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Review

"Models in Meteorology and Climatology" Fifty Years on

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Abstract: A review is presented of contributions made by the author and graduate students over the fifty years since the publication of a chapter on "Models in meteorology and climatology" by the author in 1967. Advances in the applications of general circulation models, remote sensing, and climate change and paleoclimatology are briefly described in the context of the development of climate science. Publication of the first use of a GCM to simulate Ice Age climate is noted. The application of optical and passive microwave remote sensing to mapping snow cover, glaciers, sea ice and frozen ground are discussed. Our focus was particularly on Arctic conditions. Many of the algorithms were developed in association with the National Snow and Ice Data Center that the author directed from 1976 to 2008.

Keywords: Models; remote sensing; climate change

1. Background

"Models in Geography" was published in 1967 just as I was preparing to relocate from the University of Southampton to the University of Colorado, Boulder, in the following year. The writing of my chapter on models in meteorology and climatology [1] coincided with the beginning of my long collaboration with Richard Chorley on the first edition of *"Atmosphere, weather and climate"*, which appeared in its ninth edition in 2010–a success we never imagined possible [2]!

The chapter made brief mention of general circulation models, which were first released in the 1970s and employed by one of my doctoral students, as I will recount below. The growth of numerical modeling is undoubtedly the major achievement of the meteorological profession over the last four decades. The other primary advance has been in the field of paleoclimatology and climate change that was barely recognized as appropriate for study in the 1960s. Other advances have been made possible by technological developments–the wide use of satellite remote sensing, faster computers and massive databases, and novel instrumentation systems such as ARGOS floats monitoring the world's oceans. This progress in the discipline will be reviewed here and I will also highlight the contributions that I and many of my graduate students have made.

My own trajectory reflects many of the developments in climate science since 1960. My exposure to arctic meteorology and glacial history at McGill University, Montreal and the McGill Subarctic Research Laboratory at Schefferville, PQ by the late Professor F.K. Hare and Dr. Jack D. Ives, respectively, led me into a lifelong interest in cold climates and snow and ice. This history is traced in a review paper [3]. My early work in synoptic climatology evolved into Arctic and mountain climatology, climate change and paleoclimatology. A new direction occurred after 1976 when I became Director of the World Data Center-A for Glaciology, that became the National Snow and Ice Data Center (NSIDC) in 1982. This led me into glaciology and permafrost studies, remote sensing of snow cover, glaciers, sea ice and frozen ground, and data management, as the center grew from two staff in 1976 to ninety in 2008 when I stepped down as Director.

2. Numerical Models of the General Circulation

Among the earliest numerical models of the general circulation of the atmosphere was that developed at the National Center for Atmospheric Research (NCAR) in Boulder, CO by Akira Kasahara and Warren Washington [4]. This model was used by my doctoral student, Jill Williams, to perform the first global Ice Age experiment [5]. Comparison was made between a control run and one with surface boundary conditions for the Last Glacial Maximum (LGM). Jill went on to examine the effects of snow cover on the circulation [6] A proposal to the National Science Foundation to compare the results of the NCAR, Geophysical Fluid Dynamics Laboratory (GFDL), and University of Oregon models was approved, but regrettably was never able to be implemented due to the unwillingness of the other groups to share their model outputs. The application of climate models in paleoclimatic reconstruction was reviewed in Barry [7]. A later student, Gerry Meehl, went on to modeling research at NCAR after earlier completing his MA (1978) and PhD (1986) degrees with me. He subsequently became a leading player in the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports [8]. A diagnostic analysis of observed Arctic pressure patterns compared with those simulated by the Goddard Institute for Space Sciences

(GISS) GCM was carried out by Crane and Barry [9] using synoptic pressure pattern types. Barry and Carleton [10] published a major advanced text on dynamic and synoptic climatology that included a discussion of general circulation models. The availability and utility of cryospheric data sets for model validation was discussed by Barry [11] and a review of models developed for different components of the cryosphere was published [12]. Regional models of the atmospheric circulation in the Arctic were described in a textbook by Serreze and Barry [13,14].

In 1972, a topographic model for solar radiation receipts was coded by Larry Williams and used in assessments of conditions favoring glacierization in the mountains of eastern Baffin Island [15] and later in a study of radiation potential for vegetation growth in a valley in the highlands of New Guinea [16]. A model for atmospheric emittance of infrared radiation in mountain areas was developed at Niwot Ridge, Colorado by LeDrew [17]. Snow cover modeling, using the NCAR Community Climate Model CCM3, was pursued by Susan Marshall (PhD 19890 [18], and Mike Morassutti [19] studied albedo parameterization in sea ice models. In 1996 Lauren Hay undertook an assessment of the Rhea orographic precipitation model in southwest Colorado [20], demonstrating its validity.

GCMs have rapidly evolved over the last two decades. Atmospheric GCMs were coupled initially to slab oceans and then to full ocean GCMs, eventually incorporating sea ice models. Horizontal resolutions were steadily increased and the vertical domain was extended into the upper stratosphere. Land surface models were incorporated and biogeochemical exchanges were added. A major development over the last decade has been the expansion of Climate Model Intercomparison Projects (CMIP 3 and 5) as a background for the Intergovernmental Programme on Climate Change (IPCC) Assessment Reports 4 and 5 in 2007 and 2013, respectively. I was a review editor for the cryosphere chapter of the Scientific Assessment, volume 1 in 2007 and of the polar regions chapter of volume 2.

3. Remote Sensing

While the first meteorological satellite was launched in 1960, widespread use of satellite data for climatological research awaited the creation of gridded products that were readily accessible and freely available from data archives and could be processed by fast computers. These conditions began to be met in the 1990s through NASA's Earth Observation System, although studies using hard-copy images began in the 1970s and 80s. A mapping study of landfast ice along the Beaufort Sea coast of Alaska was carried out by Barry et al. [21] using Landsat imagery. Andrew Carleton (PhD 1982) [22,23] made use of Defense Meteorological Satellite Program (DMSP) negative transparencies, then archived at the National Snow and Ice Data Center, to analyze synoptic systems in the Southern Hemisphere. This imagery was later used by Robinson et al. [24] to analyze snow melt and albedo of Arctic sea ice and to study Arctic spring cloudiness [25,26]. Later it was used to map the global occurrence of night-time lightning flashes [27]. Key and Barry [28] used Advanced Very High Resolution (AVHRR) data in a study of Arctic cloud detection. Key et al. [29] extended this work using fuzzy set algorithms in cloud classification. Early work with passive microwave data for Arctic sea ice extent and concentration was performed by Robert Crane (PhD 1981). Crane et al. [30] using Electrically-Scanning Microwave Data (ESMR), and by Mark Anderson (PhD 1982) Anderson et al. [31] using Scanning Multichannel Microwave Radiometer (SMMR) data. Axel Schweiger (MA 1987) used SMMR-derived snow cover data to compare with station observations of snow cover in Germany [32]. SMMR and drifting buoy data for 1979–1985 were used by Barry and Maslanik [33] to examine Arctic sea ice characteristics and atmosphere-ice interactions. AVHRR and SMMR data were merged in a study of Arctic sea ice and clouds by Maslanik et al. [34]. Jeff Key (PhD 1988), Jim Maslanik (PhD 1988), Mark Serreze (PhD 1989), Alfred McLaren (PhD 1986) and Martin Miles (PhD 1992) were all part of an Office of Naval Research funded project on Arctic Ocean ice, 1986–1992. McLaren undertook a comparison of submarine sonar date on sea ice draft from the 1958 USS *Nautilus* and the 1970 USS *Queenfish* transects of the Arctic Ocean [35,36]. He had been commander of the *USS Queenfish.* Key and McLaren [37] analyzed the statistical characteristics of under-ice keels reported by the USS *Queenfish*. Mark Serreze analyzed sea ice drift in the Arctic Ocean in relation to atmospheric forcing [38,29], while Martin Miles mapped leads in Arctic sea ice from DMSP imagery [40]. A study of plumes from Arctic leads based on airborne lidar measurements was undertaken by Schnell et al. [41]. Andrew Tait (PhD 1996) [42,43] developed an algorithm for passive microwave data to estimate snow water equivalent.

The characteristics, possible causes, and feedbacks involved in the amplification of global warming in the Arctic were detailed by Serreze and Barry [44]. Building on the PhD work of Shari (Fox) Gearheard in 2004 on traditional Inuit knowledge about the environment, Weatherhead et al. [45] analyzed weather persistence at an Arctic station and identified some commonalities with Inuit observations.

Richard Armstrong (PhD 1985) moved from field studies of snow processes to developing algorithms to calculate snow water equivalent (SWE) [46] and developed gridding procedures–the Equal Area Scalable Earth Grid (EASE)–at the National Snow and Ice Data Center (NSIDC), University of Colorado, Boulder, that are widely used for archival and distribution of satellite data products [47]. EASE grid version 2 was released in 2012. Later collaboration of Armstrong with T-J. Zhang at NSIDC led to the development of passive microwave algorithms to map ground freezing over the northern continents [48].

An overview of remote sensing of the cryosphere was presented by Barry [49]) while many aspects of the various components of the cryosphere were detailed in a book on the global cryosphere by Barry and Gan [50]. This addressed snow cover, avalanches, glaciers, ice sheets, ground ice, freshwater ice, sea ice, ice shelves, the past history of ice on earth, and projected future conditions. The status of the components of the Arctic cryosphere in the 21st century was reviewed by Barry [51]. The major changes in summer Arctic sea ice, mass balance of glaciers, ice cap and the Greenland ice sheet, and permafrost thawing were documented.

4. Climate Change and Paleoclimatology

In the 1960s the study of climate change and paleoclimatology was in its infancy. Radiocarbon dating was only a decade old and knowledge of Quaternary glaciations was sketchy. Climatic data were mostly undigitized and difficult to access. Barry [52] digitized the climate records from the stations installed in 1952, under the leadership of John Marr, along the east slope of the Colorado Front Range up to 3,740 m and analyzed the data for 1952–1970. Ray Bradley (PhD 1976) [53] digitized weather records from military forts in the western United States and examined secular climatic fluctuations in southwest Colorado [54]. Bradley [55] went on to publish a text on Quaternary paleoclimatology and a series of works on climate change and paleoclimatology over the next three decades. Records collected at the summit of Pike's Peak, Colorado during 1874–1888 were digitized and analyzed by Diaz et al. [56]. Henry Diaz (PhD 1985) and George Kiladis (PhD 1985) collaborated on studies of global anomalies associated with extremes in the Southern Oscillation [57] and Diaz edited a book on El Niño and the Southern Oscillation [58].

A major advance in the documentation of trends in atmospheric circulation and climatic variables was made possible by the advent of re-analyses, which assembled and quality controlled all available historical observations and input them into a consistent numerical model. Kalnay et al [59] provided the first such retrospective data set known as the National Centers for Environmental Prediction (NCEP)/NCAR re-analysis spanning 40 years, that has since been extended to cover the period from 1948 to present. The European Centre for Medium Range Weather Forecasting (ECMF) Reanalysis (ERA-40) spans 1957–2002; subsequently, several other such data sets with higher resolution have been produced and are widely used.

Another area of paleoclimatological research has involved the application of global climate models with appropriate Milankovich and other forcings, and boundary conditions, to simulate past climatic states. A Paleoclimate Modelling Intercomparison Project (PMIP) has intercompared model results for the Last Glacial Maximum and the Holocene thermal maximum.

5. Concluding Remarks

The last half-century has witnessed major advances in the development and application of models in meteorology and climatology. Subfields concerned with GCMs, climate change, and remote sensing have seen great increases in the associated literature, which is reflected in the unprecedented number of new journals and texts devoted to climate research and related remote sensing and geophysical sciences. I began my career at McGill University in 1958–1959 using punched cards and a sorter. At University of Liverpool in 1960 I used the first-generation English

Electric Deuce computer, programmed in machine language, with punched cards of upper air data from Asheville, NC. At University of Southampton I used a Pegasus computer and autocode, with paper tape. Finally, at University of Colorado in 1968 I employed a programmer for a CDC750. I began work in remote sensing using ERS-1 images in 1974 and progressed to analysis of ESMR data on Arctic sea ice in 1982. Digital analysis of passive microwave data was implemented by doctoral student Rob Crane and Mark Anderson in 1985. Climatology in the 1950s was essentially bookkeeping of climate records. By the 1970s, research on climate change and paleoclimates was growing rapidly, aided by increasing data availability. The role of greenhouse gases on global climate was beginning to be recognized and teleconnections were being investigated.

Many of my graduate students made substantial contributions to the field during their association with me and have continued to do so during their subsequent careers.

Conflict of Interest

All authors declare no conflict of interest in this review.

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