (*Way et al.*, 2017), a generalized planetary version of the GISS GCM has been developed. We have used it to explore the possibility that ancient Venus under the faint young Sun may have been habitable (*Way et al.*, 2016); to understand the processes that put excessive water vapor into the stratosphere as incident stellar flux increases, a precursor to the eventual loss of a planet's oceans (*Fujii et al.*, 2017); to determine how the thermal inertia and heat transport of a dynamic ocean might render a planet continuously habitable in the face of oscillations in planet eccentricity (*Way and Georgakarakos*, 2017); to examine scenarios for a possible habitable climate on the known exoplanet closest to Earth (*Del Genio et al.*, 2019a); to determine how the carbonate-silicate cycle feedback that regulates CO_2 and allowed Earth to remain habitable over most of its history might vary as precipitation and runoff change with insolation and planet rotation (*Jansen et al.*, 2019); to understand the transport of volatiles to permanently shadowed polar regions early in the Moon's history (*Aleinov et al.*, 2019); to predict the planetary albedos and surface temperatures of exoplanets from sparse available information using Earth climate concepts (*Del Genio et al.*, 2019b); and to understand how high obliquity allows weakly illuminated planets to remain habitable (*Colose et al.*, 2019). We have also tried to set a standard for data sharing by making the GCM output files and metadata for our published papers publicly available, as described in *Way et al.* (2018).

6 Reflections

On Earth we are now considered to be in a new epoch, the Anthropocene, in which humankind has become a leading order influence on the planet – in effect, turning Earth into a slightly different planet. In the new era of exoplanet science, formerly uncertain terms in the Drake equation such as the fraction of stars with planets are now observationally constrained – e.g., most stars have planets! One of the biggest remaining uncertainties in the equation is the average lifetime of a technological civilization before it destroys itself or consumes all its energy sources.

This is what thinking about other planets in addition to the Earth does. It takes one from wondering what the impacts of anthropogenic greenhouse gas increases will do to sea level, to extreme temperatures, to hurricane intensities, to regional drought in our lifetimes, and ups the ante to the larger question of whether in the long run, our civilization will eventually figure things out and learn to sustain itself, or perish.

As I near the end of my career, this opportunity to reflect upon it has made me more aware of lessons I have learned (mostly unintentionally) along the way:

1. *Serendipity can have a great deal to do with the progression of a career.* Many of us may have agonized about the direction we should follow in our careers when we were in school – I certainly did. My career has been anything but a straight line determined by my initial choices. Rather, it has been defined by a combination of failures, being in the right place at the right time, and openness to go in new directions. I have experienced one of the most remarkable periods in the history of science. I entered science about a decade after launch of the first Earth-orbiting weather satellites and the first successful spacecraft missions to other planets, and I have witnessed visits to every planet in the Solar System. I have been in science during the period of humanity's awakening about anthropogenic climate change (unfortunate for humanity, but a tremendous stimulus for more deeply understanding our own planet). Finally, I have seen the universe unveiled as the home of thousands (at least) of known planets orbiting other stars, and I was able to be a contributor to one of the earliest groups thinking about how to determine which of these might be good candidates to harbor life. My career has clearly been shaped by these external events.
2. *Science is usually a team sport.* The media tend to portray science using the paradigm of the heroic lone scientist, usually out in the field, gathering data and experiencing that "eureka!" moment that immediately overturns an existing science paradigm. Perhaps

that is sometimes true, but it has not been my own experience. Almost all my published papers were joint efforts with colleagues whose technical expertise and scientific insight complement my own. I hope that this essay is a suitable way to express my gratitude for how I have benefited from their talents. Some of my papers arose from data collected (by others) during field experiments, but most were modeling, theory, or remote sensing data analyses. And in fields as complex as the climates of Earth and other planets, paradigm overturning is usually a slow-motion process – several of my more successful papers have been more highly cited in recent years than in the years that followed their publication.

3. *Cross-discipline research has made me a better scientist.* I am often asked, "How does studying other planets help you understand Earth?" Although there are a few examples (*Kahn*, 1989), in general the best way to understand Earth is to study Earth. The real value of studying both Earth and other planets is the perspective it has provided me on both. A foundation in Earth science helps one interpret observations of other planets, since much of the well-explored physics of our own atmosphere can be applied to other planets. There are baroclinic eddies on Mars and Saturn, lightning storms due to water condensation on Jupiter and Saturn (and methane convective storms on Titan), and so on. But the relatively poorly observed planets of our Solar System and barely observed rocky exoplanets force us to ask basic, global questions and put our own planet in a larger context. In Earth science, we got caught up in the details so much a couple of decades ago that we largely stopped asking basic questions. In recent years, though, climate change has taught us that we don't understand Earth as well as we may have thought, and some scientists have begun once again to ask basic questions of our planet:

> What controls the width of the Hadley cell (e.g., *Levine and Schneider*, 2015)? What determines the extratropical lapse rate (e.g., *Frierson*, 2007; *O'Gorman*, 2011)? Do clouds or sea ice control Earth's planetary albedo (e.g., *Donohoe and Battisti*, 2011)? On what spatial scales is the atmosphere in radiative-convective equilibrium (e.g., *Jakob et al.*, 2019)? These papers and others like them have effectively taken a planetary perspective on our own planet, to the betterment of our field. Exoplanet science has taken things a step further by placing the "small" number of planets in our Solar System into the context of thousands of other planets. Given that large a sample, seemingly simple questions such as what determines whether a planet even has an atmosphere turn out to be much more fascinating than anticipated (e.g., *Zahnle and Catling*, 2017). Conversely, the history of habitability in our own Solar System provides insights into processes that may be in play on exoplanets that we as yet know little about (*Del Genio et al.*, 2019c). This cross-discipline fertilization is a trend I hope will continue.

I don't like the idea of starting a book and not getting to read the final chapter. At this stage in my life, though, I have to accept that the questions of the ultimate fate of our society, and the discovery of life elsewhere in the universe (a matter of when, not if, I am certain), may or may not be answered while I am still around to experience them. But to have the chance to live a life in scientific research during a time that saw the beginning of human awareness about both the effect we have on our own planet and the likelihood of alien biospheres, along with the creation of tools to begin to understand them and great colleagues with whom to share the journey, is consolation enough. Still…wouldn't it be great to get to read the final chapter?

ACKNOWLEDGEMENTS. I have tried in this essay to acknowledge people I have worked with or just encountered in my career who enabled me to achieve anything at all, but it is impossible to name everyone in the space given to me. One thing worth stating here is that none of my accomplishments would have been possible without the financial support provided by the many government programs and program managers that have funded my research. These have included the NASA Pioneer Venus and Cassini Missions, the NASA Tropical Rainfall Measuring Mission, Global Precipitation Measurement Mission, and CloudSat-CALIPSO Missions, the NASA Astrobiology Program, and the DOE Atmospheric Radiation Measurement and Atmospheric System Research Programs, as well as a variety of smaller Research and Analysis programs along the way. Thanks also to Jerry Schubert, Carolyn Porco, and a third reviewer for kind and helpful comments. My wife Nancy and daughter Anna have supported me during all of this time, putting up with my frequent absences for travel and regular disappearances *in situ* – home on evenings and weekends but working nonetheless on the next proposal, the next paper, the next talk, the next telecon or meeting. I hope to improve upon that going forward.

REFERENCES

Aleinov, I., M. J. Way, C. Harman, and Co-Authors (2019), Modeling a transient secondary paleolunar atmosphere: 3-D simulations and analysis, *Geophys. Res. Letters, 46*, 5107-5116, doi:10.1029/2019GL082494.

Allison, M., A. D. Del Genio, and W. Zhou (1995), Richardson number constraints for the Jupiter and outer planet wind regime, *Geophys. Res. Letters, 21*, 2957-2960, doi:10.1029/95GL02818.

Bauer, M., and A. D. Del Genio (2006), Composite analysis of winter cyclones in a GCM: Influence on climatological humidity, *J. Climate, 19,* 1652-1672, doi:10.1175/JCLI3690.1.

Belton, M. J. S., G. R. Smith, G. Schubert, and A. D. Del Genio (1976), Cloud patterns, waves, and convection in the Venus atmosphere, *J. Atmos. Sci., 33,* 1394-1417, doi:10.1175/1520-0469(1976)033<1394:CPWACI>2.0.CO;2.

Booth, J. F., C. M. Naud, and A. D. Del Genio (2013), Diagnosing warm frontal cloud formation in a GCM: A novel approach using conditional subsetting, *J. Climate, 26,* 5827-5845, doi:10.1175/JCLI-D-12-00637.1.

Cesana, G., A. D. Del Genio, A. S. Ackerman, M. Kelley, G. Elsaesser, A. M. Fridlind, Y. Cheng, and M.-S. Yao (2019a), Evaluating models' response of tropical low clouds to SST forcings using CALIPSO observations, *Atmos. Chem. Phys., 19,* 2813-2832, doi:10.5194/acp-19-2813-2019.

Cesana, G., A. D. Del Genio, and H. Chepfer (2019b), The Cumulus and Stratocumulus CloudSat-CALIPSO Dataset (CASSCAD), *Earth Syst. Sci. Data Discuss.,* in review, doi:10.5194/essd-2019-73.

Cess, R. D., and Co-Authors (1990), Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models, *J. Geophys. Res., 95*, 16601-16615, doi:10.1029/JD095iD10p16601.

Chen, J., B. E. Carlson, and A. D. Del Genio (2002), Evidence for strengthening of the tropical general circulation in the 1990s, *Science, 295,* 838-841, doi:10.1126/science.1065835.

Chen, J., A. D. Del Genio, and B. E. Carlson (2008), The spatio-temporal structure of twentieth-century climate variations in observations and reanalyses. Part II: Pacific pan-decadal variability, *J. Climate, 21,* 2634-2650, doi:10.1175/2007JCLI2012.1.

Chen, Y., and A. D. Del Genio (2009), Evaluation of tropical cloud regimes in observations and a general circulation model, *Clim. Dynam., 32,* 355-369, doi:10.1007/s00382-008-0386-6.

Colose, C. M., A. D. Del Genio, and M. J. Way (2019), Enhanced habitability on high obliquity bodies near the outer edge of the Habitable Zone of Sun-like stars. *Astrophys. J.,* submitted, arXiv:1905.09398.

Dai, A., I. Y. Fung, and A. D. Del Genio (1997), Surface observed global land precipitation variations during 1900-1988, *J. Climate, 10,* 2943-2962, doi:10.1175/1520-0442(1997)010<2943:SOGLPV>2.0.CO;2.

Del Genio, A. D., G. Schubert, and J. M. Straus (1979), Characteristics of acoustic-gravity waves in a diffusively separated atmosphere. *J. Geophys. Res., 84,* 1865-1879, doi:10.1029/JA084iA05p01865.

Del Genio, A. D., and R. J. Suozzo (1987), A comparative study of rapidly and slowly rotating dynamical regimes in a terrestrial general circulation model, *J. Atmos. Sci., 44,* 973-986, doi:10.1175/1520-0469(1987)044<0973:ACSORA>2.0.CO;2.

Del Genio, A. D., and K. B. McGrattan (1990), Moist convection and the vertical structure and water abundance of Jupiter's atmosphere, *Icarus, 84*, 29-53, doi:10.1016/0019-1035(90)90156-4.

Del Genio, A. D., and W. B. Rossow (1990) Planetary-scale waves and the cyclic nature of cloud top dynamics on Venus, *J. Atmos. Sci., 47*, 293-318, doi:10.1175/1520-0469(1990)0467<0293:PSWATC>2.0.CO;2.

Del Genio, A. D., A. A. Lacis, and R. A. Ruedy (1991), Simulations of the effect of a warmer climate on atmospheric humidity, *Nature, 351,* 382-385, doi:10.1038/351382a0.

Del Genio, A. D., and M.-S. Yao (1993), Efficient cumulus parameterization for long-term climate studies: The GISS scheme, In *The Representation of Cumulus Convection in Numerical Models* (K. A. Emanuel and D. A. Raymond, Eds.), AMS Meteorological Monograph 46, American Meteorological Society, Boston, pp. 181-184, doi:10.1007/978-1-935704-13-3_18.

Del Genio, A. D., W. Zhou, and T. P. Eichler (1993), Equatorial superrotation in a slowly rotating GCM: Implications for Titan and Venus. *Icarus, 101*, 1-17, doi:10.1006/icar.1993.1001.

Del Genio, A. D., M.-S. Yao, W. Kovari, and K.K.-W. Lo (1996), A prognostic cloud water parameterization for global climate models, *J. Climate, 9*, 270-304, doi:10.1175/1520-0442(1996)009<0270:APCWPF>2.0.CO;2.

Del Genio, A. D., and A. B. Wolf (2000), The temperature dependence of the liquid water path of low clouds in the southern Great Plains, *J. Climate, 13*, 3465-3486, doi:10.1175/1520-0442(2000)013<3465:TTDOTL>2.0.CO;2.

Del Genio, A. D., and W. Kovari (2002), Climatic properties of tropical precipitating convection under varying environmental conditions, *J. Climate, 15*, 2597-2615, doi:10.1175/1520-0442(2002)015<2597:CPOTPC>2.0.CO;2.

Del Genio, A. D., W. Kovari, M.-S. Yao, and J. Jonas (2005), Cumulus microphysics and climate sensitivity, *J. Climate, 18*, 2376-2387, doi:10.1175/JCLI3413.1.

Del Genio, A. D., J. M. Barbara, J. Ferrier, and Co-Authors (2007), Saturn eddy momentum fluxes and convection: First estimates from Cassini images, *Icarus, 189*, 479-492, doi:10.1016/j.icarus.2007.02.013.

Del Genio, A. D., and J. Wu (2010), The role of entrainment in the diurnal cycle of continental convection, *J. Climate, 23*, 2722-2738, doi:10.1175/2009JCLI3340.1.

Del Genio, A. D., and J. M. Barbara (2012), Constraints on Saturn's tropospheric general circulation from Cassini ISS images, *Icarus, 219,* 689-700, doi:10.1016/j.icarus.2012.03.035.

Del Genio, A. D., Y. Chen, D. Kim and M.-S. Yao (2012), The MJO transition from shallow to deep convection in CloudSat/CALIPSO data and GISS GCM simulations, *J. Clim., 25*, 3755-3770, doi:10.1175/JCLI-D-11-00384.1.

Del Genio, A. D., and Y. H. Chen (2015), Cloud-radiative driving of the Madden-Julian Oscillation as seen by the A-Train, *J. Geophys. Res. – Atmos., 120,* 5344-5356, doi:10.1002/2015JD023278.

Del Genio, A. D., J. Wu, A. B. Wolf, Y. H. Chen, M.-S. Yao, and D. Kim (2015), Constraints on cumulus parameterization from simulations of observed MJO events, *J. Climate*, *28,* 6419-6442, doi:10.1175/JCLI-D-14-00832.1.

Del Genio, A. D., M. J. Way, D. S. Amundsen, and Co-Authors (2019a), Habitable climate scenarios for Proxima Centauri b with a dynamic ocean, *Astrobiology, 19*, 99-125, doi:10.1089/ast.2017.1760.

Del Genio, A. D., N. Y. Kiang, M. J. Way, and Co-Authors (2019b), Albedos, equilibrium temperatures, and surface temperatures of habitable planets, *Astrophys. J.*, in revision, arXiv:1812.06606.

Del Genio, A. D., D. Brain, L. Noack, and L. Schaefer (2019c), The inner Solar System's habitability through time, In *Planetary Astrobiology* (V. Meadows, G. Arney, D. DesMarais, and B. Schmidt, Eds.), University of Arizona Press, in press, arXiv:1807.04776.

Dole, S. H. (1964), *Habitable Planets for Man*, Blaisdell Pub. Co., New York.

Donohoe, A., and D. S. Battisti (2011), Atmospheric and surface contributions to planetary albedo, *J. Climate, 24*, 4402-4418, doi:10.1175/2011JCLI3946.1.

Dyudina, U. A., A. D. Del Genio, A. P. Ingersoll, and Co-Authors (2004), Lightning on Jupiter observed in the H_α line by the Cassini imaging science susbsystem, *Icarus, 172*, 24-36, doi:10.1016/j.icarus.2004.07.014.

Dyudina, U. A., A. P. Ingersoll, S. P. Ewald, and Co-Authors (2007), Lightning storms on Saturn observed by Cassini ISS and RPWS during 2004-2006, *Icarus, 190*, 545-555, doi:10.1016/j.icarus.2007.03.035.

Elsaesser, G. S., A. D. Del Genio, J. Jiang, and M. van Lier-Walqui (2017), An improved convective ice parameterization for the NASA GISS Global Climate Model and impacts on cloud ice simulation, *J. Climate, 30,* 317-336, doi:10.1175/JCLI-D-16-0346.1.

Flato, G., J. Marotzke, and Co-Authors (2013), Evaluation of climate models. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, doi:10.1017/CBO9781107415324.020.

Frierson, D. M. W. (2008), Midlatitude static stability in simple and comprehensive general circulation models, *J. Atmos. Sci., 65,* 1049-1062, doi:10.1175/2007JAS2373.1.

Fu, R., A. D. Del Genio and W. B. Rossow (1990), Behavior of deep convective clouds in the tropical Pacific deduced from ISCCP radiances, *J. Clim., 3,* 1129-1152, doi:10/1175/1520-0442(1990)003<1129:BODCCI>2.0.CO;2.

Fu, R., A. D. Del Genio, and W. B. Rossow (1994), Influence of ocean surface conditions on atmospheric vertical thermodynamic structure and deep convection, *J. Climate, 7,* 1092-1108, doi:10.1175/1520-0442(1994)007<1092:IOOSCO>2.0.CO;2.

Fujii, Y., A. D. Del Genio, and D. S. Amundsen (2017), NIR-driven moist upper atmospheres of synchronously rotating temperate terrestrial exoplanets. *Astrophys. J., 848,* 100, doi:10.3847/1538-4357/aa8955.

Futyan, J. M., and A. D. Del Genio (2007a), Deep convective system evolution over Africa and the tropical Atlantic, *J. Climate, 20,* 5041-5060, doi:10.1175/JCLI4297.1.

Futyan, J. M., and A. D. Del Genio (2007b), Relationships between lightning and properties of convective cloud clusters, *Geophys. Res. Letters, 34,* L15705, doi:10.1029/2007GL030227.

Hahn, C. J., S. G. Warren, J. London, R. M. Chervin, and R. Jenne (1982), Atlas of Simultaneous Occurrence of Different Cloud Types over the Ocean. NCAR Technical Note TN-201+STR, 212 pp. National Center for Atmospheric Research, doi:10.5065/D6FQ9TJQ.

Hahn, C.J., S.G. Warren, J. London, R.M. Chervin and R.L. Jenne (1984), Atlas of Simultaneous Occurrence of Different Cloud Types over Land. NCAR Technical Note TN-241+STR, 216 pp., National Center for Atmospheric Research, doi:10.5065/D6Q81B2M.

Hansen, J., D. Johnson, A. Lacis, and Co-Authors (1981), Climate impact of increasing atmospheric carbon dioxide, *Science, 213,* 957-966, doi:10.1126/science.213.4511.957.

Hou, A. Y. (2014), The Global Precipitation Measurement Mission, *Bull. Amer. Meteorol. Soc., 95,* 701-722, doi:10.1175/BAMS-D-13-00164.1.

Houze, R. A. Jr. (1977), Structure and dynamics of a tropical squall-line system, *Mon. Wea. Rev.*, 1540-1567, doi:10.1175/1520-0493(1977)105<1540:SADOAT>2.0.CO;2.

Jakob, C., M. S. Singh, and L. Jungandreas (2019), Radiative convective equilibrium and organized convection: An observational perspective, *J. Geophys. Res.: Atmos., 124*, doi:10.1029/2018JD030092.

Jansen, T., C. Scharf, M. J. Way, and A. D. Del Genio (2019), Climates of warm Earth-like planets II: Rotational 'Goldilocks' zones for fractional habitability and silicate weathering, *Astrophys. J., 875*, 79, doi:10.3847/1538-4357/ab113d.

Jensen, M. P., and A. D. Del Genio (2006), Factors limiting convective cloud-top height at the ARM Nauru Island climate research facility, *J. Climate, 19,* 2105-2117, 10.1175/JCLI3722.1.

Kahn, R. (1989), *Comparative Planetology and the Atmosphere of Earth*, A report to the Solar System Exploration Division, NASA.

Kim, D., A. H. Sobel, A. D. Del Genio, and Co-Authors (2012), The tropical subseasonal variability simulated in the NASA GISS general circulation model, *J. Climate, 25,* 4641-4659, doi:10.1175/JCLI-D-11-00447.1.

Koch, D., and A. D. Del Genio (2010), Black carbon absorption effects on cloud cover: Review and synthesis, *Atmos. Chem. Phys., 10*, 7685-7696, doi:10.5194/acp-10-7685-2010.

Levine, X. J., and T. Schneider (2015), Baroclinic eddies and the extent oft he Hadley circulation: An idealized GCM study, *J. Atmos. Sci., 72,* 2744-2761, doi:10.1175/JAS-D-14-0152.1.

Menon, S., A. D. Del Genio, D. Koch, and G. Tselioudis (2002), GCM simulations of the aerosol indirect effect: Sensitivity to cloud parameterization and aerosol burden, *J. Atmos. Sci., 59,* 692-713, doi:10.1175/1520-0469(2002)059<0692:GSOTAI>2.0.CO;2.

Miller, R. L., and A. D. Del Genio (1994), Tropical cloud feedbacks and natural variability of climate, *J. Climate, 7,* 1388-1402, doi:10.1175/1520-0442(1994)007<1388:TCFANV>2.0.CO;2.

Mrowiec, A. A., C. Rio, A. M. Fridlind, and Co-Authors (2012), Analysis of cloud-resolving simulations of a tropical mesoscale convective system observed during TWP-ICE: Vertical fluxes and draft properties in convective and stratiform regions, *J. Geophys. Res., 117,* D19201, doi:10.1029/2012JD017759.

Naud, C. M., A. D. Del Genio, M. Bauer, and W. Kovari (2010), Cloud vertical distribution across warm and cold fronts in CloudSat-CALIPSO data and a general circulation model, *J. Climate, 23,* 3397-3415, doi:10.1175/2010JCLI3282.1.

O'Gorman, P. A. (2011), The effective static stability experienced by eddies in a moist atmosphere, *J. Atmos. Sci., 68,* 75-90, doi:10.1175/2010JAS3537.1.

Porco, C. C., E. Baker, J. Barbara, and Co-Authors (2005), Imaging of Titan from the Cassini spacecraft, *Nature, 434,* 159-168, doi:10.1038/nature03436.

Rio, C., A. D. Del Genio, and F. Hourdin (2019), Ongoing breakthroughs in conective parameterization, *Curr. Clim. Change Rep., 5,* 95-111, doi:10.1007/s40641-019-00127-w.

Schiffer, R. A., and W. B. Rossow (1983), The International Satellite Cloud Climatology Project (ISCCP): The first project of the World Climate Research Programme, *Bull. Amer. Meteorol. Soc., 64,* 779-784, doi:10.1175/1520-0477-64.7.779.

Schmidt, G. A. (2009), Wrong but useful, *Phys. World, 13,* 33-35.

Shklovskii, I. S., and C. Sagan (1966), *Intelligent Life in the Universe*, Holden-Day, San Francisco.

Simpson, J., and V. Wiggert (1969), Models of precipitating cumulus towers, *Mon. Wea. Rev.*, *97*, 471-489, doi:10.1175/1520-0493(1969)097<0471:MOPCT>2.3.CO;2.

Simpson, J., R. F. Adler, and G. R. North (1988), A proposed Tropical Rainfall Measuring Mission Satellite, *Bull. Amer. Meteorol. Soc.*, *69*, 278-295, doi:10.1175/1520-0477(1988)069 <0278:APTRMM>2.0.CO;2.

Smith, S. A., and A. D. Del Genio (2002), A simple conceptual model of cirrus horizontal inhomogeneity and cloud fraction. *Q. J. Roy. Meteorol. Soc.*, *128*, 149-171, doi:10.1256/00359000260498833.

Stephens, G. L., D. G. Vane, R. J. Boain, and Co-Authors (2002), The CloudSat Mission and the A-Train: A new dimension of space-based observations of clouds and precipitation, *Bull. Amer. Meteorol. Soc.*, *83*, 1771-1790, doi:10.1175/BAMS-83-12-1771.

Stokes, G. M. (2016), Original ARM concept and launch, In *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years* (D. D. Turner and R. G. Ellingson, Eds.), AMS Meteorological Monograph 57, Chapter 2, pp. 2.1-2.11, doi:10.1175/AMSMONOGRAPGHS-D-15-0021.1.

Stone, P. H. (1975), Dynamics of the atmosphere, In *The Atmosphere of Venus*, NASA SP-382, pp. 85-102, Washington, DC.

Stramler, K., A. D. Del Genio, and W. B. Rossow (2011), Synoptically driven Arctic winter states, *J. Climate*, *24*, 1747-1762, doi:10.1175/2010JCLI3817.1.

Tselioudis, G., A. D. Del Genio, W. Kovar, Jr., and M.-S. Yao (1998), Temperature dependence of low cloud optical thickness in the GISS GCM: Contributing mechanisms and climate implications. *J. Climate, 11,* 3268-3281, doi:10.1175/1520-0442(1998)011 <1997:CVITHCC>2.0.CO;2.

Turtle, E. P., J. E. Perry, J. M. Barbara, and Co-Authors (2018), Titan's meteorology over the Cassini mission: Evidence for extensive subsurface methane reservoirs, *Geophys. Res. Letters, 45*, 5320-5328, doi:10.1029/2018GL078170.

Way, M. J., A. D. Del Genio, N. Y. Kiang, and Co-Authors (2016), Was Venus the first habitable world of our solar system? *Geophys. Res. Letters, 43,* 8376-8373, doi:10.1002/2016GL069790.

Way, M. J., I. Aleinov, D. S. Amundsen, and Co-Authors (2017), Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics 1.0: A general circulation model for simulating the climates of rocky planets, *Astrophys. J. Supp. Ser., 231,* 12, doi:10.3847/1538-4365/aa7a06.

Way, M. J., and N. Georgakarakos (2017), Effects of variable eccentricity on the climate of an Earth-like world, *Astrophys. J. Lett., 835,* L1, doi:10.3847/2041-8213/835/1/L1.

Way, M. J., A. D. Del Genio, I. Aleinov, and Co-Authors (2018), Climates of warm Earth-like planets I: 3-D model simulations, *Astrophys. J. Supp. Ser., 239,* 24, doi:10.3847/1538-4365aae9e1.

Winker, D. M., and J. Pelon (2003), The CALIPSO mission. *IEEE International Geoscience and Remote Sensing Symposium Proceedings*, IEEE Cat. No. 03CH37477, doi:10.1109/IGARSS.2003.1294098.

Wolszczan, A., and D. A. Frail (1992), A planetary system around the millisecond pulsar PSR1257 + 12, *Nature, 355,* 145-147, doi:10.1038/355145a0.

Wu, J., A. D. Del Genio, M.-S. Yao and A. B. Wolf (2009), WRF and GISS SCM simulations of convective updraft properties during TWP-ICE, *J. Geophys. Res., 114*, D04206, doi:10.1029/2008JD010851.

Ye, B., A. D. Del Genio, and K. K.-W. Lo (1998), CAPE variations in the current climate and in a climate change, *J. Climate, 11*, 1997-2015, doi:10.1175/1520-0442(1998)011 <1997:CVITHCC>2.0.CO;2.

Zahnle, K. J., and D. C. Catling (2017), The cosmic shoreline: The evidence that escape determines which planets have atmospheres, and what this may mean for Proxima Centauri b, *Astrophys. J., 843*, 122, doi:10.3847/1538-4357/aa7846.

Zipser, E. J. (1977), Mesoscale and convective-scale downdrafts as distinct components of squall-line structure, *Mon. Wea. Rev., 105*, 1568-1589, doi:10.1175/1520-0493(1977)105 <1568:MACDAD>2.0.CO;2.