Following the Science by Roger A Pielke Sr.

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1. Introduction

The pursuit of basic knowledge and conveying that knowledge for the benefit of society is one of the most rewarding endeavors of life. The opportunity to devote one's professional life to science in order to learn and create new knowledge is intoxicating. This short article highlights some of the aspects of my career that perhaps students and others will find useful, including life experiences that directly affected my career. I also suggest opportunities for major advances in our understanding and predictability of Earth system processes.

My overarching message is that whatever path one chooses for a scientific career, success is more likely if you are passionate about the subjects that you study. I have been fortunate to choose a career that I enjoyed and that gave me the ability to mentor younger students and other colleagues and see them grow professionally in stature. It has been rewarding to watch my chosen discipline advance with improved scientific understanding, more refined methodologies, and to become even more integral to our daily lives. My students and close colleagues have played a major role in these advancements.

2. Career path

Of all the sciences, why did I get into meteorology and climate? My second scientific interest was astronomy. However, weather is something we can directly and personally experience. As children, we view the sky with excitement to watch the falling rain, sleet, or snow as we monitor approaching snowstorms or hurricanes that can cancel school. Only later did I realize that higher-level math and physics are needed for a career in meteorology

I grew up in a blue-collar town (Baltimore). As a result, as a teenager I was employed in jobs that were outdoors and involved physical labor exposing me to the diverse communities that lived in this city. This included the ugly exposure to the hyper-segregation of the city. I went to only all-white schools and lived in a Jim Crow environment. Working with inner-city men, however, educated me how much they are deprived of the same opportunities, despite similar interests and talents. I also learned that tradesmen are, in fact, practical engineers**.** Expertise in science and technology is not limited to those who have Ph.D.'s.

After receiving an undergraduate degree in mathematics at Towson State College (now Towson University), with strong encouragement and support from my soon to be wife, Gloria Coleman, I was admitted to the Pennsylvania State University for graduate school in meteorology. There I worked with an internationally respected boundary layer meteorologist (Hans Panofsky) as my advisor and was assigned to work on analyzing vertical turbulence statistics within the boundary layer. This information was needed as input to assess risks from turbulence stress as rockets were launched from the Kennedy Space Center. This experience (which culminated in my Master thesis –Pielke and Panofsky, 1970) broadened my knowledge of the science of meteorology and showed me that this professional discipline is much more than weather observations and forecasting.

During my master's program I was office roommates with Bill Cotton, who became a close friend. This was well before he achieved the world class respect he has today in cloud physics, mesoscale modeling and dynamics, and weather modification. When he received his doctorate, he was hired by Joanne Simpson (Fleming, 2020; Tao et al., 2003) in NOAA's Experimental Meteorology Lab (EML) in Coral Gables Florida. Among the new activities under her supervision, they offered me the opportunity to complete my doctoral research there. Moreover, it was a broad responsibility. I was to create a model of the weather over South Florida as part of their cumulus cloud seeding experiment.

This was the start of a long and fruitful mentorship with not only William (Bill) R. Cotton (where I was de facto his first of many Ph.D. students he advised), but by another giant in the science of meteorology, Joanne Simpson. Joanne is one of the pioneers of a wide range of topics in tropical meteorology including her seminal contribution of the role of "hot towers" in deep cumulus clouds in driving the Earth's transfer of energy poleward from lower latitudes (Tao et al., 2003; AGU, 2021). Even more important to me was the model of supervision she (and Bill) practiced (Pielke Sr., 2003a). Joanne felt that she should allow the maximum amount of independence to perform the research. This permission to "think outside the box" and freedom for students to choose paths for research is a philosophy I adopted for my students. She also allowed me to set up and conduct a field campaign in south Florida (Pielke and Cotton, 1977) even though my research focus was modeling. She felt that all scientists need to be grounded with real world observations. I was also tasked with flying on research aircraft flights in south Florida, some at only 200 m over land and 50 m over the ocean. The American Geophysical Union "Joanne Simpson Medal for Mid-Career Scientists" is one example of the formal recognition of her life's goal to support younger scientists (see AGU, 2021).

As part of my research, I developed a three-dimensional model of the sea breezes over south Florida. In the early 1970s working with a CDC 6600 computer at NOAA in Washington D.C., I made the model domain and spatial resolution so that it would just fit into the available core (worked out to be 10 km delta x/delta y). Each hour of simulated time required a day to get results back as the program, on computer cards, was sent electronically to the National Meteorological Center in Washington D.C. and results sent back to be output on computer printout paper the next day. It is remarkable how much technology has progressed since then, considering that this model could easily be run today on a 2020 smart phone! The model results showed that the sea breeze forms well-defined low-level convergence zones, and focused where deep cumulus convection was more favored to develop (Pielke, 1974). This is critical information for the objective assessment of the value of cloud seeding since whether or not a cloud is in one of these convergence zones makes a big difference on the eventual rainfall. In our book (Cotton and Pielke, 2007) we discussed how overstating the capabilities of weather modification resulted in its loss of credibility. Such a risk now exists, in my view, with respect to the advocacy of geoengineering to deliberately alter the climate system.

Another benefit of working at EML was that we were co-located at the University of Miami in Coral Gables with the National Hurricane Research Lab and the National Hurricane Center. I was able to interact with each. Indeed, the Director of NHC, Robert Simpson, encouraged us to stand behind operational weather forecasters and see them prepare their forecasts. I recall, for example, watching them discuss model results and make predictions as Hurricane Agnes in 1972 began its destructive path inland over the Florida Panhandle and then up the east coast. This taught me the value of research meteorologists interacting with operational weather forecasters. It is an effective reality test of what we really understand. All scientists would benefit by this exposure to making predictions and seeing how well they do in real time.

Joanne was subsequently offered an endowed chair in the Department of Environmental Sciences at the University of Virginia. As part of her start up package she requested an Assistant Professorship for me. This led to another broadening of my research perspective in that the Department had internationally respected faculty in a range of environmental subjects. I was able to sit in on classes and learn cutting edge research in hydrology, oceanography, and ecology. I even taught a course on the U.S. Wilderness System. From this background, I was appointed to a committee of The Nature Conservancy for one of their preserves and was also active in promoting several areas in Virginia for federal Wilderness preservation. As part of her encouragement to think outside of the box, I led an effort to assess the distribution of Red Spruce in Virginia. With the cooperation of the state of Virginia, we obtained and planted red spruce at a variety of locations in the mountains of the Blue Ridge and Alleghenies. We even discovered a heretofore unknown tract of red spruce and alerted The Nature Conservancy to it. The significance of this was that we concluded that this type of boreal tree species type was much more widely distributed than traditionally assumed (Pielke, 1981).

What I found in my expansion outside of meteorology was that by collaborating with ecologists, oceanographers, and hydrologists, research results could be achieved that could not have been completed from just one discipline. I was joined in this outreach by fellow faculty member and meteorologist Mike Garstang who, among his many accomplishments, has authored seminal work on elephants and their social life (Garstang, 2015). Indeed, my cross-discipline interactions convinced me that *ecology* is just a term biological scientists use to refer to the *climate system*. They are looking at the same topic – just from two distinctly different perspectives. We need much more interaction including with social scientists.

I also learned to work with the students and postdoctoral researchers in my group as colleagues who could teach me as much, or more, than I would teach them. This symbiotic relationship resulted in a number of peer-reviewed papers, theses, and dissertations including those on interdisciplinary studies. I also adopted the approach that in addition to satisfying requirements and goals of specific research projects, I worked with the students to complete other, non-funded research topics. This culminated in numerous original papers.

Working with Joanne also introduced me to sexism and discrimination which she experienced throughout her career and is documented in detail in Fleming (2020). I saw this firsthand by a subset of faculty in my Department at Virginia where they made insulting comments about her when she was absent. This sensitized me to the difficulties that women have in entering science, and I tried to help remedy, at least to a small amount, by recruiting women graduate students.

My interaction with Joanne Simpson included Robert Simpson who was the former director of the National Hurricane Center. He was also a pioneer in tropical meteorology. He and I collaborated on contracts through his company, Simpson Weather Associates, on several topics including hurricanes, hurricane modification, and the value of satellite rectennas to power electricity on the ground (Pielke Sr., 1976). This collaboration taught me the use of private companies as an effective mechanism to translate research into benefits for society. Private companies are effective when networked with research universities. This later led to me starting a private company (Aster) at Colorado State University for which Bill Cotton and I were awarded Researcher of the Year in 1993 by the Colorado State University Research Foundation (CSURF) for the development of the Regional Atmospheric Modeling System (RAMS). When supported by Universities and also the faculty's Department, these outreach companies can directly transfer fundamental new knowledge in science and engineering to practical uses throughout society (Pielke Jr. et al., 2003).

I collaborated with Robert Simpson on research publications (Simpson and Pielke, 1976; Pielke Sr., 2002a), and motivated by my interactions with him and my interest in hurricanes, wrote two books on hurricanes, one in which my son took the lead (Pielke Sr., 1990; Pielke Jr. and Pielke Sr., 1997). This was the proudest moment in my career, watching my son's maturation over the years into an outstanding, internationally well-respected scientist and policy expert.

After seven years, at the encouragement of Bill Cotton (Cotton, 2020), who was now on the faculty in the Atmospheric Science Department at Colorado State University (CSU), and with support from Tom Vonderhaar at CSU, I moved there. Bill and I coauthored a book on weather modification and on the climate issue (Cotton and Pielke, 2007), which urged that the climate researchers learn from the mistaken overconfidence and overselling of predictions in our ability to deliberately alter the weather.

At CSU, Bill and I also worked together with Craig Tremback and Bob Walko to create the Regional Atmospheric Modeling System (RAMS) – Pielke et al. (1992) and Cotton et al. (2003). This model has been used worldwide, including its very successful adoption and improvement for Brazil's forecast system (http://brams.cptec.inpe.br/). I worked closely with outstanding U.S. and foreign Ph.D. Research Associates who were supported on our grants and contracts or short- and longer-term visitors, including Debbie Abbs, Jimmy Adegoke, Roni Avissar, Marina Baldi, Haroldo Campos Velho, Giovanni Dalu, George Kallos, John Garratt, Khishig Jamiyansharav, Bob Kessler, Tsengdar Lee, Lixin Lu, Walt Lyons, the late Ytzhaq Mahrer (Haikin and Pielke Sr., 2018), Dick McNider, Dragutin Mihailovic, Joseph Mukabana, Mel Nicholls, Dev Niyogi, Yoshi Ookouchi, Joe Otterman, Bill Physick, Moti Segal, Yongnian Shi, Herbert ter Maat, Marek Uliasz, Zhoujia Ye, and Conrad Ziegler. I also served on external Ph.D. committees at other U.S. and foreign universities.

At CSU, while we accomplished important research as part of the goals of funded grants and contracts, some of our best achievements were not specifically funded. Working with world-class students and research staff across a range of disciplines provided an opportunity for original research studies. I also was fortunate to have an exceptionally qualified research coordinator for my project group – Dallas Staley. She has contributed and continues to contribute to a wide range of editorial and managerial tasks. She has worked with me for over 30 years and was, and is, a valuable contributor to the vigor of our research group.

I spent two sabbaticals at The Natural Resource Ecology Lab (NREL) at CSU. During the first visit, we coupled our atmospheric weather model to two biogeochemical models (e.g., Pielke et al., 1999; Lu et al., 2001). In one of our papers we showed that on the shorter time period, the biogeochemical effect of carbon dioxide on weather was much more important than the radiative effect of added carbon dioxide (Eastman et al., 2001). This cross-discipline work provided a perspective that could not have been achieved without interacting with the ecological community. In conjunction with ecologists and hydrologists, we alerted the community that risks from the human intervention in the climate system involve more than the emission of CO_2 into the atmosphere (McAlpine et al., 2010; Pielke et al., 2009).

There was also an opportunity at CSU to integrate the physical component of weather with atmospheric chemistry. In the 1980s, air quality was not considered part of our weather. The federal management of these two issues was led by two different agencies (National Weather Service; Environmental Protection Agency). Indeed, the American Meteorological Society stated that flash floods were the greatest reason for the loss of life due to weather in the United States. I wrote an essay (Pielke, 1979) challenging this view where I documented a much larger loss of life due to air pollution than all other weather hazards combined. This finding has wide-reaching implications for environmental justice and equity that continues to be overlooked.

This interest in combining atmospheric physics and atmospheric chemistry led me to become one of the faculty proponents of bringing this discipline into the atmospheric science program at Colorado State University. As a result of this effort, we hired two excellent atmospheric chemists (Sonia Kreidenweis and Jeff Collet). In the years since, these two colleagues have built an impressive world-class program on this subject. The Department is known today for its excellent graduate studies in atmospheric chemistry. During my two terms as a Commissioner on the Colorado Air Quality Commission, I was able to participate in policymaking on this subject as well as on asbestos regulation and EPA criteria pollutant requirements.

I was also able to reach out to mathematicians and physicists to broaden the understanding of fundamental behavior in the climate system. During my second sabbatical, which I also spent at NREL, I focused on nonlinear dynamics and chaos. Among our results was discussing how chaos theory applies to the atmosphere (e.g., Zeng et al., 1990, 1993). For example, in Rial et al. (2004) and Sveinsson et al. (2003), we used real world data to show that the climate system is highly nonlinear in which inputs and outputs are not proportional and change is often episodic and abrupt. More recently, we have shown that the statement that small perturbations can ever affect large-scale atmospheric circulations at long distances (i.e., a flap of a butterfly wing can cause a tornado) is completely erroneous (Shen et al., 2018).

During my tenure at CSU, we started research on using artificial intelligence to supplement, and maybe even replace the traditional grid-based numerical weather prediction models (Pielke et al., 2006, 2007). The field of atmospheric modeling is entering a major shift in the tools used for weather prediction. Rather than continue to develop the models using grid based and/or spectral wave number techniques, such as I discuss in detail in Pielke Sr. (2013), the new generation models will be based on machine learning in part, or in their entirety.

I discussed this concept, for example, in Chapters 7 and 8 in Pielke Sr. (2013). With respect to traditional parameterizations, the physical fidelity of the parameterization is not important as long as it is as least as accurate as the traditional parameterization. In an atmospheric model, several different parameterizations usually are applied to reproduce the various physical processes (e.g., radiative fluxes, turbulence, cumulus clouds, etc.). However, it is unrealistic to separate the processes in this way since the observations and physics make no such artificial separation. These processes are, in fact, three dimensional and interact with each other. Thus the most effective way to implement a machine learning-based parameterization is to combine all of the relevant physics that result in diabatic heating and cooling, precipitation, atmospheric moistening and drying, etc.

In weather (short and long term) and more generally in climate forecasting, we want the most accurate predictions as they affect society and the environment. Explaining why the weather behaves the way observed, of course, is a process study and we do want to understand the physics, but it is not a necessary requirement for skillful forecasts. Machine learning will complement process understanding as we seek to explain its results. Therefore machine language-based atmospheric prediction models will be a path forward to more skillful model predictions.

I also applied the concept that spatial and temporal averaging (integral properties) can provide robust measures of key climate metrics. For instance, in Pielke Sr. (2003b, 2008) it was shown how measurements of ocean heat content change averaged over monthly and longer-time periods and over the entire ocean can be used to obtain an accurate measure of the top of the globally-averaged atmosphere radiative imbalance over that time period. We also showed that using the well understood relationship between pressure, temperature, and winds on the synoptic scale at mid and high latitudes, 200 mb winds can be used monitor long-term changes in the zonally-averaged temperature gradient as a function of latitude (Pielke Sr. et al., 2001). The winds at the level are the result of the integration of the spatial temperature distribution below that level.

I also visited the University of Arizona multiple times over the last twenty years. Working with Ben Herman and Xubin Zeng we observed that temperatures at 500 mb seldom go below -40°C or so even after first reaching these values in late Fall (Chase et al., 2002). We followed up with several papers and extended it to the finding that temperatures also seldom warm above about -3°C in the tropics and elsewhere all year (Chase et al., 2015). This self-regulation of tropospheric temperatures constrains changes in the jet stream and baroclinic storm dynamics and therefore restricts changes in climate variability and longer-term change. I continue to have close research collaboration with Professor Zeng on the subjects of predictability of weather, machine learning capabilities, nonlinear dynamics, and chaos theory.

At CSU, I was invited to serve as State Climatologist for Colorado. This was an opportunity to do more outreach to the public to communicate weather and climate data and interpretation. I also was elected as President of the American Association of State Climatologists where our annual meeting was sponsored in the state of a different State Climatologist each year. This again broadened my perspective in seeing what users (stakeholders) require in terms of weather and climate data. We also published a statement on climate (Pielke Sr., 2002b).

One of my most enjoyable components of my career is the cultural diversity I was introduced to. I traveled widely as part of my research and also sponsored students and researchers from many countries including Japan, Australia, New Zealand, China (both the PRC and Taiwan), India, Israel, Kenya, Brazil, Peru, Colombia, South Africa, Turkey, Serbia, Argentina, Mexico, Brazil, Columbia, Bangladesh, Mongolia, Germany, Italy, Brazil, Canada, France, The Netherlands, and England. In addition, the U.S. Air Force sent officers to our research group where they earned masters and doctoral degrees. A list of their names, research papers, and theses and dissertations are available at the link https://cires.colorado.edu/research/research-groups/roger-pielke-sr-group. I continue to interact with many of my former students and research staff. My daughter, Tara Green (an outstanding creative author web designer), invited me to work with AOL as the Weather Guy, answering weather questions that were asked by children each day via the internet which I did for several years and very much enjoyed.

My travels exposed me to diverse cultures and history. It enriched my experiences and helped place my life in perspective, including seeing what life experiences others had and have today. As an example, this included my attendance at a Dahlem Conference (Pielke, 1998; Dalem Konferenzen, 2021) in Berlin (West Berlin at the time) which was in a home confiscated by the Nazis in the 1930s during their horrific campaign of genocide. The house, owned by the Free University of Berlin, was left as it existed for homeowners who presumably were killed. It placed what we read in history books in stark reality. I also visited Masada in Israel during an extended visit there with Ytzhaq Mahrer of the University of Jerusalem at Rehovot, where Jews fought the Roman Empire for independence in a revolt in 74 AD and retreated to a large fortified mesa adjacent to the Dead Sea. There they fought to the death rather than surrender. In the Golan Heights of Israel, in a more recent threat, we drove by a cannon destroyed from the last Israeli-Arab war as well as mine fields.

In Amsterdam, I visited the Anne Frank house with Pinhas Alpert of Tel Aviv University. He mentioned that even at that time, he was concerned about wearing a yamaka due to still existing anti-Semitism in Europe. Ytzhaq's father, who was a judge in the 1930s, related to me how he and his wife escaped Germany to British controlled Palestine just before the opportunity for Jews to leave Germany was closed.

I was invited to a conference in Kenya by Joseph Mukabana of the University of Nairobi, where not only did I experience a rich fauna and flora in the parks, but saw the vast poverty in our travel between parks. I also saw the excellent scientific talent in the region, equal to scientists everywhere, including colleagues from Kenya, Ethiopia, Madagascar, Botswana, and other sub-Saharan countries. When I visited India, I found it incredibly diverse, but also densely populated with widespread poverty. In both these poor counties, however, the pleasantness and welcoming of almost all the local people I interacted with is a memory I will always cherish. It confirmed, that despite horrendous behavior by some in leadership positions, most people, irrespective of culture, race, nationality, or gender have the same life goals and values that most of us do. The world really is a village and being a scientist permits lifelong diverse interactions and collaborations.

After working at Colorado State University for 25 years, I decided to retire and accepted a part-time position at CIRES at the University of Colorado in Boulder. I taught several courses in the first few years and have continued part-time research in that venue with colleagues at The University of Arizona (Xubin Zeng), San Diego State University (Bo-Wen Shen), Western Kentucky University (Eric Rappin), University of Nebraska (Rezaul Mahmood), the University of Washington (Faisal Hossain), and the University of Alabama at Huntsville (U.S. Nair).

As part of my retirement activities, I started a weblog which I wrote for 8 years (https://pielkeclimatesci.wordpress.com/). These social platforms have provided a very effective way to bypass institutional roadblocks and have revolutionized how scientists can communicate with the public and policymakers. My involvement broadened to include policy-relevant environmental studies. Currently, the Paris 1.5°C/2°C global surface temperature anomalies are used as the primary starting metric to assess future environmental and social vulnerabilities to water resources, energy, food, ecosystem function, and human health, primarily from added CO_2. These temperature anomalies from added greenhouse gases, particularly added CO_2, is assumed to cause and dominate "climate change" on multi-decadal time scales.

There is the issue, of course, in that the term 'climate' has two definitions. A broader view is that climate consists of the atmosphere, oceans, land, and cryosphere. The second definition is that climate is the term used for the long-term (e.g., multidecadal) statistics of weather (the latter use of the term "climate" is just a definition for longer-term weather statistics; e.g., "so-called "seasonal climate predictions" are really just three-month averaged weather data). We associate "weather" with shorter-term statistics (e.g., today's maximum and minimum temperature).

The first definition, illustrated in Figure 1, is the framing that should be used for assessing multi-decadal risks. The natural components and increasingly the human disturbance of the climate system, should be the focus with respect to the issue of climate. The International Geosphere-Biosphere Programme (IGBP) was ideally suited to advance the understanding of the climate as a system but was unfortunately terminated at the end of 2015 (IGBP, 2015). In contrast, the IPCC framing of the climate issue starts with the physical part of the climate system, which, in my view, limits the accurate assessment of the role of humans in the climate system.

These human influences include greenhouse gas emissions, land-use changes, and aerosol pollution as they affect the state variables in Figure 1. Each are contributing to local, regional, and global climate changes, which are superimposed on natural changes and variability (NRC, 2005; Kabat et al., 2004; Matsui and Pielke, 2006; Pielke et al. 2016). All of these will affect future risks. Unfortunately, the IPCC has adopted the use of multidecadal climate projections run with added CO_2 and other human greenhouse gases as the primary climate forcings over this time scale (IPCC, 2014). The first Working Group report of the IPCC adopts this view, and subsequent Working Group reports are based on this view. The term "top-down approach" can be also used to characterize its methodology as the global climate models provide the overall foundational structure for the IPCC framing.

The top-down outcome vulnerability approach, however, depends on skillful decadal and longer regional and local climate predictions. However, summaries of multidecadal climate model prediction skill (e.g., Pielke et al., 2012, 2013; IPCC, 2013 Chapter 11), when tested with hindcast runs of changes in regional climate statistics, show little if any skill in this metric over decadal (and longer) time scales. If sufficient skill cannot be shown for these tests, they either should not be used at all, or presented as just model sensitivity tests. We also further documented the failure of regional skill of downscaling from the global models (Pielke and Wilby, 2012). In coming years, and even to an extent at the present, computer power has matured to the extent that global models themselves are achieving sufficient resolution to avoid the need for downscaling, but their regional predictive skill still needs to be improved.

A paradigm shift is, therefore, needed to move away from the current, too narrowly confined top-down IPCC approach based on these models. We have proposed the adoption of the bottom-up, vulnerability approach (Pielke et al., 2012). I anticipate this will be increasingly adopted as the serious predictive limitations of the top-down approach become better recognized. Examples of this more inclusive approach are presented in Kabat et al. (2004), Kling et al. (2020), Kittel et al. (2011), Hossain et al. (2017, 2020a,b), and Pielke Sr. and Hossain (2020). The goal is to focus on the weather (short-term) and climate (longer-term) component of stress, but also consider in-depth, other environmental and social threats. In terms of upcoming opportunities to advance environmental science and to make optimal policy decisions on reducing threats to key resources including with respect to climate, the application of broad-based resource-based assessments are needed, of which climate models are only one tool.

3. Conclusions

I have enjoyed a productive and enjoyable professional career. In this article, I provide some highlights and several research topics which I encourage readers to build on.

My largest pleasure and achievement are the graduate students and post-doctoral research associates I advised or co-advised, and who became my colleagues. I was pleased to play a role in their career development and continue to enjoy collaborating with some of them. This is the highest goal of being an academic scientist. The research knowledge that we jointly introduced advances society. My students were at the University of Virginia, Colorado State University, and the University of Colorado and their theses and dissertations are listed at https://cires.colorado.edu/research/research-groups/roger-pielke-sr-group.

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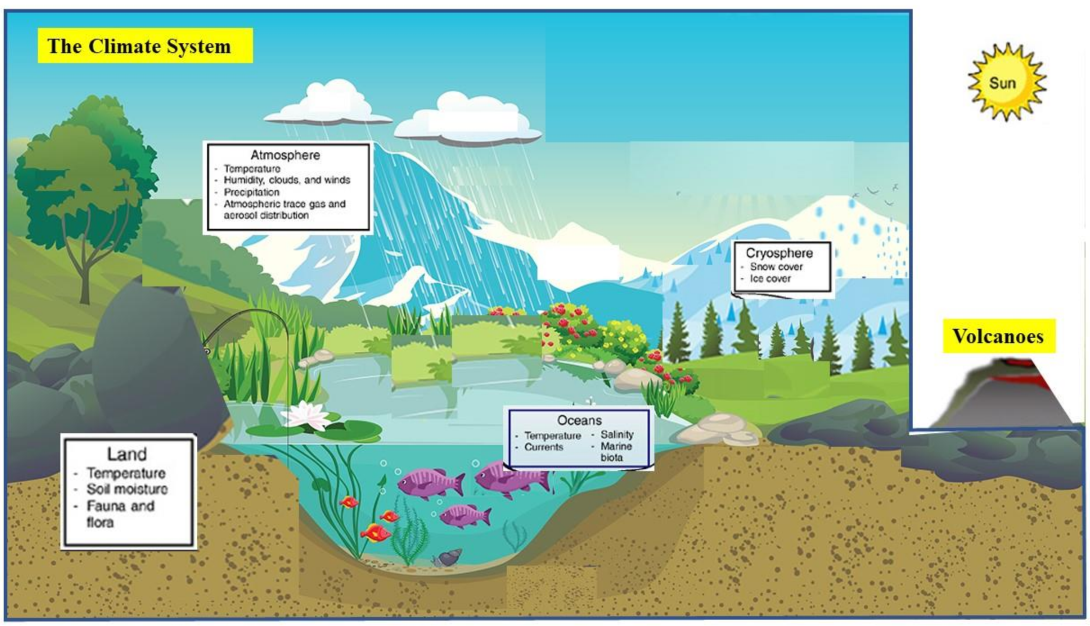

Figure 1: The climate system, consisting of the atmosphere, oceans, land, and cryosphere. Important state variables for each sphere of the climate system are listed in the boxes. For the purposes of this report, the Sun, volcanic emissions, and human-caused emissions of greenhouse gases and changes to the land surface are considered external to the climate system (adapted from National Research Council, 2005 by Olusola Festus, University of Missouri Kansas City in Pielke et al., 2021).