Mission-Driven Climate Computing at NASA's Goddard Space Flight Center

For more than half a century, the advancement of NASA's satellite missions has demanded the highest performing computer systems of the day

Climate Science

At the equator, Earth receives more heat than it can re-radiate to space; at the poles, it re-radiates more heat than it receives. Thus the climate system, as a thermodynamic engine, serves to transport heat from the equator toward the poles. The most fundamental climatological questions regard exactly how much heat is retained (the global average temperature), where the energy resides (in the oceans, atmosphere, land surfaces, etc.), how it is distributed, and how it circulates around the globe in the course of moving poleward.

This poster is dedicated to the many hundreds of computing center and scientific staff, whose commitment to the Goddard vision and mission over half a century made this possible.

Measurements

- Sputnik Launched
- International Geophysical Year – studies Earth as a "single physical system"
- NASA Founded
- Goddard's Vanguard-II Launched
- 1st Earth photo from satellite
- Goddard's TIROS-1 Launched
- President Kennedy calls for a satellite-based global weather observing system
- IGY data catalog is published – IGY observations preserved on 10 million punch cards weighing 30 tons
- 1st successful weather satellite. Onboard television camera photographs cloud cover.
- Atmospheric CO_2 monitoring begins in Antarctica and on Mauna Loa, Hawaii
- Goddard's ECHO-1 Launched
- Goddard's Explorer-VII Launched
- Analysis by Goddard of its orbit contributes to early understanding of atmospheric density and solar pressure
- 1st meteorological instruments for measuring radiation balance
- Goddard Space Flight Center established – NASA's 1st space flight complex
- William Nordberg – Microwave sensor systems
- Building 1 at Goddard is fully occupied and other buildings are under construction
- Albert Arking – 1st global cloud distribution
- Goddard's NIMBUS-1 Launched
- 1st data mosaic of Earth using near-polar, Sun-synchronous orbit
- Goddard's ATS-1 Launched
- 1st full-disk Earth images every 30 minutes black and white cloud cover taken at geosynchronous orbit
- Goddard's TIROS-2/3 Launched
- 1st observations of the net radiation energy balance at the top-of-the-atmosphere (Rasool)
- Ichtiaque Rasool – 1st global net radiation balance
- Analysis of Tiros 2/3 video pictures derives the 1st global datasets (Arking)
- David Atlas – Radar meteorology
- Goddard's NIMBUS-3 Launched
- 1st satellite sounder – Space Infra-Red Sounder (SIRS-A) – acquires global vertical temperature profiles
- 1st Earth Day
- Plans for a commercial supersonic transport (SST) focus scientific attention on the issue of anthropogenic aerosols
- Brings public attention to environmental protection
- *The Limits to Growth* published by the Club of Rome brings global simulation modeling into the public sphere
- Global Atmospheric Research Programme (GARP) gets underway as the research arm of the WMO's World Weather Watch
- Robert Jastrow – GARP data assimilation & simulation
- Goddard's Landsat-1 Launched
- Measures land surface changes at high-resolution in 4 spectral bands – polar Sun-synchronous orbit
- Goddard's SMS-A Launched
- Geostationary weather research satellite
- Goddard's GOES-1 Launched for NOAA
- Delivered in orbit
- GARP Atlantic Tropical Experiment (GATE) uses SMS-A to gather unprecedented data variety and volume for 100 days
- Joanne Simpson – Cloud systems
- Goddard's NIMBUS-7 Launched
- Total Ozone Mapping Spectrometer (TOMS)
- Digitization projects make it possible to transfer formerly inconceivable volumes of global data via exchanging data tapes
- Jule Charney – Global assimilation, GARP
- The beginning of the "satellite era" for meteorology – The FGGE Year
- Goddard's GOES-EAST, GOES-WEST, & GOES-Indian Ocean Launched
- First GARP Global Experiment (FGGE) involves 140+ countries & 1000s of observing stations – of the 5 polar orbiting & 5 geostationary weather satellites used, Goddard develops 6
- Luis and Walter Alvarez determine that the K-T mass extinction 65 million years ago was caused by a meteor

Reanalysis / Assessment

- S. P. Shukla – Climate sensitivities
- Pilot Climate Data System and Pilot Land Data System developed to demonstrate feasibility of giving scientists access to large collections of satellite data independent of specific satellite missions – evolve into components of EOSDIS a decade later
- Huge Antarctic ozone hole confirmed by the TOMS instrument on Nimbus-7
- The idea that a nuclear war might produce a "nuclear winter" becomes an issue of global atmospheric politics
- Data assimilation schemes applied to FGGE data to determine how satellite observations affect them, producing the most detailed data image of global circulation ever created – cementing the role of satellites as the most important instruments in the arsenal of global meteorology
- Eugenia Kalnay – Ensembles
- 1st comprehensive global surface temperature dataset (land and marine) from 1850 to present
- 43 nations sign Montreal Protocol agreeing to reduce use of chlorofluorocarbons by 50% by the year 2000
- Intergovernmental Panel on Climate Change (IPCC) established to assess – collect, synthesize, and evaluate – knowledge about climate change
- Goddard's James Hansen testifies before the House Energy Committee presenting simulation model results – global warming enters mass politics
- Shukla/GSFC and Bengtsson/ECMWF publish landmark paper having demonstrated the power of the analysis model as a "unique and independent observing system"
- Reanalysis of decades of observations using a "frozen" data assimilation system that doesn't change during the reanalysis
- Fall of the Berlin Wall
- Russian data becomes available
- WWW – World Wide Web first demonstrated
- Game-changer for sharing of data
- Earth Summit in Rio de Janeiro
- IPCC First Assessment Report – includes CO_2 doubling results for 13 coupled ocean-atmosphere models in 22 variations
- Mount Pinatubo eruption reduces global temperatures by about .5 degrees C for a number of months, dramatically increasing attention to aerosols
- Robert Atlas – Scatterometer, weather
- Richard Rood – Data assimilation
- A typical mission (including launch, satellite, insurance, and ground monitoring over the satellite's lifetime of 3-10 years) costs between \$500 million and \$1 billion. But since a single polar-orbiting satellite can survey the entire planet twice a day, such satellites actually cost little relative to the gigantic quantities of information they provide
- Kyoto Protocol drawn up
- IPCC Second Assessment Report
- Goddard's Data Assimilation Office completes 5-year GEOS-1 reanalysis and eventually covers 1980-1995
- ECMWF completes "ERA-15" reanalysis covering 1979-1994
- NCEP-NCAR reanalysis begins – its 1996 publication of partial results quickly becomes one of the most cited articles in the history of meteorology (Kalnay)
- NCAR finishes assembling 50-year dataset (1948-1998) having invested 30 person-years at NCAR alone
- NCEP-NCAR complete 50-year reanalysis (1948-1998)
- Begins the EOS era to collect long-term, comprehensive climate datasets
- By permitting regular, direct, and meaningful comparisons of models with one another and with standardized datasets, model intercomparisons have helped to transform climate modeling from a craft activity of individual laboratories into a more modular and standardized collective activity involving virtually all the world's climate modeling groups
- Increasing mathematical complexity and higher model resolutions devour computer memory and processing power. For example, doubling the resolution of a three-dimensional grid calls for eight times the number of gridpoints and can require a smaller time step
- Reanalyses of global weather data produce consistent gridded data on the planetary circulation at resolutions much higher than achieved with traditional climatological datasets. This involves years of effort to prepare datasets with nearly all of the world's synoptic-scale observations
- Goddard's TERRA Launched
- Primary studies precipitation, evaporation, & cycling of water
- Goddard's AQUA Launched
- Goddard's ICESat Launched – Ice, clouds, & land elevation
- Goddard's AURA Launched – Ozone, air quality, & climate
- IPCC Third Assessment Report
- ECMWF completes "ERA-40" reanalysis covering 1958-2002 (45 years). Some reanalysis are later repeated using newer higher-resolution assimilation systems
- A significant change in the height of the tropopause is detected in ERA-15 and ERA-40 reanalysis data – this is a GCM-predicted response to anthropogenic greenhouse gases and stratospheric ozone depletion
- IPCC Fourth Assessment Report – refers to the ERA-40 and NCEP-NCAR reanalyses frequently but treats them as supplementary evidence rather than primary data
- Michele Rienecker – Ocean data assimilation
- Al Gore and the IPCC share the Nobel Peace Prize for "efforts to build up and disseminate greater knowledge about man-made climate change"
- GMAO's MERRA reanalysis (1979-present) uses GEOS-5 to place NASA EOS observations into a climate context and improve on the hydrologic cycle represented in earlier reanalyses
- Max Suarez – Coupled atmosphere/ocean
- Goddard's Suomi-NPP Launched
- Goddard's Aquarius Launched – Global sea surface salinity
- Atmospheric & sea surface temperatures
- Model evaluation input for the IPCC's Fifth Assessment Report
- JPL's OCO-2 Launched – Atmospheric carbon dioxide
- Goddard's GPM Launched – Global precipitation measurement
- IPCC Fifth Assessment Report
- Climate Model Data Services broaden use of large complex climate model data products from GMAO and GISS by scientific, business, and political communities
- Nature Run done for OSSEs at 7km resolution using nonhydrostatic version of GEOS-5
- GMAO's MERRA 2 reanalysis (1979-present) uses GEOS-5 to add aerosol data

Models

- 1st computerized weather forecast – on the ENIAC at Aberdeen Proving Ground – by group headed by Jule Charney
- Routine real-time numerical weather forecasting begins (in Sweden and U.S.)
- 1st working numerical general circulation model (2-layer, hemispheric, quasi-geostrophic)
- 1st high-level programming language, Fortran, appears
- National weather services become "centers of calculation"
- Meteorology is the foremost civilian consumer of supercomputing power
- 1st UCLA GCM completed (Mintz, Arakawa)
- Skill of surface-level numerical weather prediction begins to outperform "subjective" forecasts
- 1st coupled atmosphere-ocean general circulation model (with highly idealized ocean)
- Continuous assimilation of temperature profiles can be used to infer the complete global state of the atmosphere (Charney, Jastrow, & Halem)
- UCLA GCM brought to GISS to assimilate complete temperature fields synoptically into a GCM to infer geostrophic winds (1st OSSE)
- Operational forecasts begin to incorporate temperature soundings from radiometers
- One-dimensional radiation-balance model reveals that aerosol cooling could trigger an ice age (Rasool-Schneider)
- GISS GCM 72 x 46 9 Layers
- Two opposing schools of thought emerge: the climate 'coolers' and the climate 'warmers'
- Global climate models put forward as the only way that we now conceive of to explore the tangle of relations involved in climate
- Milton Halem – Global modeling, 4-D assimilation
- Goddard Laboratory for Atmospheres adopts the "UCLA IV" 15-Layer GCM
- 1st global numerical weather prediction models, eliminating the problem of artificial boundaries
- 1st use of a GCM to simulate effects of CO_2 doubling
- 1st global spectral GCM (Australia)
- Sahel Experiment uses AVHRR data from Tiros-N to study the effect of drought on vegetation – confirms "Charney hypothesis" that land surface processes have to be incorporated into Earth system models
- The National Research Council's *Charney Report* is the 1st policy-oriented assessment to claim a concrete, quantitative estimate of likely global warming
- GSFC GCM 4th Order 72 x 46 9 Layers
- James Hansen – Climate sensitivities
- WCRP's TOGA program couples observations and models to study ocean-atmosphere interactions
- 1st 2-D model representing most major atmospheric chemical interactions appears
- For the 1st time a model predicts El Niño more than weeks in advance – by coupling ocean and atmosphere models
- GARP Data Assimilation System
- David Randall – Climate GCMs
- Bretherton Report leads to stated need for Earth system models
- Scientific Visualization Studio formed
- Goddard and JPL run a 14-year technology project applying scalable parallel computing technologies to NASA science as part of the Federal High Performance Computing and Communications Program
- GEOS-1 Data Assimilation System
- Round-1 Teams restructure model codes to run on scalable parallel computers
- Some climate models include the entire carbon cycle
- NSIPP Coupled Ocean/Atmosphere Model
- GEOS-3 144 x 91 48 Layers
- Round-2 Teams adapt parallel model codes to extreme performance
- Three rounds of HPCC Grand Challenge Investigator Teams are competitively selected by NASA Headquarters and then supported by center staff to make progress toward Grand Challenge goals
- GEOS-4 55 Layers
- Round-3 Teams place systems of model codes onto software frameworks to manage increased complexity
- Earth System Modeling Framework (ESMF) – infrastructure to increase software interoperability and promote reuse of model software components developed at different sites
- GEOS-5 540 x 361 1152 x 721 (25km) 72 Layers
- 1st Model Compliant with ESMF
- GISS ModelE
- Gavin Schmidt – Climate variability, modeling
- GEOS-6 10km & less 128 Layers global nonhydrostatic

1950 1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

Glossary

ATS – Applied Technology Satellite
AVHRR – Advanced Very High Resolution Radiometer
CDC – Control Data Corporation
ECMWF – European Centre for Medium-Range Weather Forecasts
ENIAC – Electronic Numerical Integrator and Computer
EOS – Earth Observing System
EOSDIS – Earth Observing System Data and Information System
ESMF – Earth System Modeling Framework
FGGE – First GARP Global Experiment
GARP – Global Atmospheric Research Program
Gbytes – Billion bytes
GCM – General Circulation Model; Global Circulation Model
GEOS – Goddard Earth Observing System Model
GISS – Goddard Institute for Space Studies
GMAO – Global Modeling and Assimilation Office
GOES – Geostationary Operational Environmental Satellite
GPM – Global Precipitation Measurement
HP – Hewlett-Packard
HPCC – High-Performance Computing and Communications
IBM – International Business Machines
IGY – International Geophysical Year
IPCC – Intergovernmental Panel on Climate Change
JPL – Jet Propulsion Laboratory
K-T – Cretaceous-Tertiary
Mbytes – Million bytes
MERRA – Modern-Era Retrospective Analysis for Research and Applications
MPP – Massively Parallel Processor
NASA – National Aeronautics and Space Administration
NCAR – National Center for Atmospheric Research
NCCS – NASA Center for Computational Sciences; NASA Center for Climate Simulation
NCEP – National Centers for Environmental Prediction
NOAA – National Oceanic and Atmospheric Administration
NSIPP – NASA Seasonal-to-Interannual Prediction Project
OCO-2 – Orbiting Carbon Observatory-2
OSSE – Observing System Simulation Experiment
Pbytes – Quadrillion bytes
SGI – Silicon Graphics Incorporated
SMS – Synchronous Meteorological Satellite
Tbytes – Trillion bytes
TOGA – Tropical Oceans Global Atmosphere
TOMS – Total Ozone Mapping Spectrometer
WCRP – World Climate Research Programme
WMO – World Meteorological Organization

Goddard High-End Computing

- IBM 7090 32K (36-bit) words
- IBM 7094 – 32K (36-bit) words
- Acquired with four typed sheets of paper – two to specify the equipment and two to tell procurement to pay for it after it was installed and tested
- Goddard installs six IBM 7094 systems – one tracks, captures, and analyzes instrument data for Robert Jastrow's Theoretical Laboratory – the other five support the Mercury Program
- Goddard rumored to house 1% of total computing power in the U.S.
- Goddard also pioneers use of dedicated small computers for mission support – each mission has small computers to handle data reduction and day-to-day operation of the spacecraft
- IBM 360/91 – 2 Mbytes magnetic core
- IBM 360/95 – 1 Mbyte thin film, 4 Mbytes magnetic core
- Programs are submitted on decks of punched cards
- All 3 are the world's fastest!
- At GSFC in Greenbelt for mission support
- At GSFC in NYC (GISS) for science research
- The IBM 360/95 is nearly identical to the 360/91, except its main memory is thin-film, giving it a speed advantage, but the floating point performance is the same
- IBM only makes two 360/95 computers, both for NASA
- CRJE (Conversational Remote Job Entry) gives remote access to the IBM systems from special terminals
- Goddard researchers pioneer "massively parallel" computing
- Challenged to digest the approaching data flood from Landsat sensors, the idea originates of a computer to process every pixel in a Landsat image simultaneously
- David Schaefer
- James Strong – Massively parallel computing
- Optical approaches abandoned as efforts refocus on large-scale integrated circuits, soon to hold thousands of transistors (Fung)
- 64-processor prototype runs benchmark algorithms to specify a much larger machine (Fischer)
- Architecture Research
- Serial # 00001
- Amdahl 470V/6 – 8 Mbytes
- The computing center van makes 3 runs a day to move card decks, tapes, and printout around Goddard
- GISS GARP Project and Amdahl V6 relocate to Greenbelt
- Amdahl 470V/7 – 8 Mbytes
- IBM 3081 – 48 Mbytes – 2 processors
- CDC Cyber 205 – 32 Mbytes – 2 vector pipelines
- ETA/10 – 128 Mbytes
- 16,384-processor Massively Parallel Processor delivered to Goddard under contract by Goodyear Aerospace Corporation
- Acquired competitively to meet operational requirement for GARP
- NASA Space and Earth Sciences Computing Center (NSESCC) is formed from the Science and Applications Computing Center (SACC) and the Vector Processing Facility (VPF) to support Earth and space science research
- MPP Working Group investigators report MPP architecture is appropriate for many of their diverse applications – gains international attention
- Frontiers of Massively Parallel Computation symposia run through 1999
- Goddard replaces MPP with MasPar Computer Corporation's MP-1, then MP-2, commercializations of MPP architecture
- Smithsonian collects MPP – by 2007 its architecture is embodied in NVIDIA's GPU accelerators
- Cray Y-MP – 512 Mbytes (1 Gbyte SSD) – 8 processors
- NCCS migrates to a completely UNIX-based software environment – sea change to staff and users
- NASA Center for Computational Sciences (NCCS) is formed from existing organizations – computer equipment is consolidated into Building 28 from Buildings 1 and 22
- Last card punch is retired
- Cray C98 – 2 Gbytes (4 Gbytes SSD) – 6 processors
- Cray J932se – 20 Gbytes – 96 processors
- Cray T3D 32 Gbytes
- #5 in world's Top 500 supercomputers
- Cray T3E 64 Gbytes
- Workstations in scientists' offices draw users away from the NCCS
- Goddard computer scientists combine commodity PCs, Ethernet interconnects, and the open source Linux operating system to create an inexpensive parallel workstation termed Beowulf
- Beowulf system wins Gordon Bell Prize for best price/performance
- *How to Build a Beowulf* published by MIT Press
- Thomas Sterling, Don Becker – Beowulf commodity clusters
- Computer History Museum collects the 1st Beowulf
- Cray T3E 130 Gbytes
- Cray T3E – 162 Gbytes – 1,360 processors
- SGI Origin 3000 128 Gbytes 512 processors
- Cray SV1 – 16 Gbytes 48 processors
- SGI Origin 2000 – 21 Gbytes – 64 processors
- SGI Origin 3800 304 Gbytes 608 processors
- NCCS brings in an integrator to operate the facility – 5-year contract goes to CSC
- Dispatch window closes. NCCS goes to lights out operation – no operators on duty
- Beowulf approach represents most of the world's Top 500 supercomputers and makes commodity clusters available to a broad community
- HP/Compaq SC45 720 Gbytes – 1,440 processors
- NCCS machine time becomes free to Headquarters-funded users – chargeback ends – NCCS's capital and operational budgets are merged
- NCCS's Data Portal provides mechanism for distribution of products controlled by NCCS and its user community
- 2.8 Tbytes 2,584 core
- 7.2 Tbytes 4,632 core
- Discover system – an evolving assembly of multiple Linux scalable units built with commodity components. Older scalable units are regularly replaced with current technology units acquired competitively, and have come from IBM, Dell, and SGI. (Duffy)
- NCCS rebrands to NASA Center for Climate Simulation
- 25 Tbytes 11K cores
- 38 Tbytes 15K cores
- 74 Tbytes 32K cores
- 101 Tbytes 43K cores
- 107 Tbytes 43K cores
- 255 Tbytes 80K cores
- 1.7 Pflops
- Scalable Units
- Processor memory, over a 50-year period, grows by a factor of 1.7 billion
- NCCS disk capacity grows from 8 Tbytes in 2006 to 25 Pbytes in 2014, a factor of 3,000 in a decade

TERAFLOPS: 100, 10, 1 · GIGAFLOPS: 100, 10, 1 · MEGAFLOPS: 100, 10, 1 · KILO: 100

Legend

- Goddard Contribution
- Scalable Parallel
- Vector
- Scalar

Goddard Mass Storage

- Data is held on 10 inch "round" tapes, either 7-track or 9-track, written at densities of 200, 556, 800, 1,600 or 6,250 bits per inch depending on the age
- Goddard's Building 1 science tape library stores more than 100,000 "round" tapes – many Goddard hallways contain endless floor-to-ceiling tape racks – machine rooms contain dozens of tape drives
- Robotic IBM 3851 Mass Storage System, attached to the IBM 3081 mainframe, houses 300 Gbytes of data on thousands of 50-Mbyte tape strips kept in cylindrical cartridges – it serves as tape library and low-cost, near-line storage expanding disk capacity
- Operators mount 65,000 tapes per month
- Following a two-year procurement the Unitree based Mass Data Storage and Delivery System is acquired – the initial contract allows capacity to scale up to 225 Tbytes (Palm)
- Unitree software begins to manage NCCS's mass storage data, held on square tapes in silos from multiple vendors
- Unitree robotic storage now holds all data in NCCS – the age of "round tapes" ends
- Unitree system becomes fully automated – no manual tape mounts
- "Square" tapes in Unitree robotic silos each hold 800 Mbytes (linear format) and 50 Gbytes (experimental helical)
- Unitree system absorbs data at the rate of 4 Tbytes per month – it is the largest and most active Unitree system in the unclassified world
- "Square" tapes in Unitree robotic silos each hold 1 Tbyte, 5 Tbytes, and 8 Tbytes uncompressed

PBYTES: 100, 10, 1 · TBYTES: 100, 10, 1

Visit the NASA Center for Climate Simulation online via this QR code for current system status:

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Context gleaned from *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*, by Paul N. Edwards

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