Global Land Ice Measurements from Space

Jeffrey S. Kargel, Gregory J. Leonard, Michael P. Bishop,
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Dedication

We dedicate this book to our families, who endured our absences from them and endured as well our dispositions, whether joyous or vexed, during our time on the book. In dedication we also recognize the world's land ice, those frozen lands from the majestic ice sheets of the white circumpolar realms, to the graceful valley glaciers and fast-disappearing glacier bits; and to those glaciers no longer here.

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Figures

Tables

Acronyms and abbreviations

AABI	Area–Altitude Balance Index
AABR	Area–Altitude Balance Ratio
AAO	AntArctic Oscillation
AAPO	AntArctic–Pacific Oscillation
AAR	Accumulation Area Ratio
ACC	Antarctic Circumpolar Current
ADD	Antarctic Digital Database
ADO	Analytical Discrete Ordinates (method)
AHAP	Alaska High Altitude Aerial Photography
ALE	Antarctic Logistic and Expeditions (a private company)
ALI	Advanced Land Imager
ALOS	Advanced Land Observing Satellite
AMS	Army Map Service
ANN	Artificial Neural Network
AP	Antarctic Peninsula
APAC	Annual Percentage of glacier Area Change
APU	Alaska Pacific University
AR	Assessment Report
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATBD	Algorithm Theoretical Basis Document
ATM	Airborne Topographic Mapper
AVHRR	Advanced Very High Resolution Radiometer
AWS	Automatic Weather Station
BC	British Columbia
BEST	Basic Envisat and ERS SAR Toolbox
BIA	Blue Ice Area
BIRZ	Bare Ice Radar Zone
BJ54	Beijing 54 (coordinate system)
BKG	*Bundesamt für Kartographie und Geodäsie* (Federal Agency for Cartography and Geodesy)
BLM	Bureau of Land Management
BRDF	Bidirectional Reflectance Distribution Function
BRF	Bidirectional Reflectance Factor
CAREERI	Cold and Arid Regions Environment and Engineering Research Institute 182
CAREERI	Cold and Arid Regions Environmental and Engineering Research Institute 593
CBERS	China Brazil Earth Resources Satellite
CCD	Charge-Coupled Device
CCI	Climate Change Initiative
CDED	Canadian Digital Elevation Dataset
CDOM	Colored Dissolved Organic Matter
CEC	*Centro de Estudios Científicos* (Scientific Study Center)
CFCAS	Climate and Atmospheric Sciences
CGI	Chinese Glacier Inventory

CGIAR-CSI	Consultative Group on International Agricultural Research–Consortium for Spatial Information
CIAS	Correlation Image Analysis Software
CIRES	Cooperative Institute for Research in Environmental Sciences
CNES	*Centre National d'Études Spatiales* (National Center for Space Studies)
COART	Coupled Ocean Atmosphere Radiative Transfer code
CONICYT	*COmisión Nacional de Investigación CIentífica y Tecnológica de Chile* (National Commission of Scientific and Technological Investigation)
COTS	Commercial Off-The-Shelf
CP	Check Point
CR-D-InSAR	Corner Reflector Differential Interferometry
CRB	Copper River Basin
CRU	Climatic Research Unit, University of East Anglia
D-B-E	Dinsmoor–Bombardier–Edgeworth
DAR	Data Acquisition Request
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System 118, 596
dGPS	differential GPS 117
DInSAR	Differential radar interferometry
DISORT	DIScrete Ordinates Radiative Transfer model
DLR	*Deutschen Zentrums für Luft- und Raumfahrt* (German Aerospace Center)
DMS	Desktop Mapping System
DMSP	Defense Meteorological Satellite Program
DN	Digital Number (reflects radiation value measured by a radiometer)
D-O	Dansgaard–Oeschger
DOQQ	Digital Orthophoto Quarter Quadrangle
DOS	Dark Object Subtraction
DSM	Digital Surface Model
DSRZ	Dry Snow Radar Zone
DTM	Digital Terrain Model
ECV	Essential Climate Variable
ELA	Equilibrium Line Altitude
ENSO	El Niño–Southern Oscillation
ENSO–SOI	El Niño–Southern Oscillation Index
ENVI	ENvironment for Visualizing Images
EO-1	Earth Observing-1 (satellite)
EOS	Earth Observing System
EROS	Earth Resources Observation and Science
ERSDAC	Earth Remote Sensing Data Analysis Center 147
ERSDAC	Earth Remote Sensing Division (Japan) 238
ESA	European Space Agency
ESRL	Earth System Research Laboratory
ETM+	Enhanced Thematic Mapper Plus
FAC	Fractional Area Change
FAGS	Federation of Astronomical and Geophysical Data Analysis Services
FCC	False-Color Composite
FONDECYT	*FOndo Nacional de DEsarrollo Científico Y Tecnológico* (National Fund for Scientific and Technological Development)
FPRZ	Frozen Percolation Radar Zone
G-DEM	Global DEM
GDEM1	First ASTER Global DEM
GCM	General Circulation Model
GCOS/GTOS	Global Climate/Terrestrial Observing System
GCP	Ground Control Point
GDEM	Global Digital Elevation Map 493
GDEM	Global Digital Elevation Model 247, 639
GDL	Glacier-Dammed Lake
GDS	Ground Data System
GEMS	Global Environment Monitoring System
GeoTIFF	Geographic Tagged Image File Format
GFDL	Geophysical Fluid Dynamics Laboratory
GHOST	Global Hierarchical Observing STrategy
GIA	Glacial Isostatic Adjustment

GIFOV	Ground-projected Instantaneous Field Of View
GINA	Geographic Information Network of Alaska
GIPSY	195
GIS	Geographic Information System 23, 164, 241
GIS	Greenland Ice Sheet 184
GL	Grounding Line
GLACE	GLacier Analysis Comparison Experiments
Glaciers_CCI	Glaciers Climate Change Initiative
GLACIOCLIM	GLACIers, an Observatory of the CLIMate
GLAS	Geoscience Laser Altimeter System
GLCF	Global Land Cover Facility
GLIMS	Global Land and Ice Measurements from Space
GLOF	Glacier Lake Outburst Flood
GNE	Greater Nahanni Ecosystem
GNSS	Global Navigation Satellite System
GPR	Ground-Penetrating Radar
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GSFC	Goddard Space Flight Center
GSI	Geologic Survey of India
GSSI	Geophysical Survey Systems, Inc.
GTA	Glacier Terminus Altitude
GTN-G	Global Terrestrial Network for Glaciers
H-G-E	Hektoria–Green–Evans
HDF	Hierarchical Data Format114
HKH	Himalaya–Karakoram–Hindu Kush
HRS	High Resolution Sensor 115
HRS	High Resolution Stereoscopic (instrument) 348
HRS	High Resolution Stereoscopic Sensor 232
HRTI	High-Resolution Terrain Information
HTP	Himalaya and Tibetan Plateau
IACS	International Association of the Cryospheric Sciences
IandM	Inventory and Monitoring program

ICESMAP	Image Change Evaluation by Subtraction of Multispectral Anniversary Pairs
ICSI	International Commission on Snow and Ice
IDL	120
IDW	Inverse Distance Weighted
IGM	*Instituto Geográfico Militar* (Chilean Military Geographical Institute)
IGN	*L'information grandeur nature* (National Institute of Geographic and Forest Information) 621
IGN	*Institut Géographique National* (National Geographical Institute) 766
IGS	International GNSS Service
IHP	International Hydrological Program
IHS	Intensity Hue Saturation
IKP	International Karakoram Project
IL	Iceberg Lake
IMCORR	Software distributed by NSIDC
IMS	Interactive Multi-sensor Snow and Ice Mapping System 37
IMS	IP Multimedia Subsystem 146
INGEOMINAS	*INstituto Colombiano de GEOlogía y MINería* (Geology and Mining Institute)
INPE	*Instituto Nacional des Pesquisas Espaciais* (National Institute for Space Research)
InSAR	Interferometric Synthetic Aperture Radar
IOP	Inherent Optical Property
IPA	Independent Pixel Approximation
IPG	Institute of Physical Geography, University of Freiburg
IPO	Interdecadal Pacific Oscillation
IPY	International Polar Year
IRS	Indian Remote Sensing (satellite)
IRS LISS	Indian Remote Sensing Linear Imaging Self Scanner
ITCZ	Inter-Tropical Convergence Zone
IUGG	International Union of Geodesy and Geophysics
J-C-M-M	Jorum–Crane–Mapple–Melville (glacier system)

JAROS	238
JAXA	Japanese Aerospace eXploration Agency
JRI	James Ross Island
KATM	KATMai National Park and Preserve
KEFJ	KEnai FJords National Park
L1T	Level 1 Terrain corrected
LACL	LAke CLark National Park and Preserve
LBE	Linearized Boltzmann Equation
LDCM	Landsat Data Continuity Mission
LGM	Last Glacial Maximum
LIA	Little Ice Age
LIAM	Little Ice Age Maximum
LIDAR	LIght Detection And Ranging
LP DAAC	Land Processes Distributed Active Archive Center
LPS	Lightweight Portable Security
LST	Land Surface Temperature
LUT	Look-Up Table
MADOC	Multi-layer Analytic Discrete Ordinate Code
MAE	Mean Absolute Error
MAGRA	Mean Annual Global Radiation modeled for Alaska
MASTER	395
MATLAB	High-level computing language
MDL	Moraine-Dammed Lake
MDOW	MultiDirectional, Oblique-Weighted
MEG	Median Elevation of a Glacier
MELM	Maximum Elevation of Lateral Moraines
met.no	Norwegian Meteorological Institute
METI	Ministry of Economy, Trade and Industry (Japan)
MGM	Morphometric Glacier Mapping
MIS	Marine Isotope Stage
MISR	Multiangle Imaging SpectroRadiometer
MM	Mesoscale Model
MMD	Minimum–Maximum Difference
MO	Mission Operations
MODIS	MODerate-resolution Imaging Spectroradiometer
MODTRAN	MODerate resolution atmospheric TRANsmission (computer program)
MODVOLC	MODIS Thermal Alert System
MSS	MultiSpectral Scanner

MT DEM	MultiTemporal DEM
MTF	Modulation Transfer Function
MWE	Meters Water Equivalent
NAALSED	North American ASTER Land Surface Emissivity Database
NAO	North Atlantic Oscillation
NARR	North American Regional Reanalysis
NASA	National Aeronautics and Space Administration
NBR	Navigation Base Reference
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Center for Environmental Prediction
NDI	Normalized Difference Index
NDSI	Normalized Difference Snow Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NEM	Normalized Emissivity Method
NESDIS	National Environmental Satellite, Data, and Information Service
NIR	Near-InfraRed
NLSI	National Land Survey of Iceland
NNPR	Nahanni National Park Reserve
NOAA	National Oceanic and Atmospheric Administration
NPI	Northern Patagonia Icefield 639
NPI	Norwegian Polar Institute 231
NPOC	14
NPS	National Park Service
NSERC	Natural Sciences and Engineering Research Council of Canada
NSIDC	National Snow and Ice Data Center
NT	Northwest Territories
NTDB	National Topographic Data Base
NVE	*Norges Vassdrags- og Energidirektorat* (Norwegian Water Directorate)
OAR	Office of Oceanic and Atmospheric Research
OBC	OnBoard Calibration

ORE	*Observatoire de Recherches en Environnement* (Observatory for Research in the Environment)
OSCAR	Ocean Surface Current Analyses Real-time
OSU	Ohio State University752
PACC	*Programa de Adaptación al Cambio Climático en el Perú* (Program on Climatic Change Adaptation in Peru)
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PCA	Principal Component Analysis
PCI	120
PDD	Positive Degree-Day
PDO	Pacific Decadal Oscillation
PDOP	Position Dilution of Precision
PF	Polar Front
PGC	Prince Gustav Channel
PI	Principal Investigator
POLDER	POLarization and Directionality of Earth Reflectance instrument
PRISM	Panchromatic Remote-sensing Instrument for Stereo Mapping 129
PRISM	Parameter–elevation Regression on Independent Slope Model 440
PROMICE	PROgramme for Monitoring of the Greenland ICE Sheet
PSD	Physical Sciences Division
PSFG	Permanent Service on the Fluctuations of Glaciers
PSI	Perennial Snow and Ice
PSU	Pennsylvania State University
QB	QuickBird
QC	Quality Control
QEI	Queen Elizabeth Islands
RAMP	Radarset Antarctic Mapping Project
RBV	Return Beam Vidicon
RC	Regional Center
RCC	Radiometric Calibration Coefficient
RES	Radio Echo Sounding
RGI	Randolph Glacier Inventory
RMS	Root Mean Square
RMSE	Root Mean Square Error
RT	Radiation Transfer
RTC	Radiative Transfer Code
RTE	Radiation Transfer Equation
RTK	Real Time Kinematic (survey system)
SAM	Southern Annular Mode
SAR	Synthetic Aperture Radar
SDC	Swiss Agency for Development and Cooperation
SF	Subantarctic Front
SFAR	Steep Front at the Angle of Repose
SILC	Sensor Information Laboratory Corporation
SLC	Scan Line Corrector
SLE	Sea Level Equivalent
SMARTS2	Simple Model of the Atmospheric Radiative Transfer of Sunshine (radiation model)
SMB	Surface Mass Balance
SN	65
SOI	Southern Oscillation Index
SOPAC	Scripps Orbit and Permanent Array Center
SPI	Southern Patagonia Icefield
SPIRIT	SPOT-5 stereoscopic survey of Polar Ice: Reference Images and Topographies
SPOT	*Satellite Pour l'Observation de la Terre* (satellite for observaion of the Earth)
SPRI	Scott Polar Research Institute
SQL	Structured Query Language
SRFT	SAR Feature-Tracking
SRTM	Shuttle Radar Topography Mission
SSI	South Shetland Islands
SST	Sea Surface Temperature
SSW	Sudden Stratospheric Warming
STAR	Science Team Acquisition Request
SWAN	SouthWest Alaska Network
SWIR	ShortWave InfraRed
TES	Temperature Emissivity Separation
THAR	Toe-to-Headwall Altitude Ratio
TIN	Triangulated Irregular Network
TIR	Thermal Infrared
TM	Thematic Mapper
TOPOGRID	Command in ArcInfo software
TP	Qinghai–Xizang (Tibet) Plateau
TRIM	Terrain Resource Information Management
TSAM	Toe-to-Summit Altitude Method
TSL	Transient Snow Line
TTS/WGI	Temporal Technical Secretary for the World Glacier Inventory

TUD DTM	Technical University of Darmstadt Digital Terrain Model
TVZ	Taupo Volcanic Zone
UNESCO	United Nations Educational, Scientific and Cultural Organization
USAID	U.S. Agency for International Development
USGS	U.S. Geological Survey
USNPS	U.S. National Park Service
UTM	Universal Transverse Mercator
VI	Vega Island
VICC	Valdivia Ice and Climate Change (a series of conferences held in Valdivia, Chile)660
VIS	VISible
VM	Virtual Machine
VNIR	Visible and Near InfraRed
WAIS	West Antarctic Ice Sheet
w.e.	water equivalent
WC2N	Western Canadian Cryospheric Network
WGI	World Glacier Inventory
WGMS	World Glacier Monitoring Service
WGS 84	World Geodetic System 1984
WIS	Wilkins Ice Shelf
WRC	25
WRS	Worldwide Reference System
WSRZ	Wet Snow Radar Zone
WV2	WorldView-2 (satellite)
WWW	World Wide Web

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PROLOGUE

Scientific and public perceptions about the importance of fluctuations in glaciers and ice sheets

Jeffrey S. Kargel

P.1 EARLY SCIENTIFIC RECOGNITION OF THE SIGNIFICANCE OF GLACIERS

There have been few revolutions in Earth sciences as impactful as the discovery of modern and ancient glaciation. Glacial theory is exceeded in impact perhaps only by the advent of superposition principles, biological evolutionary theory, radiometric dating, and plate tectonics. The intellectual reach of glacial theory is vast and is intertwined with the development of physics and the establishment of Earth's deep-time geological history. Many of the implications of ancient and modern flowing ice were recognized immediately following the first detailed and most compelling scientific publication and presentation by Louis Agassiz in 1840. Glaciers have been a point of fascination for scientists from many disciplines ever since then, and remain so today. Though Agassiz was among the founders of modern glaciology and often is credited as the father of the field, Jens Esmark and several others had previously arrived at glacial interpretations of boulder erratics and other landscape elements. Esmark concluded, a decade before Agassiz published his first work on glaciers, that glaciers in his field area of Scandinavia had once been more extensive than they are now (Andersen 1992).

From the beginnings of modern glaciology and evolutionary theory in the early and mid-19th century, glaciation has been recognized as a dynamic signpost of changing climate, a controller of habitats, and a driver of biological evolution (Agassiz 1840, Darwin 1859, notwithstanding arguments between those two on evolution). The root of this interest derives from the very visual dynamic nature of glaciers, and their close relationship to the triple point of water (H_2O), and hence their relationship to climate; and though the public would not phrase it this way, these same things motivate public interest as well. Agassiz's work had immediate impact among physicists, such as John D. Forbes, who formulated a viscous flow explanation of glaciers.

The interest of 19th century geologists in glaciation is well documented and primarily will not be repeated here. These days, the world over, glaciology, geology, physical geography, and climate studies tend to be closely affiliated. There is a perceived less direct connection with modern physics, which today is usually viewed as an analytical toolbox by glaciologists and geologists. Modern culture in the physics community tends to rank physics as somehow a "harder" science than either geology or glaciology; in fact, this was clearly not the case in the 19th century, when all of these, and many other disciplines, were viewed as components of natural philosophy, and the chief drivers of science were highly interdisciplinary. The crucial role played by physics in understanding glaciation and relationships to climate is well recognized; possibly less recognized is the role that glaciation and glaciology have played in catalyzing the interests of physicists and the development of physics.

A nascent theory of planetary climate control by radiatively active atmospheres began with the calculations of Jean Baptiste Joseph Fourier, who otherwise is known for many advances in mathematics and the study of heat transfer. Fourier (1824, 1827) recognized that Earth should be far colder if its surface had been warmed only by its absorption of solar illumination; he performed benchtop experiments, which provided the insight that perhaps the atmosphere contains a gas that allows sunlight in but traps heat. Fourier included an intriguing postulate maintaining that, had it not been for the Sun, Earth's surface temperature would be only slightly colder than the polar countries are, because that is the background temperature of the sky due to starlight and other sources of heat. Though incorrect quantitatively, it was a prescient statement about a cosmic background temperature, whose value was then deduced to be about −40°C,[1] being a little colder than Earth's icy polar realms, Fourier claimed. With the Sun, but without our atmosphere, the surface of Earth should still be colder than it actually is, he deduced. Fourier showed at length that geothermal heat was utterly insignificant in warming Earth's surface, despite its prodigious ability to maintain a warm interior for geological durations. His entire set of calculations was based on a knowledge of conductive heat transfer (the theory which he first developed), but lacked the advantages of the Stefan–Boltzmann Law, which took another half century to be formulated using key inputs from John Tyndall, who drew heavily from Fourier's advances. Therefore, a theoretical basis for the warmth of Earth's surface was at that time lacking, although the warmer-than-expected Earth surface was clear from calculations. Since the Earth's interior heat flow already had been approximated (and found negligible in controling Earth's average surface temperatures), it became evident that the heat transfer mystery was somewhere in the atmosphere.

After the death of Joseph Fourier, but clearly motivated by his work, experimental measurements by John Tyndall (1863, republication in 1893) began in 1859 on the radiative transfer properties of gases identified as likely contributors to the greenhouse effect, as it became known: primarily water vapor; secondarily carbon dioxide. Tyndall later became a leader in the early development of radiative transfer theory, following Fourier. Tyndall's experiments and interest in radiative transfer stem clearly from formative experiences he had among the glaciers of the Alps. Tyndall was an avid alpinist.[2] Throughout his career, glaciology—his contributions including an early and scientifically accurate sketch of Mer de Glace (French Alps), a theory of glacial flow, and field measurements of glaciers, among others—was interleaved with laboratory work explaining the greenhouse effect. By 1859, the intriguing phenomenon of glaciation and the newly inferred existence of climate change, argued compellingly by Agassiz, was already profoundly influencing the development of modern physics through Tyndall's work.

James Croll, initially an amateur scientist inspired by discussions with Charles Lyell, in an 1864 paper and then in an 1875 book provided a new hypothesis on the origin of glacial–interglacial cycles. Croll (1875) provided a detailed account of his proposal that climate and glaciers were affected by changes in the amount of sunlight received by the Northern and Southern Hemispheres of Earth due to cyclic changes in the eccentricity of Earth's orbit and the obliquity of the spin axis, which others had worked out from astronomical theory. Fleming (2006) provides an excellent review of Croll's ideas and how they relate to the later, more detailed, and better-known work of Milutin Milankovitch (1941). This theoretical work was largely validated by detailed and globe-spanning studies of Earth's sedimentological and glaciological record (Imbrie and Imbrie 1986). Croll advocated the crucial role played by feedback mechanisms, including changes in ocean currents, such as the Gulf Stream, in controlling the onset and pattern of glaciation as an indirect result of astronomical perturbations. Croll's main purpose was to explain glacial–interglacial cycles, but he also described in detail the origins of coal and other matters of sedimentology. He argued against glaciations having geological causes (such as mountain building and continental drift, which already was being discussed), though he allowed that those processes may affect glaciation. Alfred Russell Wallace (1879), and many others, wrote in support of Croll's hypothesis.

Svante Arrhenius (1896, 1908) made some astronomical observations and calculated that CO_2 (which he referred to as carbonic acid)—even as a

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[1] The cosmic background temperature is now known to be −270.45°C and is related to Big Bang radiation rather than distant starlight, and has no significance for the thermal regime at Earth's poles.

[2] The massive Tyndall Glacier in the South Patagonia Icefield and Tyndall Glacier in Colorado's Rocky Mountain National Park (a small cirque glacier) are named for him.

trace gas in Earth's atmosphere—is a potent greenhouse gas and works with water vapor to warm the Earth's surface. He and other scientists showed that a 4–5°C global cooling (sufficient to cause ice ages) could have been brought on by a 50% reduction in atmospheric CO_2; that reduction could plausibly have occurred by reduced emissions of geological sources of CO_2 and geochemical uptake of CO_2 into the solid Earth by rock weathering and carbonate deposition. He also recognized that Earth's obliquity and orbital eccentricity variations would eventually bring on a new ice age. He felt that industrial emissions of CO_2 could double atmospheric CO_2 over a period of several millennia (later he scaled that back to a few centuries), raise global temperatures by 5–6°C, and thus help save the world from what he thought to be the impending grip of readvancing ice (Arrhenius 1908). He could not have predicted the myriad additional climatic effects and impacts that just 1°C warming has had to date.

A contemporary of Arrhenius and one of the most prescient theorists in the history of Earth and planetary science, Thomas Chrowder Chamberlin (1899), made the strongest link yet between greenhouse gas abundances, net carbonate deposition and dissolution, the waxing and waning of glacial climates and of the great Pleistocene ice sheets, and future anthropogenic greenhouse warming over a period of millennia. Arrhenius and Chamberlin reinforced the foundations of climate change research; there was little to criticise scientifically either then or now. However, until another century had passed, recognition of their contributions was largely restricted to the geologic past.

What these classic scientists—Fourier, Agassiz, Forbes, Tyndall, Darwin, Wallace, Croll, Arrhenius, Chamberlin, and Milankovitch—have in common is that they dared to think on planetary scales, and they trusted either well-validated physics theory or common sense interpretations of the Earth's landscape; they let the inferences of basic observation, math, and logic drive bold conclusions. Although Fourier died before the advent of modern glacial theory, the others listed here had another thing in common—they were fascinated by glaciers as a planetary phenomenon, by the evidence of glacier fluctuations, and by the implications of these fluctuations for colder past climates and, hence, for climate change on a planetary scale. Several of them spent much time on glaciers and pondered Earth's climatic future.

In the mid-1800s the link between climate state and greenhouse gases was still mainly circumstantial. The key missing parts of radiative transfer and atmospheric theory were developed in thermodynamic theory, which became largely complete in the 1870s, and in electromagnetic and radiation theory, which were largely understood before the turn of the 20th century, aside from quantum aspects, which took a little longer. Thus, it is not surprising that the recent climate history of the Earth and the role of the greenhouse effect in warming the Earth was first explained by physicists and mathematicians, but it was the power of basic empiricism and interpretation of landform evidence related to glaciation that drove climate evolution studies. The immense and geologically recent climate changes begged an explanation, and so geologists, physicists, and astronomers looked to the solid Earth, to the atmosphere, and to the Solar System beyond Earth to find an explanation.

Many famous physicists weighed in on the rapidly developing field of glaciology in the decades following Agassiz's discoveries. John David Forbes (1846) maintained that glaciers behaved with a plastic rheology and flowed with viscous characteristics; he drew an analogy between glaciers and lava flows, and made field observations of the flow of Mer de Glace. Forbes (1855) critically commented (correctly) on a model that tried to account (incorrectly) for glacier motion by thermal expansion and contraction (Moseley 1855). When Moseley (1869) later returned with a detailed mathematical physics model of glacial viscous deformation, and concluded that glacier weight alone would not drive the deformation, James Clerk Maxwell (1869) responded with a brief communication about slow viscous deformation mechanisms; thus, Maxwell and Forbes were thinking about ice rheology in a way Moseley was not. When glaciers were discussed, physicists listened, reacted, and contributed. Michael Faraday discovered regelation, and Hermann von Helmholtz applied that discovery to glacier flow processes. William Thomson (Lord Kelvin) and his brother James Kelvin were both major figures in experimental and theoretical approaches to the motion of glaciers. These physicists made big contributions in other areas of science, but in the mid and late 19th century it was almost the popular fashion of physicists to deal with glaciation in some way. Glacier studies also permeated down to humble student inquiries, including an essay by no less than the young Albert Einstein.[3]

Walker and Waddington (1988) wrote a review of "the early discoverers"—glaciologists, geologists, and physicists—who developed the early theory of glacier flow; they tell the story of how many able physicists flatly failed to explain much about glaciers, despite trying (although some succeeded famously). Some physicists, such as Einstein, did better as humble young students than later as accomplished physicists in matters glaciological. Although it is difficult to find fault with Einstein, it happens that in one of his last writings on the topic of glaciation, he subscribed to a hypothesis that almost immediately was revealed to be demonstrably wrong;[4] even the greatest scientists are fallible.

Radok (1997) provides a review of the origin and early development of internationally coordinated glacier observations, which became known as the World Glacier Monitoring Service based in Zurich, Switzerland (see Section 1.4.1). While science was blossoming around the world, the World Glacier Monitoring Service gained its ancestral foothold in late 19th century science, beginning with the 1894 founding of the Glacier Commission Internationale (CIG)—under the lead of François-Alphonse Forel—at a geological congress in Zurich (Forel 1895). The CIG's second President, Eduard Richter, Professor of Geography at Graz University, in 1899 urged increased efforts toward measurement and understanding of glacier mass budgets, seasonal speed variations, and moraines. In 1903, the third CIG President, Sebastian Finsterwalder, Professor of Analytical Geometry and Calculus at the Munich Technische Hochschule (TH), presented a model that related glacier sizes and shapes to mass balance changes (Radok 1997). Finsterwalder is otherwise known for use of vector terminology in the early development of quantitative aerial photogrammetry, thus helping to found the basis of a technology that today looms large in satellite-based analysis of glaciers.

The connections among climate, glaciers, and the solid Earth beneath the glaciers also received much attention in those early decades of modern glaciology. The dynamic interactions among these components of the Earth were perhaps most evident to glaciologists who spent their time either working in or growing up amongst the world's most active orogenic belts. For example, in 1888 Olinto De Pretto, who was born at the foot of the Italian Alps in Schio, wrote about *The Influence of the Raising and the Degradation of Mountains on the Development of Glaciers*. De Pretto (1903) later contributed to the theoretical development of mass–energy equivalence (briefly mentioning uranium and thorium decay transformation of mass to energy) and thus might have been a help to Einstein's theoretical work, though their respective physics differed totally (De Pretto's physics turned out to be wrong, and Einstein's well validated).

Active foundational glaciological research, by physicists and others, continued into the early 20th century. Wegener (1912, 1915) famously formulated the continental drift theory (Frankel 2012), but he was also fervently into Greenland field studies; he drilled an ice core, probed the thickness of the ice sheet, published on ancient climates (Köppen and Wegener 1924), and went on to die there as well. Greenland geology integrated closely into his continental drift hypothesis. Glacial geomorphology—including the global pattern of the great Permian glaciation—also helped him link continents into a former megacontinent. Ironically, though he was in need of a deformation mechanism for what later became known as plate tectonics, the viscous flow of glacial ice—which we find to be so evident on the Greenland ice that Wegener knew so well—barely, if at all, entered into Wegener's ideas on how continents moved across the face of the

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[3] Albert Einstein, 17 years old and starting university studies at what now is ETH-Zurich, presented an examination essay on "Evidence of the earlier glaciation of our country" (Einstein 1896). His essay was mainly on moraine evidence for the former more extensive glaciation of Switzerland. It was objective, mainstream, and correct, but fully devoid of the greatness Einstein would soon reveal.

[4] Glaciology was never key to Einstein's work, but in his later years he wrote a foreword to a book in 1953 (published in 1958, after Einstein's death; Hapgood 1958) on polar wander. Hapgood's hypothesis was that the asymmetric deposition of polar ice resulted in rotation-induced torque on the lithosphere, which drove the polar lithosphere toward the equator, thus explaining the sudden climatic shifts in Earth's record. The revolution in plate tectonic theory began the year of Hapgood's book publication. Within a few years, the overwhelming evidence for plate tectonics undermined the credibility of Hapgood's hypothesis. Einstein, alongside his effusive admiration of Hapgood, also included notes of caution about the hypothesis. When Einstein wrote the foreword, he understood the value of boldness and creativity in science, but he could not have known how wrong Hapgood was.

Earth. Nevertheless, the big picture of shifting continents and shifting climate and waxing and waning of ice sheets was at the heart of this theory, and today still is important in the more comprehensive theory of plate tectonics.

A few years before Wegener published his first classic paper on his theory of continental drift, another continental drift hypothesis—very similar to Wegener's (probably mutually independent, Frankel 2012)—was published in a paper by Frank Bursley Taylor (1910). Taylor included a deformation analog, though not actually a mechanism. Taylor was a glacial geomorphologist, and his experience showed in what he proposed as homologous Pleistocene moraine patterns in North America and convergent plate margin patterns in places like Indonesia and the western Pacific. Taylor clearly was thinking in terms of relatively thin-skinned ice sheet–like deformation of the continents along convergent boundaries, as well as rifting along places like the Mid-Atlantic Ridge. Wegener, though highly experienced in field glaciology, did not seem to apply much insight from that experience to his continental drift ideas (Frankel 2012).

Physicists of the 19th century were engrossed in theory development for several key natural phenomena including heat and thermodynamics, mass, light, magnetism, electricity, gravity, rheology, and glaciers. Physicists were also pursuing validation of theory using elegant but simple benchtop experiment approaches; they were looking at phenomena easily seen and measured, and which carried both immensely practical and less tangible concepts that formed the technical foundation of our modern civilization. Similarly, glaciology offered a rich variety of observable phenomena that were readily understood at a basic and almost instinctive level, but which posed vexing challenges to explain scientifically.

Glaciers—past, present, and future—were at the nexus of mid and late 19th century scientific advances in physics and geology. The impacts of glacial theory extended throughout the natural sciences by the start of the 20th century. Taylor's and then also Wegener's ideas on continental drift or creep took more than a nugget of insight from glacial flow (as well as mechanical and geological inaccuracies and informational gaps). The essence of their hypothesis turned out to be on the whole correct, but, it was partly rooted in an analogy to what by 1910 had become a well-known tangible phenomenon—that of glacial flow, which in the previous century was an exciting novelty in scientific considerations.

Glaciology in the 19th century helped define the emergent field of biogeography. John Muir famously arrived at the glacial hypothesis of valley development in the Sierra Nevada and proposed Pleistocene glaciation to explain the geographic range of the giant sequoia (Muir 1876). Wallace (1879, 1880, 1886, 1889) presented detailed treatises on continental glaciation and other Earth changes, as well as a hypothesis of how the waxing and waning of ice sheets would affect animal and plant migration and primary succession.

Glaciation has figured prominently and repeatedly in the development of plate tectonic theory, including the important aspects of postglacial rebound, which provides some of the best information on upper mantle and lithospheric rheology, and insights from glacial creep into mantle creep processes (Weertman and Weertman 1975). Rheological characterization of ice and glaciers largely preceded and has helped to motivate rheological studies of mantle silicates and studies of mantle convection. Thus, glacier physicists and geomorphologists were concerned with the rheology of both ice and silicate materials. Glacier rheology deduced from field observations and lab studies (starting with Glen's Flow Law; Glen 1955, 1958; and more recent lab work by Durham and colleagues; reviewed in Durham et al. 2010) and theoretical applications to glacial flow (starting with Nye 1953, 1957, 1960 and Paterson 1994) underpins modern analytical and numerical glacial flow modeling in a major way. Ice rheology is also key to tectonic, geologic, and thermal modeling of the icy satellites of the gas giant planets and of Martian polar caps and glaciers (Durham et al. 2010).

The importance of glaciers to many great classical scientists of the 19th century, and still today for scientists across many disciplines, stems mainly from glaciers' extremely visual display of dynamics and their evolution on human-observed timescales. The significance of this for scientists is not much different than for the layperson. The graceful curve of medial moraines, the wave patterns of ogives, the arcs of crevasses, the symmetry of parabolic form, and blueness of light scattered within are each spectacular; the sum of the parts, which we call glaciers, is something of inexplicable beauty. The physical phenomena presented by glaciers are equally amazing; superlatives aside, the phenomenology is measurable and explicable by science. John Tyndall

(1863, republished in 1893) in his 1863 article—and in a public lecture explaining the greenhouse effect and meteorological phenomena based on the radiative opacity of water vapor as well as describing the supportive experimental evidence—wrote "we conceive the invisible by means of proper images derived from the visible, and purify our conceptions afterwards." Though he was specifically referring to radiative transfer through water vapor, his statement applies equally to all science, including the science of glaciers, to which Tyndall contributed immensely. The fact is, despite their geographic remoteness, glaciers are eminently tangible in the processes they embody and display.

Starting with J.D. Forbes and continuing for generations and still today, glaciologists have spent thousands of person-years in the field making measurements of many types. Through the 20th century, the knowledge of glaciers increased dramatically through new geophysical field-sounding methods, application of aerial photography, new lab data on the mechanical properties of ice, new analytical models and early computer numerical models of glacier behavior, and access to an ever-increasing number of glaciers. However, on the global scale, the vast area covered by glaciers and ice sheets and the difficulty and cost of their study has sharply limited ground-based and airborne investigations. Volume IX of *Fluctuations of Glaciers* (WGMS 2008), one in a series of periodic reports published by the World Glacier Monitoring Service, most recently included data—mainly field-acquired observations—for glaciers in 28 countries and other geographic entities. Glacier frontal positions, for example, are reported for 605 glaciers (not all of these have data for more than one year), roughly 0.3% of the world's glaciers. Mass balance data are much more limited due to the great effort needed to gain this information from field-based observations, which remains the most reliable and accurate method.

With the advent of satellite imaging and remote geophysical probing, entirely new ways of looking at glaciers became available; from the very moment ERTS-1 (Landsat-1) was launched, satellite applications to glaciology began. Places as remote and immense as Antarctica and the Himalaya could be mapped in their entirety and the dynamics of ice sheets and glaciers measured (Southard and MacDonald 1974, Krimmel and Meier 1975, Østrem 1975, MacDonald 1976, Rott 1976, Swithinbank et al. 1976, Orheim 1978, Rundquist et al. 1980, Williams et al. 1982, 1995, Berg et al. 1982, Howarth and Ommanney 1986, Lucchitta and Ferguson 1986, MacDonald et al. 1990, Lucchitta et al. 1991, 1993, 1994, 1995, Bindschadler and Scambos 1991, Scambos et al. 1992, Ferrigno et al. 1980, 1993, 1994, Bishop et al. 2000). From those early satellite-based studies, and midway through production of the *Satellite Image Atlas of the Glaciers of the World* (Ferrigno and Williams 1980 and the whole series by Williams, Ferrigno et al., Vols. A–K), GLIMS and other systematic satellite-based surveys of the world's land ice were conceived and implemented (Kieffer et al. 2000, Bindschadler et al. 2001, Raup and Kargel 2012). As the number of satellites and the capabilities of their sensors have improved, so too has the technology to extract information from these sensor data. Data relevant even to mass balance—just 10–20 years ago thought exclusively the domain of field investigations (Scherler 1983)—now can be acquired with the use of satellites. This book is largely about modern techniques of glacier mapping and analysis using satellite data, the contributions of satellite analysis to regional and world glacier inventories, and use of these data to enhance understanding of glacier–climate–land–ocean linkages (Bishop et al. 2004, Kargel et al. 2005, Raup et al. 2007, Bolch et al. 2012, Arendt et al. 2012, Raup and Kargel 2012).

P.2 THE PRACTICAL AND PERCEIVED IMPORTANCE OF GLACIERS TODAY

P.2.1 Modern understanding of climate change due to greenhouse gases and other causes

The two related concepts of natural and anthropogenic greenhouse effects have been well developed in theory for over a century but the latter has been widely accepted by scientists only for the past 40 years, during which time evidence has mounted exponentially in its favor. However, the evidence indicates that a much more rapid rate of global warming is occurring than was thought possible a century ago, mainly because of the exponential growth in anthropogenic greenhouse gas emissions. Earth's climate is a little less sensitive to CO_2 concentration (gauged by the amount of global warming or cooling for a given change in CO_2) than what Arrhenius calculated, because now we have a greater understanding of the important negative feedback of increased cloud cover as CO_2 rises.

Rather than saving the world *with* global warming as Arrhenius suggested, saving the world *from* anthropogenic greenhouse warming has emerged as one of the world's biggest challenges. Global climate change has some positive effects but many serious deleterious ones, which pertain as much to the rapid pace of global warming (unanticipated by Arrhenius) as to its magnitude.

Besides the influences of greenhouse gases on climate and glacier variations, other climate-forcing phenomena are also recognized and now very widely accepted, including orbital variations (Croll 1875, Milankovitch 1941, Hays et al. 1976, Berger 1978, Muller and MacDonald 1997, Ruddiman 2003), large volcanic eruptions (Robock 2000), and solar activity cycles (Bard and Frank 2006). The important roles of planetary gravitation-driven and rotation-driven cycles in affecting Earth's climate were confirmed in the landmark studies of Hays, Imbrie, and Shackleton[5] (1976) and Imbrie and Imbrie (1986), who documented sedimentary rhythms matching expectations from astronomical theory.

The Sun itself is steadily brightening along the stellar main sequence, but by less than 1% per hundred million years (Sagan and Mullen 1972). The sunspot cycle alone accounts for an oscillation of about 2 W m^{-2} (or about 0.15% of total solar irradiance) on an 11-year cycle, and about twice that on a cycle of several centuries. Solar activity variations could account for 0.1–0.2°C oscillations of global temperature (not including feedbacks, which could increase the impact). The climate impact from solar activity cycles appears to be an order of magnitude less substantial than needed to explain ice ages. Bard and Frank (2006) considered solar activity variability to be a possible contributing cause of the Medieval Warm Period and Little Ice Age, but that overall it is a secondary effect modulating the climate changes induced by other causes.

Geological and solar evolution and solar oscillations can control huge planetary-scale climatic changes without any human influences, as the rock records of Mars and Venus attest. The extreme climatic fluctuations of those planets as well as of Earth reinforce prevailing scientific theories and models of climate change controlled partly by greenhouse gas abundances in geologic deep time (Kirschvink 1992, Hoffmann et al. 1998, Baker 2001, Bullock and Grinspoon 2001, Jakosky and Phillips 2001, Kasting 2003, Kargel 2004, Kasting and Howard 2006, Wilson et al. 2007, Winguth et al. 2010). The physics of radiative transfer (see Chapters 2, 3, and 33 of this book by Bishop et al., Furfaro et al., and Kargel et al., respectively) are unchanged with or without humans. With anthropogenic climate change occurring ever more rapidly, no legitimate questions are being raised about the fundamental planetary habitability of Earth in the same way that habitability is being explored for exoplanets (Kasting 2011) or for Venus in the past (Grinspoon and Bullock 2007). The magnitude of anthropogenic climate changes—even in worst-case scenarios—is simply too small to call into question Earth's habitability for life in general. However, the ongoing mainly human-caused changes to the Earth's biosphere and lithosphere have motivated a new term for our epoch: the Anthropocene (Crutzen and Stoermer 2000). There are few serious suggestions that this informally defined human-affected geologic epoch will be comparable with the first-order geologic transitions in Earth history, such as the atmosphere and climate-change–linked Proterozoic/Paleozoic transition (Kasting 2003, Maruyama and Santosh 2008), but the term "Anthropocene" does have rising currency within the scientific community, as the term connotes widespread deep-cutting changes to the Earth system.

Climate change has been linked to the rise and fall of ancient civilizations (Binford 1997, Peterson and Haug 2005, Dugmore et al. 2007). The impacts of more recent climate changes may have been felt in the economies of many poor nations and may affect the political stabilities of some of them (Dell et al. 2008). Some 20th–21st century economic declines and demographic shifts within the United States also have been linked to climatic fluctuations (Feng et al. 2012, Hornbeck 2012). Hence, the roles played by 20th and 21st century climate change on the global economy and even on the suitability of Earth for modern civilization are serious needed topics of discussion. In much the same way as glaciers are important to climate change, they also are necessarily a part of one of the most important global scientific and political discussions of our day. Not surprisingly, such "pocketbook" topics engender much controversy. This book is not about those

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[5] The third author was the great nephew of the polar explorer Ernest Shackleton. He was also the intellectual force behind the development of oxygen isotope geothermometers and magnetic dating of sedimentary rocks, both of which have been crucial in the establishment of Earth's climate and glacial history.

humanly relevant matters, it is specifically about the pure record of Earth's glacier state and dynamics and their links to climate change and other dynamic components of the physical Earth system.

It is now accepted that climate and climate change on Earth are controlled by: solar main sequence brightening (timescales for major changes 10^8–4.5×10^9 years), biological influences on atmospheric composition (10^9 years), geological controls by mountain building and the distribution of continents and interaction of rock weathering with the biosphere (5×10^6– 5×10^8 years), obliquity and eccentricity variations (10^4–10^6 years), short-term solar activity cycles (10^1–10^3 years), greenhouse gas uptake and release from the solid Earth (10^4–10^8 years when natural, 10^2 years due to industrial emissions), soot emission and deposition (10^1–10^2 years), redistribution of heat by ocean currents (1–10 years for the faster changes), and acid aerosols injected into the stratosphere by volcanic eruptions (1–10 years). The Sun keeps its own schedule, as does the solid Earth. Humans mainly affect greenhouse gas abundances, which top the list for potent effects on climate, and soot.

Ensemble models combining the effects of orbital variations, volcanic aerosol emissions, solar activity oscillations, and greenhouse gas emissions are pretty good at explaining 20th century decadal climatic fluctuations and long-term warming (Meehl et al. 2003, 2004). Anthropogenic greenhouse gases are forcing inexorable warming and are largely responsible—according to prevailing scientific thought and modeling—for a century-long reversal of slow global cooling that had been under way for millennia due to orbital variations (Kaufman et al. 2009). Arrhenius (1908) was right in his lab measurements and math, though he somewhat overestimated climate sensitivity because he did not take full account of negative feedbacks, such as cloud influences, now known to be part of the system. Arrhenius also lacked understanding of how rapidly greenhouse gases would increase and, therefore, miscalculated the timescale of climate warming; he also failed to recognize the deleterious impacts of climate change, and thus had the wrong cost/benefit relation.

P.2.2 Modern impacts of changing glaciers and ice sheets on people

Glaciers are among the most dynamic elements of the solid Earth and are fascinating in their own right. This was enough to drive largely esoteric inquiries by physicists, geologists, and glaciologists during the 19th century, when the implications of greenhouse gas emissions were little more than distant considerations and when common snow avalanches seemed more of a concern to human well-being than glacier fluctuations. Additionally, by the mid to late 19th century, glaciers were at their greatest elongation of the Little Ice Age, driven there ultimately by Jupiter's (and somewhat by Saturn's) gravitational influences on Earth's orbital eccentricity and by Earth's spin–axis obliquity cycle and precession of the spin axis (Croll 1875, Milankovitch 1941, Hays et al. 1976, Berger 1978, Imbrie and Imbrie 1986, Muller and MacDonald 1997, Ruddiman 2003). The modern idea of ongoing anthropogenic greenhouse gas-driven climate change stems straight from that era of fervent observation, theoretical development, and experimentation regarding Ice Age Earth and modern glacial activity.

Not recognized in the 19th century, glaciers and ice sheets are also an important freshwater resource, an important contributor to ongoing sea level rise (Meier 1984, IPCC 2007, Rignot et al. 2011), and a cause of serious natural hazards. Because they are close to the melting point and react strongly to small changes in climate, glaciers provide some of the clearest evidence of climate change and constitute key variables for early-detection strategies in global climate-related observations (GCOS 2004, 2006). The most crucial humanly important aspects of glacier and ice sheet fluctuations depend on where one lives—near the sea, in a glacierized mountain valley, or on a farm downstream of a glaciers, for instance.

In coral atoll nations, on barrier islands, and marine deltas—places like the Maldives, New Orleans, New York City, the Florida Keys, the Netherlands, and the Mekong Delta—sea level is a big issue; whereas alpine glacier change represents a warning sign to those coastal people, it is the large ice masses, such as Greenland, that fuel the greatest concern about sea level change. As Alley et al. (2010), Kargel et al. (2012a), and Chapter 8 of this book "Mapping of glaciers in Greenland" by Stearns and Jiskoot point out, the Greenland Ice Sheet and peripheral ice bodies are melting rapidly enough this century to be a fate-determining concern to the world's populations who are most vulnerable to coastal infringements by the sea. The pace at which the large ice sheets and largest ice caps are melting is such that the biggest impacts for most other people this century are apt to include costs incurred in the construction of new airports and seaports where vulnerable ones are flooded, higher food prices where delta farmlands are inundated, loss of tourism on some barrier islands, and increased insurance premiums and taxation to cover catastrophic losses related to storm damage of coastal populations and infrastructure. Melting in Greenland, Antarctica, and the largest ice caps is thus immediately highly consequential for comparatively few people (a few million) and an increasingly important pocketbook issue for billions of others. Sea level rise of just a few decimeters this century, then eventually (in a few centuries) a few meters, is also an enormous ecological issue in places like the Florida Everglades and the lagoons of coral atolls.

For people living in glacierized mountain valleys—again numbering a few million worldwide—the impacts of climate change on fast-responding valley glaciers, particularly those in the more temperate or maritime environments, pose the greatest concern. For many of these people, glaciers supply water for drinking, irrigation, heavy industry, electrical power, and sanitation. For others, the release of too much water at once (e.g., glacier lake outburst floods) can be a life-and-death issue irrespective of whether it is linked to climate change or simply part of the *modus operandi* of normal glaciers. There is also an issue regarding people's well-being, where glacier runoff drives hydroelectric power projects, vital for electrical power and reliable drinking water. If climate changes, then glaciers change, and these changes can be for the better or worse; they are individual and circumstance dependent. Clearly, the next generation to live in glacierized mountain regions and lowland coastal areas worldwide will not live in the same way or as securely as today's generation.

Recent glacier-related disasters in the Himalaya–Karakoram region—including the Attabad landslide that formed glacier meltwater-fed Lake Gojal (Kargel et al. 2010), the Gayari ice avalanche/landslide that buried a Pakistani Army base (deemed by some to be sabotage), and the Seti River outburst flood—raise the question of whether these types of disasters are on the rise in that region, and perhaps globally. Science is not yet ready to offer a full answer to this question, but it is an important one to address and resolve in light of the demands of future land use planning and protective measures in each glacierized region.

Certainly, the threat and occurrence of natural disasters have been commonplace throughout the lengthy history of humans residing in certain regions, such as the Caucasus (Kääb et al. 2003), the Peruvian and Colombian Andes (Carey 2005, Kargel et al. 2011), and the Himalaya–Karakoram region (Richardson and Reynolds 2000, Quincey et al. 2007, Ives et al. 2010, Kargel et al. 2010), to name a few. The changing natural (and human-affected) environment of cryospheric processes, natural hazards, and risks is dominated by the rapid expansion of human land use and infrastructure development in once-forbidding and remote mountains (e.g., Kargel et al. 2012b). Risk too is shifting because climate change is modifying the land surface process system, and development is encroaching into affected areas.

Rapidly changing glaciers—whether retreating or advancing—destabilize the landscape and for a time may increase the frequency of mass movements such as debris avalanches, ice avalanches, and debris flows due to glacier lake outbursts. Glaciers are fundamentally a metastable phenomenon. Atmospheric precipitation places ice at high gravitational potential energies, and this energy must be released. As glaciers flow downslope, they erode and transport rocks and deposit debris in gravitationally unstable positions. As glaciers flow downslope, they encounter warmer conditions and so they melt, thus producing lakes, streams, and wet sediment. The ice, debris, and meltwater are forced gravitationally to move downslope. When they do so steadily or in small increments the problems that arise are few or manageable; furthermore, meltwater is a valued resource and helps to smooth out seasonal variations in water flow. Disaster happens when an unstable mass (ice, water, or sediment—or, most formidably, all three together) accumulates excessively, moves suddenly, and infrastructure or people get in the way. Any change in the climate–land–glacier system must result in a change in the land process system, with hazards and risks rising, falling, or changing location accordingly.

Most commonly, glacier-related disasters involve a natural process cascade effect; as the factors that affect land surface processes and the frequency or magnitude of any component of the process cascade changes, the net hazard and risk to people also changes. A glacier in a metastable dynamical steady state will pose one set of natural hazards, a glacier in retreat poses another set, and an advancing glacier yet another. The overall risk to people will depend on the details near, say, a particular village, bridge, or railroad. One size does not fit all. Hence, climate change—which is documentably having large impacts on glaciers both regionally and globally—is affecting the natural process, natural hazard, and human risk environment. Overwhelmingly, however, changing land use inevitably has the greatest impact on the natural hazard and risk environment. Nevertheless, of all the factors involved in the natural disaster process cascade (causes and effects, and changes in the system), land use in mountain environments and vulnerable coastal locales may be the most readily controlled by people. In principle, this could be a good thing, as it allows people to become better masters of their own destiny. Too often, people enter into risky situations as a result of ignorance or informed acceptance of risk in favor of some perceived benefit, and as a consequence avoidable tragedies continue to happen. The impact of climate change and cryospheric response makes informed decision making more of a challenge as the local history of glaciological hazards and disasters loses its guiding value.

P.2.3 Recent public perceptions about the importance of glacier fluctuations

Much as they did for the great 19th century scientists, glacier variations today provide the general public with the most compelling visual evidence of climate change. The foremost thing that the general public are aware of concerning glaciers, besides their being icy and cold, is that they are melting. The people of the world are divided and many are confused about climate change (the citizens of some countries are notable exceptions). However, it is not simply a case of total rejection or unawareness of the relevant science. A huge international Gallup survey in 2007–2008 in 128 countries indicated a 61% global awareness of climate change among individuals 15 years old and above (Pelham 2009). The results of the poll varied markedly among different countries. Awareness was 99% in Japan, and 35, 62, and 97% in India, China, and the U.S., respectively, to take four examples. Attribution of climate change to human activities, the poll showed, was believed by 91% in Japan, 58% in China, 53% in India, and 49% in the U.S. Asked whether global warming was a serious personal threat, the response was in the affirmative for 80% in Japan, 63% in the U.S.A., 29% in India, and 21% in China.

A separate survey by the Brookings Institution of American adults in fall 2011 indicated that 62% thought that there was solid evidence of global warming over the past 40 years (Borick and Rabe 2012). That survey also found that personal observation was the most frequently cited (of nine "most important factors" listed) forming the opinions of those accepting the existence of evidence of global warming; the second most frequently cited involved reports of melting of the world's polar ice sheets and glaciers. A slightly different inquiry in the same poll listed melting glaciers and polar ice as the most frequently mentioned contributory factor (of the same nine factors) that helped forge their acceptance of global warming. This poll also examined perceptions about scientists' integrity and media objectiveness; noteworthy is the finding that, among individuals disbelieving the case for global warming, 80% believe that scientists are overstating evidence for their own interests and 90% claim that the media are overstating the case for global warming.

Media misreporting and misrepresenting climate and glacier data, and in some cases clearly errant scientific reporting, have been a serious hindrance to communicating facts and understanding that are likely relevant to public well-being. Noted cases of misrepresentation of scientific findings and knowledge have pertained to Peruvian and Himalayan glaciers and the Greenland Ice Sheet (Cogley et al. 2010, Kargel et al. 2011, 2012a). The film industry is notorious for misrepresenting science, particularly when such phenomena as climate change are involved. Glacier melting and sea level rise is not as some Hollywood doomsday films (e.g., *The Day After Tomorrow*, 20th Century Fox, 2004; or *Waterworld*, Universal Pictures, 1995) make it out to be. It is perhaps more useful to comment on genuine public misperceptions that are closer to reality than to waste time on evident absurdities. Such films, while viewed by most of the public as mere entertainment, nonetheless have the potential to contribute to public confusion about climate change, which in extreme cases might bring about political backlashes or other illogical responses to nonsense contained in sensationalistic films.

In this book's Epilogue, Victor Baker argues that the most important factor limiting public understanding of climate change is not deficiencies in knowledge of scientific "facts" (part of the education gap comprising widespread scientific illiteracy), but rather a broad misconception about how science works. This misconception enables the more extreme forms of climate change skepticism and climate change denialism to go unchallenged by much of the public and causes many governments to be unwilling to make logical decisions on relevant matters. The public's confusion between science and nonscience and manipulation of the public by some narrow special interests is a serious challenge to solid decision making.

A certain amount of public confusion is understandable. Both climate records and glaciological records show that there is nothing simple about global climate change and the roles played by greenhouse gases, let alone the basic essence of the theory. Climate change is about much more than anthropogenic and natural greenhouse gases. Whereas the 11-year solar activity cycle is recognized as having a minor but measurable control on climate, major controls include orbital variations and various geological processes including volcanism, carbonate formation in shallow inland seas, and other phenomena that may be broadly linked to plate tectonics (Imbrie and Imbrie 1986, Kasting and Seifert 2002). The plate tectonic components of climate change are variable on timescales of tens of millions of years, though volcanism can be more episodic, as can of course asteroid and comet impacts, which also can affect climate.

The only major components of the Earth climate system that vary on the scale of human lifetimes and are either progressive and cyclic (thus somewhat predictable) are solar activity cycles (which have minor climate influences), cycles related to deep oceanic circulation, feedbacks such as Arctic sea ice coverage, and anthropogenic greenhouse gas emissions and aerosol pollutants. Volcanic eruptions despite being important, frequent, and occurring on human timescales are not predictable or progressive. The only component of this set of humanly relevant climate change forcings which is new to Earth—and can cause fundamentally new climate ordering on human timescales—is the industrial and consumer-driven emission of greenhouse gases and aerosol pollutants. Despite the many contributory and complicating factors that affect climate, whether they operate episodically and on short timescales or inexorably on geologic timescales, it is human influences on climate that are most dramatically affecting glaciers on timescales that are relevant to the lives of people today. This is recognized by most people on Earth, more so in Europe, the Americas, and Australia/Oceania than in parts of Asia and Africa. Thus, people generally recognize that we are affecting the global climate and that glaciers are melting largely as a consequence; the actual complexities are manifold, but the basic perception is correct.

People's perceptions of glaciers vary widely depending on whether they live in an area continually under threat from glaciers, have livelihoods directly tied to glaciers, derive reliable year-round electrical power or water from them, merely visit them on occasion, view them from a distance—perhaps via television—as a signpost of a changing global environment, or have no personal or intellectual relationship to glaciers. Governments likewise can have very different perspectives about glaciers, depending on whether there is a scientific underpinning of the government or a large economic stake rooted in glaciers or contingent on keeping the public in the dark about glaciers.

As happens with other natural hazards and public responses to them, people and governments also respond very differently to the risks posed by glaciers. Glacier hazards and disasters, much like floods, fires, and earthquakes in other parts of the world, are not simple matters to deal with. The issues are multidimensional and any solutions are likely to be at cross purposes with other values. The situation is directly analogous to the long-term response to Hurricane Katrina, which involved questions about whether to rebuild the most damaged parts of New Orleans, how much to invest in flood protection, or even whether to relocate the city entirely. As is so often the case with natural disasters and Earth hazards, as explained for the Katrina case by Baker (2007), social, cultural, and humanistic values can sometimes conflict with economic values, which in turn may conflict with geophysical and Earth surface science, engineering, and technology. What may seem a logical response may not be politically or socially possible; and what may be popularly demanded might be economically infeasible. Finding a compromise can be difficult, a process often made worse by irresponsible, errant, or accidentally inflammatory reporting of the issues by the media and the timeless problem of influence peddling at broad and illogical public expense.

Given the visually compelling evidence and partially intuitive nature of scientific deductions related to glacier fluctuations, it is not surprising that glaciers figure prominently in today's public debate about climate change. The tangibility of such information is there for all to see; like Jupiter's satellites from the time of Galileo to now, glaciers are there to be observed and refute antiscience dogma, whether from the climate change denial perspective or from a climate change exaggeration vantage point. Though public perceptions may be clouded by antiscience dogma, the confusion cannot last because of the unrelenting changes to the Earth that are under way and occurring at a pace that humans can perceive. There is little point in my reviewing the prodigious and highly varied evidence that global climate change is under way and is linked partially to anthropogenic greenhouse gases, as excellent modern reviews are already available (Mitchell 1989, Ledley et al. 1999, Le Treut et al. 2007). However, we will return to this topic in connection to glaciers in Chapter 33.

Remarkably, the fundamentals of greenhouse climate theory have not changed much since the 19th century, and this is clearly because the basic physics are comparatively simple and have been understood for over five generations. The important details—cloud cover feedback effects, trace gas influences, and the all-important evaluation of climate sensitivity (the amount of warming per increment rise in atmospheric CO_2 abundance)—have been steadily developed, as have increasingly detailed spatially resolved general circulation models of global and regional climate. Rather than reviewing climate theory and modeling (which is dealt with in various chapters), we use this book to highlight the abundant glacier evidence—obtained both from space-based and ground-based observations of glaciers—that climate is changing and affecting the world's ice and, further, to highlight the many complexities and dynamical aspects of glacier fluctuations that are not related directly to climate change.

The Alps have given rise to much of the world's scientific interest in glaciers and their links to climate, and Zurich much more so than most other places. Thus it is fitting that the GLIMS initiative held its first workshop in Zurich in 1999, one century after Professor Richter's (the CIG President) mandate to look more deeply into the problems of glacier change.

P.2.4 Time to move on

In sum, glaciers and the associated issues of climate and climate change have been a topic of exceptional scientific interest for nearly two centuries. Now that evidence of natural and anthropogenic climate change is widely perceived as being relevant to people today, these matters are top of the agenda in public discussion and policy development. Skepticism or public questioning of science is healthy and should be welcomed. People rightly perceive climate change as a multi-trillion dollar issue spanning generations. Public questioning has had the positive effect of focusing more scientific attention on uncertainties. Unfortunately, much public discourse has misinterpreted scientific concepts of uncertainty to mean a void of understanding or a prevailing state of confusion due to intractable ambiguities. Furthermore, much of so-called climate change skepticism is tantamount to spheroidal Earth skepticism, or questioning whether, despite centuries of scientific understanding, heat and energy flows from hot things to cold things. That said, climate is changing in complex ways and glaciers are responding with their own individual complexities. In essence the issue is simple: climate warms when we add visibly transparent gases that are opaque in the infrared to the atmosphere and glaciers melt when they are heated, but the details are not simple. This book is about the complexities of glaciers and how we measure and monitor them. The satellite era and remote sensing may provide the necessary answers.

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Something is done the first time only once—

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