Modeling Earth's climate: A bit of history...

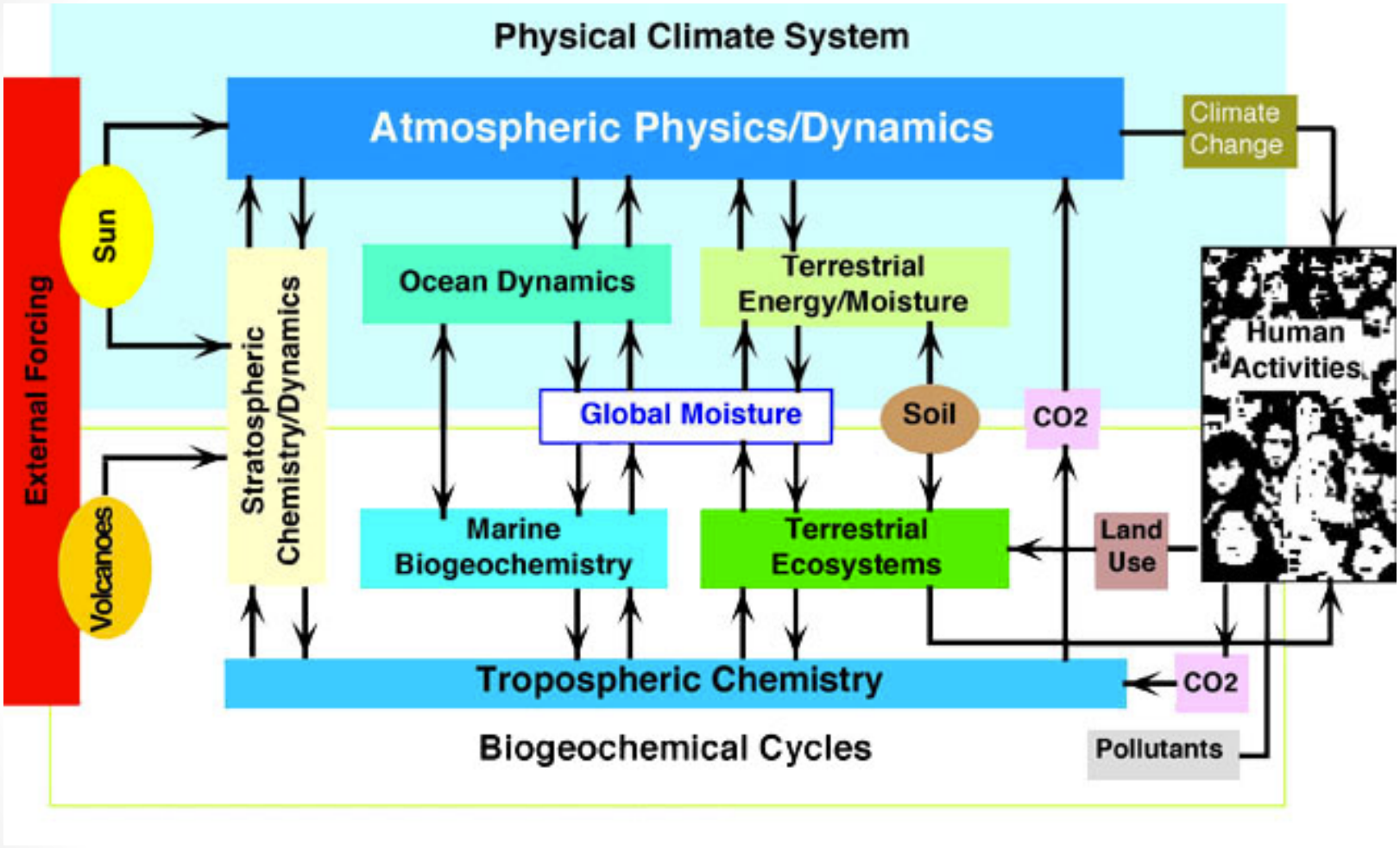
H. Nüzhet Dalfes

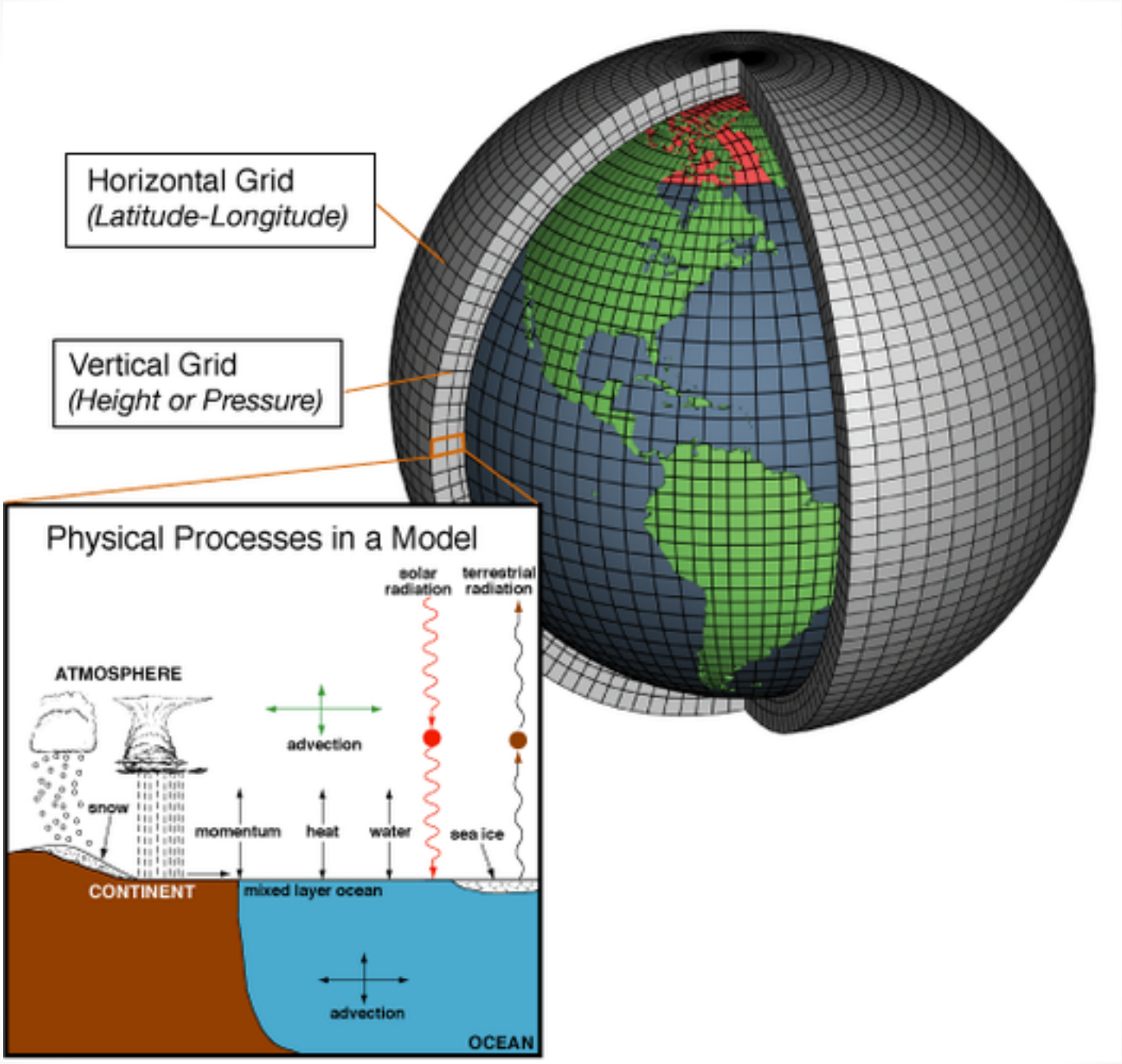
Eurasia Institute of Earth Sciences

Ecology & Evolution Dept.

Outline

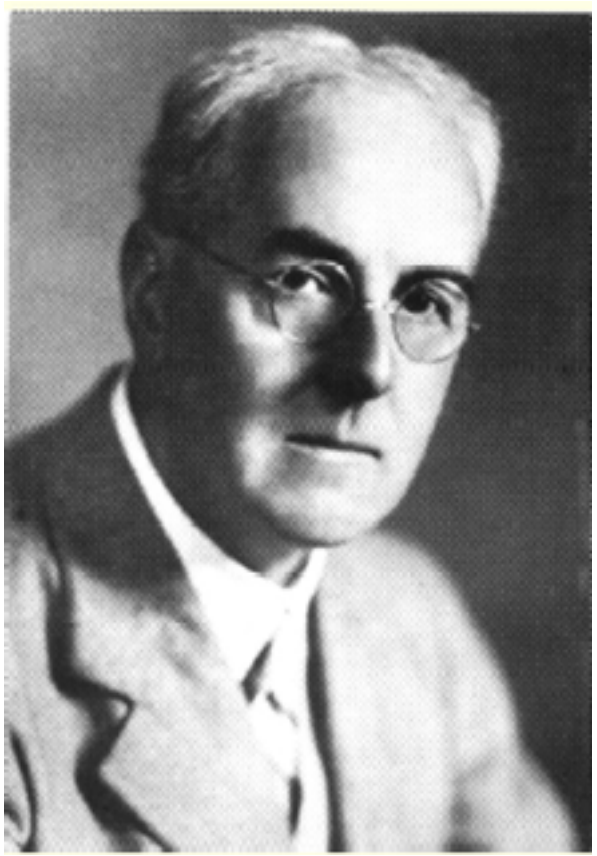
- The Earth System
- Numerical weather prediction
- Evolution of computing
- Climate models
  - Atmospheric models
  - Ocean models
- NCAR: Community Climate Model (CCM)
- RegCM*n*
- WRF

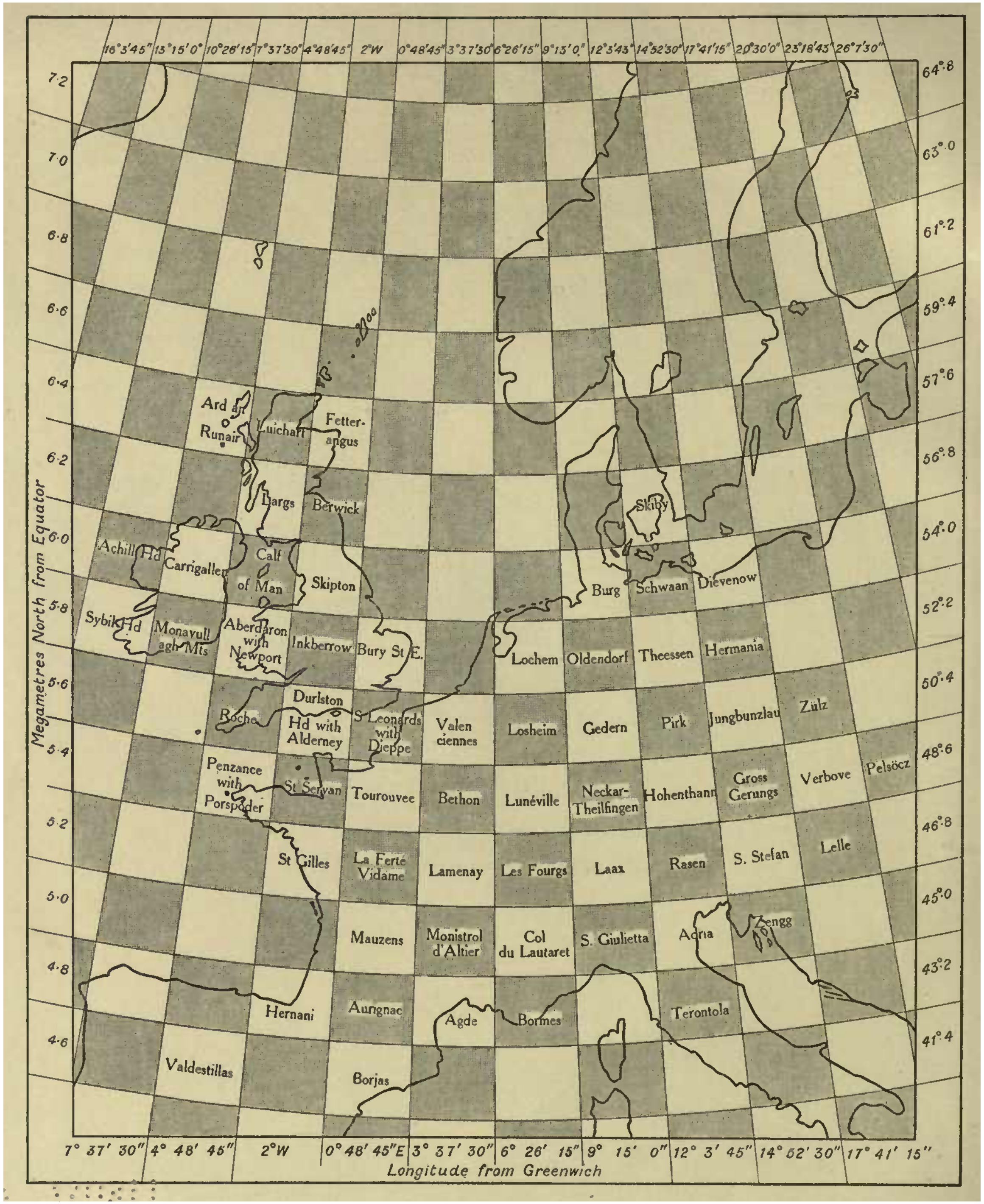

Physical Climate System
Atmospheric Physics/Dynamics
Climate Change
External Forcing
Sun
Volcanoes
Stratospheric Chemistry/Dynamics
Ocean Dynamics
Terrestrial Energy/Moisture
Global Moisture
Soil
CO2
Human Activities
Marine Biogeochemistry
Terrestrial Ecosystems
Land Use
Tropospheric Chemistry
CO2
Biogeochemical Cycles
Pollutants


Horizontal Grid
(Latitude-Longitude)
Vertical Grid
(Height or Pressure)
Physical Processes in a Model
solar radiation
terrestrial radiation
ATMOSPHERE
advection
snow
momentum
heat
water
sea ice
CONTINENT
mixed layer ocean
advection
OCEAN

Modeling the atmosphere...

- Equations are known already: Navier-Stokes eqn (1822) in a rotating frame (1835, 1856)
- Lewis Fry Richardson (1881-1953)
  - *Weather Prediction by Numerical Process* (1922)

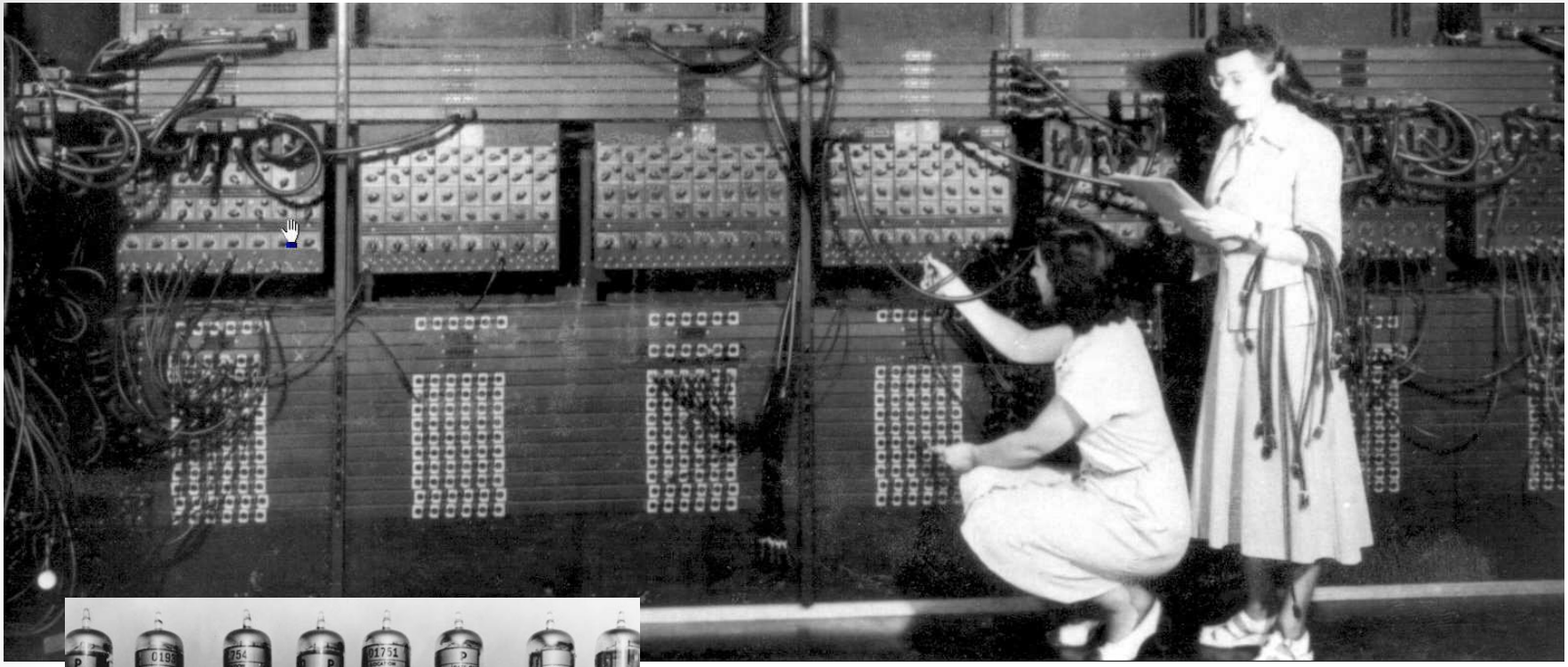


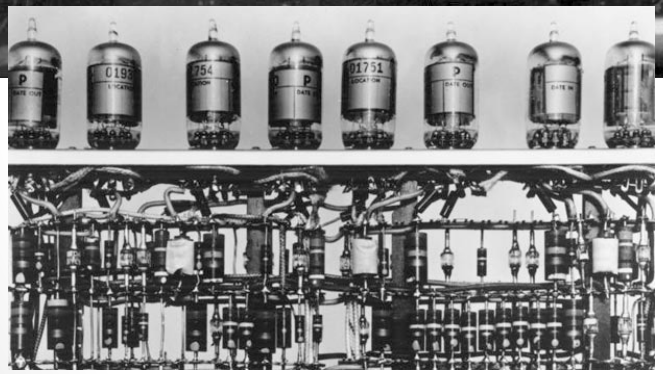


16°3'45" 13°15'0" 10°26'15" 7°37'30" 4°48'45" 2°W 0°48'45" 3°37'30" 6°26'15" 9°13'0" 12°3'45" 14°52'30" 17°41'15" 20°30'0" 23°18'45" 26°7'30"
7·2
7·0
6·8
6·6
6·4
6·2
6·0
5·8
5·6
5·4
5·2
5·0
4·8
4·6
Megametres North from Equator
64°·8
63°·0
61°·2
59°·4
57°·6
55°·8
54°·0
52°·2
50°·4
48°·6
46°·8
45°·0
43°·2
41°·4
Ard an Runair
Luichart
Fetter-angus
Largs
Berwick
Skiby
Achill Hd
Carrigallen
Calf of Man
Skipton
Burg
Schwaan
Dievenow
Sybil Hd
Monavullagh Mts
Aberdaron with Newport
Inkberrow
Bury St E.
Lochem
Oldendorf
Theessen
Hermania
Roche
Durlston Hd with Alderney
S Leonards with Dieppe
Valenciennes
Losheim
Gedern
Pirk
Jungbunzlau
Zülz
Penzance with Porspoder
St Servan
Tourouvee
Bethon
Lunéville
Neckar-Theilfingen
Hohenthann
Gross Gerungs
Verbove
Pelsöcz
St Gilles
La Ferte Vidame
Lamenay
Les Fourgs
Laax
Rasen
S. Stefan
Lelle
Mauzens
Monistrol d'Altier
Col du Lautaret
S. Giulietta
Adria
Zengg
Hernani
Aurignac
Agde
Bormes
Terontola
Valdestillas
Borjas
7° 37' 30" 4° 48' 45" 2°W 0° 48' 45"E 3° 37' 30" 6° 26' 15" 9° 15' 0" 12° 3' 45" 14° 52' 30" 17° 41' 15"
Longitude from Greenwich

First numerical weather forecast

- 1950 using ENIAC
- Jule Charney, Philip Thompson, Larry Gates, Ragnar Fjørtoft **John von Neumann**
- a simplified form of atmospheric dynamics based on solving the **barotropic vorticity equation**
- over a single layer of the atmosphere, by computing the geopotential height of the atmosphere's 500 millibars pressure surface.
- for a 24−hour forecast took ENIAC nearly 24 hours to produce!





ENIAC, 1946
(Electronic Numerical Integrator and Computer)

NWP *vs.* climate modeling

- NWP: an initial value problem
  - CM: a boundary value problem!
- NWP: short integration times
- CM: long integration times
  - conservation of energy, mass, etc. is very important
- CM: radiative and surface processes very important

Hierarchy of climate models

- 0-d models: energy balance of the Earth
  - can include ice-albedo feedbacks
- 1-d models
  - 1-d vertical: radiative-convective models
  - 1-d latitudinal: energy balance models
- 2-d models:
  - vertical-latitudinal
- 3-d models:
  - atmosphere GCM
  - atmosphere-ocean GCM
  - Earth System models:
    - atmosphere+oceans+hydrosphere
    - + biosphere
    - + ice sheets

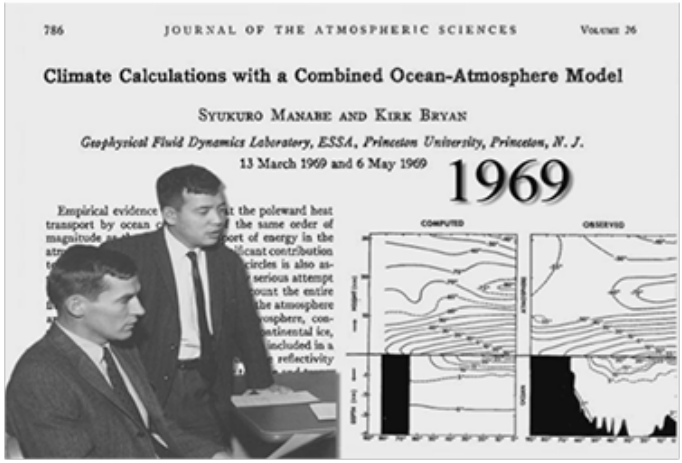
Solving the primitive equations…

- Conservation of
  - momemtum
  - mass
  - energy
- first law of thermodynamics
- choose a coordinate system:
  - *e.g.* sigma coordinate system, polar stereographic projection
- How to solve these equations?
  - Finite-difference schemes
  - (Semi) spectral methods

Radiative-convective models

- **Syukuro Manabe**
  - Manabe, S., J. Smagorinsky, and R.F. Strickler, 1965: Simulated climatology of a general circulation model with a hydrologic cycle. *Monthly Weather Review*, 93(12), 769-798.
  - Manabe, S., and R. T. Wetherald, 1967: Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *Journal of the Atmospheric Sciences*, 24 (3), 241-259.
  - Manabe, S. and R.T. Wetherald, 1975: The effect of doubling of CO2 concentration in the atmosphere. Journal of Atmospheric Sciences, 32(1), 3-15

Ocean modeling


786 JOURNAL OF THE ATMOSPHERIC SCIENCES VOLUME 26

Climate Calculations with a Combined Ocean-Atmosphere Model

SYUKURO MANABE AND KIRK BRYAN

Geophysical Fluid Dynamics Laboratory, ESSA, Princeton University, Princeton, N. J.

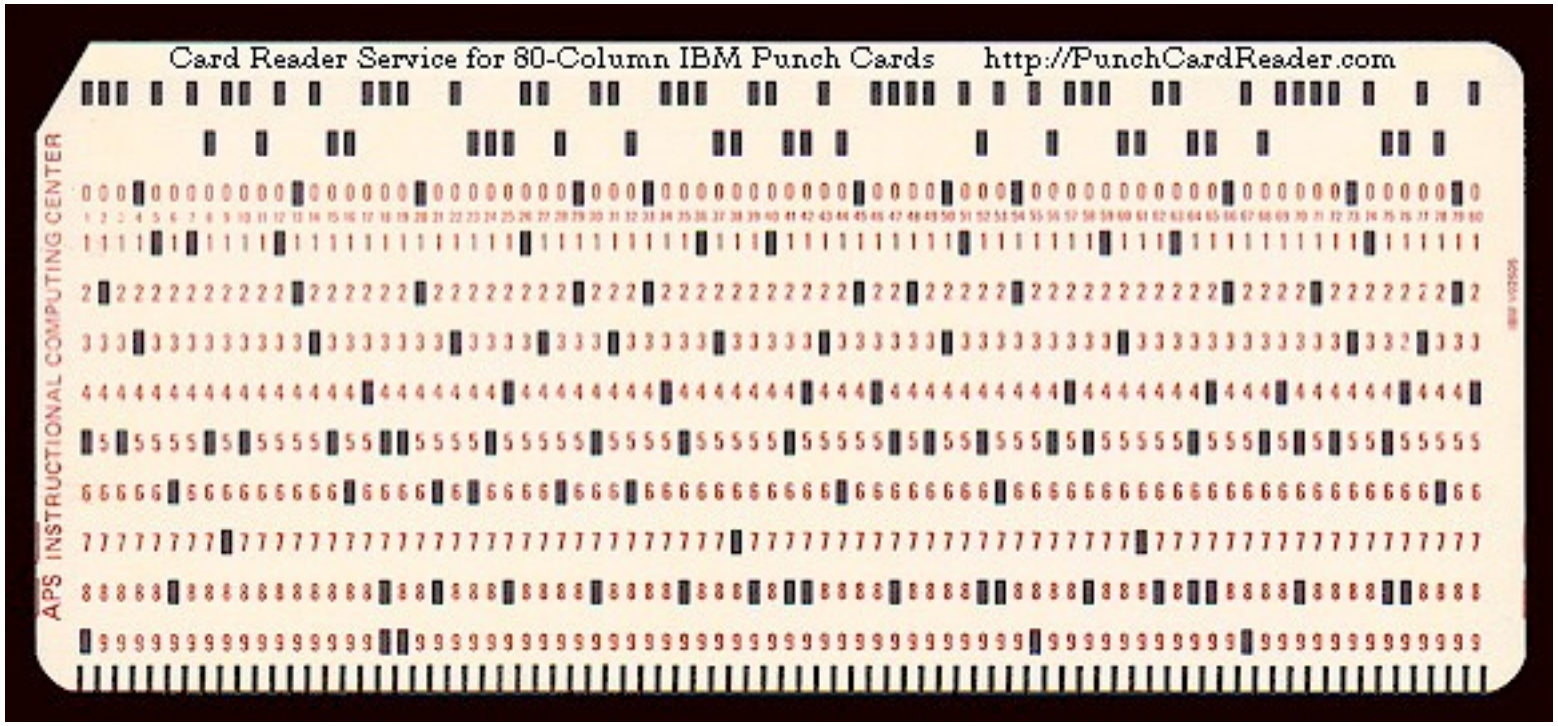
13 March 1969 and 6 May 1969

1969

COMPUTED OBSERVED

- **Kirk Bryan**
  - Bryan, Kirk; Cox, M. D. (1967), "A numerical investigation of the oceanic general circulation", *Tellus*, 19 (1): 54–80
  - Bryan, K; Komro, F. G.; Manabe, S.; Spelman, M. J. (1982), "Transient climate response to increasing atmospheric carbon dioxide", *Science*, 215 (4528): 56–58
- Manabe, S. and K. Bryan, 1969: Climate Calculation with a combined ocean-atmosphere model. *Journal of Atmospheric Sciences*, 26(4), 786-789

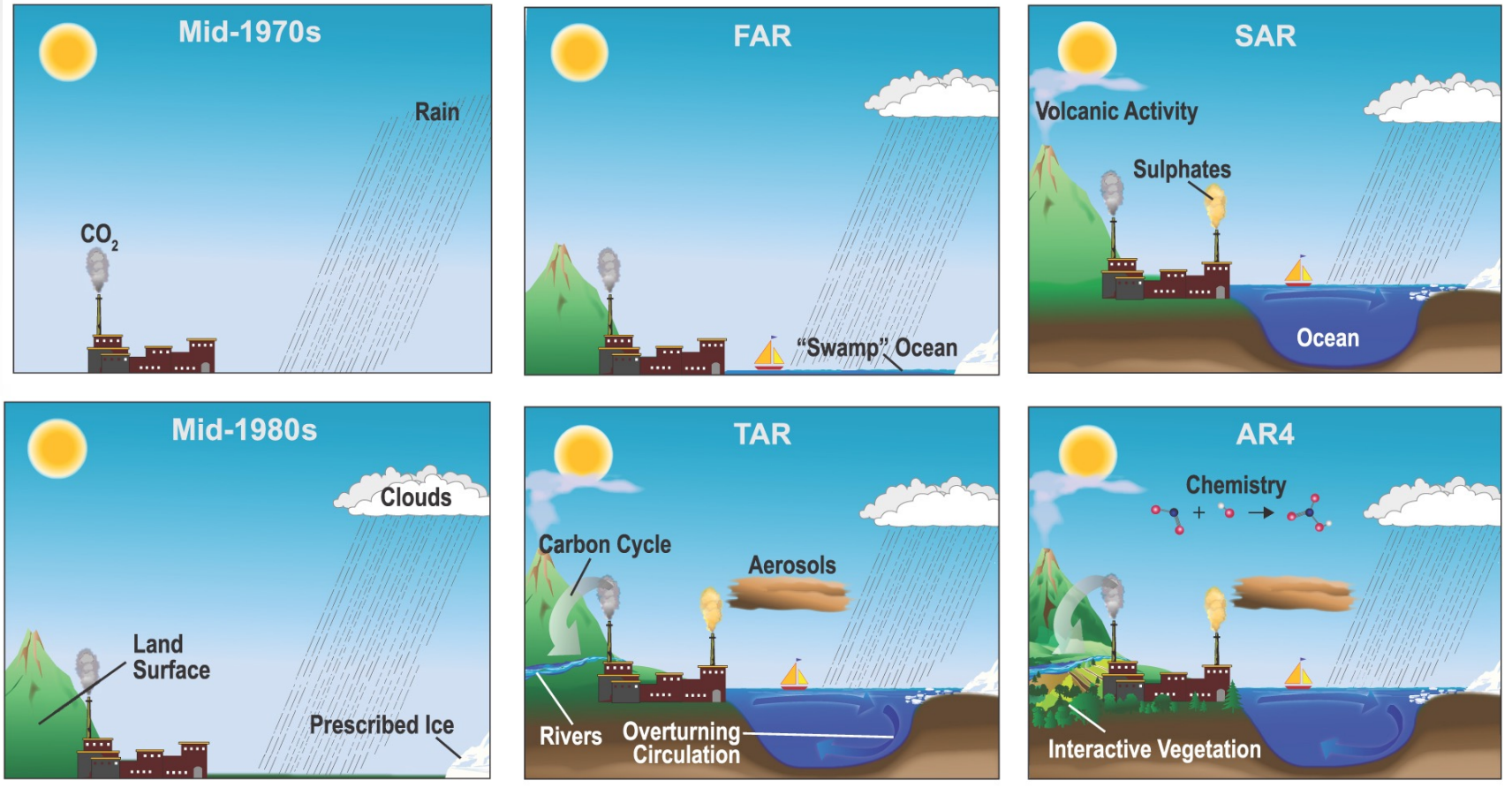
CDC 7600

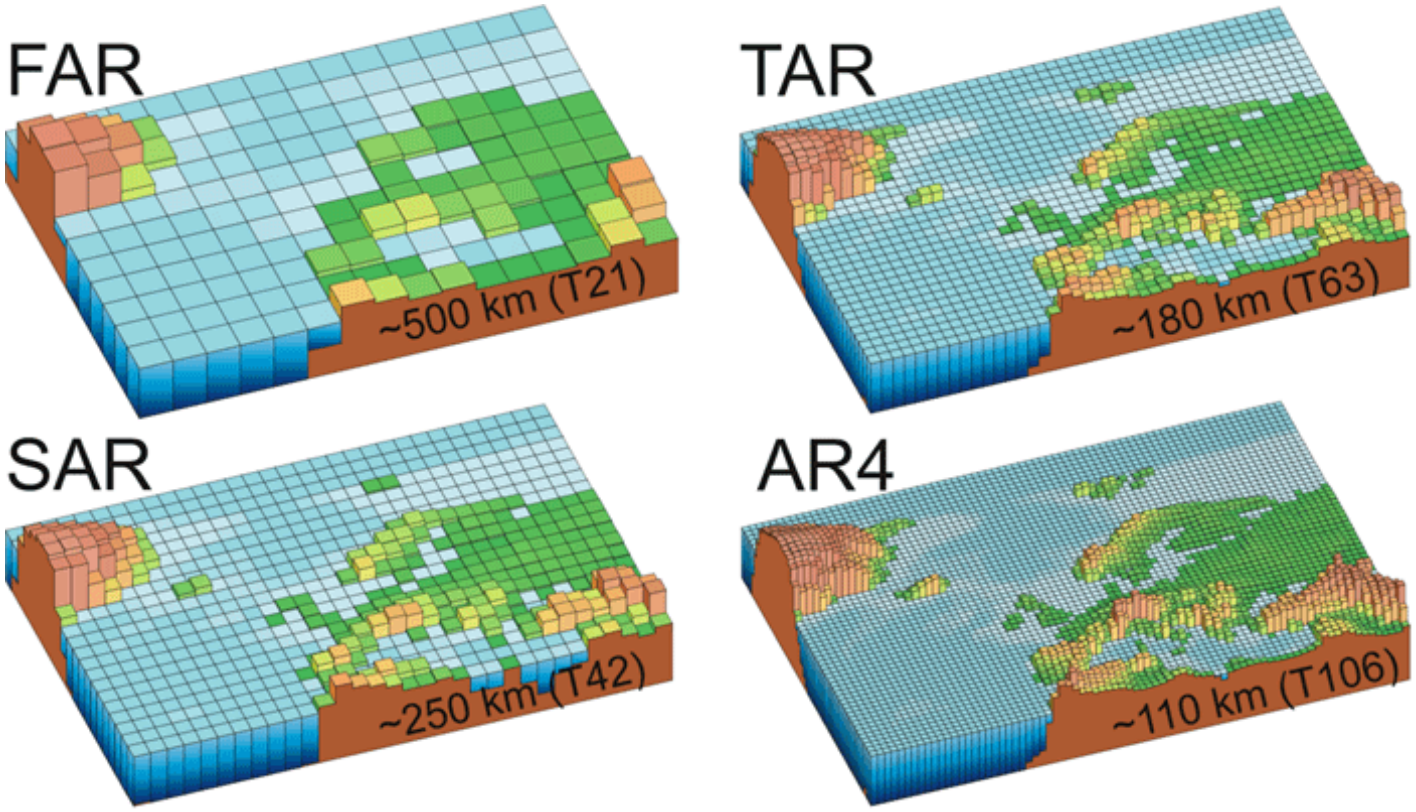

Card Reader Service for 80-Column IBM Punch Cards
http://PunchCardReader.com
APS INSTRUCTIONAL COMPUTING CENTER

Cray 1A + Seymour Cray

1976

Cyber 205


Mid-1970s
Rain
CO_2
FAR
"Swamp" Ocean
SAR
Volcanic Activity
Sulphates
Ocean
Mid-1980s
Clouds
Land Surface
Prescribed Ice
TAR
Carbon Cycle
Aerosols
Rivers
Overturning Circulation
AR4
Chemistry
Interactive Vegetation


FAR
~500 km (T21)
TAR
~180 km (T63)
SAR
~250 km (T42)
AR4
~110 km (T106)

CCM (Community Climate Model)

- Developed under the leadership of the **National Center for Atmospheric Research**
  - To build a community:
    - ONE model, many users
  - Well documented
  - Versioning
  - Semi-spectral
    - ‘physics’ on a grid
    - ‘dynamics’ spectral
  - CESM (Community Earth System Model)

RegCM*n*

- Based on MM4 (Mesoscale Meteorological Model version 4) of Penn State/NCAR
- RegCM0 = MM4 + CCM ‘physics’ (1986)
- Originally thesis project of Filippo Giorgi
- Now developped by the Earth System Physics Section of ICTP

WRF (Weather Research and Forecast Model)

- Late 1990's -
- Joint effort:
  - NCAR
  - NOAA/NCEP
  - US Air Force Weather Agency
  - Naval Research Lab.
  - U. of Oklahoma
  - FAA
- Physical scientists design, computer scientists program!
- WRF-ARW (NCAR) + WRF-NMM (NCEP)
- WRF-Chem, WRF-Hydro…

Trends

- Climate models —> Earth System Models
  - Atmosphere + Oceans
  - Atmosphere + Oceans + Sea ice
  - Atmosphere (+ aerosols) + Oceans + Sea ice
  - Atmosphere (+ aerosols) + Oceans + Sea ice + ‘Biosphere’
- Better software design
- Clear interfaces between subsystems
  - ESMF (Earth System Modeling Framework)
- Better data management