The Abdus Salam
International Centre for Theoretical Physics

United Nations
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International Atomic Energy Agency

1986-1

WCRP and ICTP Interpreting Climate Change Simulations: Capacity Building for Developing Nations Seminar

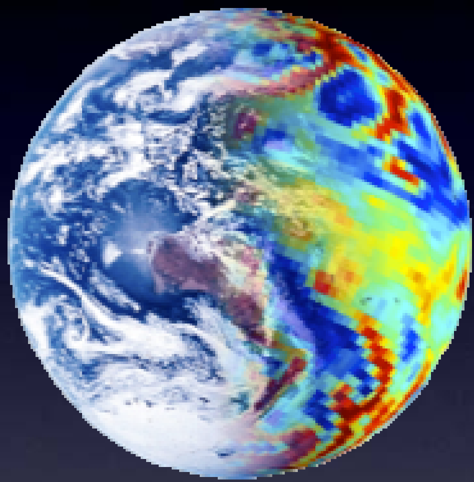
26 - 30 November 2007

History of climate model.

Kendal McGuffie

Department of Physics and Advance Materials, University of Technology Sydney

History of Climate Models



Kendal McGuffie
Department of Physics and Advanced Materials
University of Technology Sydney

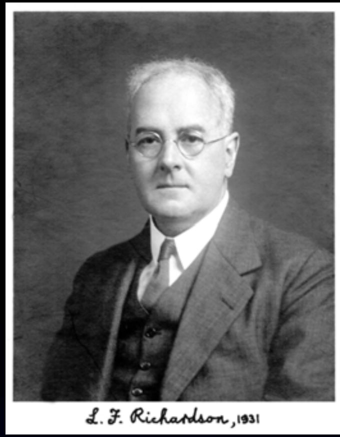
Climate modeling is perhaps the largest computational challenge the human race has attempted to date. Only a handful of applications exist on a larger scale, and none require the same level of detail. The number of components required to work together is also unprecedented in the field of computational science: atmosphere, land, ocean and ice models (joined by a flux coupler) must work with radiation, cloud, chemistry, advection, soil, vegetation, and water runoff models (not to mention a whole host of subgrid parameterizations) to produce meaningful results. We can simplify some of these models, depending on the question to be answered, but our climate system's complex interactions will continue to strain the limits of our largest supercomputers for the foreseeable future.

Spotz, W.F.; Swarztrauber, P.N.
Computing in Science & Engineering
Volume 4, Issue 5, Sep/Oct 2002 Page(s): 24 - 25

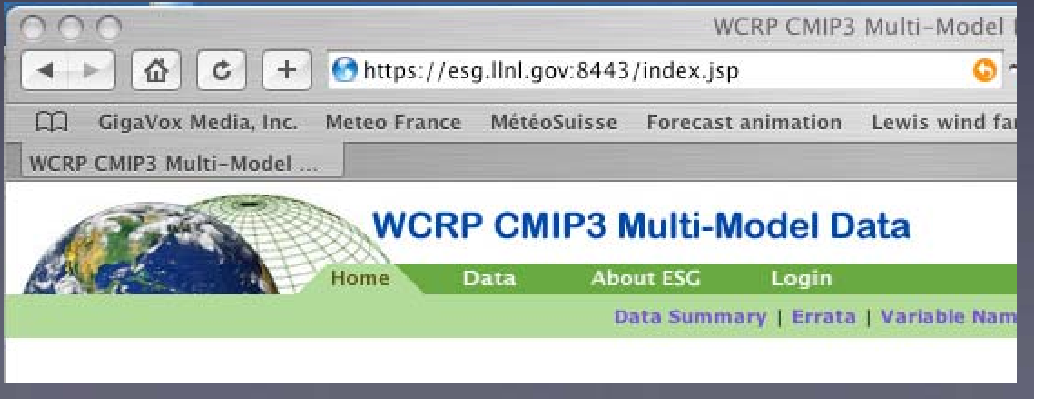
Lecture Summary

- Deep beginnings
- History of climate models (sort of)
- Main theme: Six key catalysts in model development have drive climate modelling's directions

How we got here



- A history of climate models: building frameworks.
- The driving forces behind development and how they work.
- Six key milestones and triggers for activity in modern climate modelling.
- Key characteristics of models and how they arise.
- Key outcome: understand where the CMIP3 results come from.



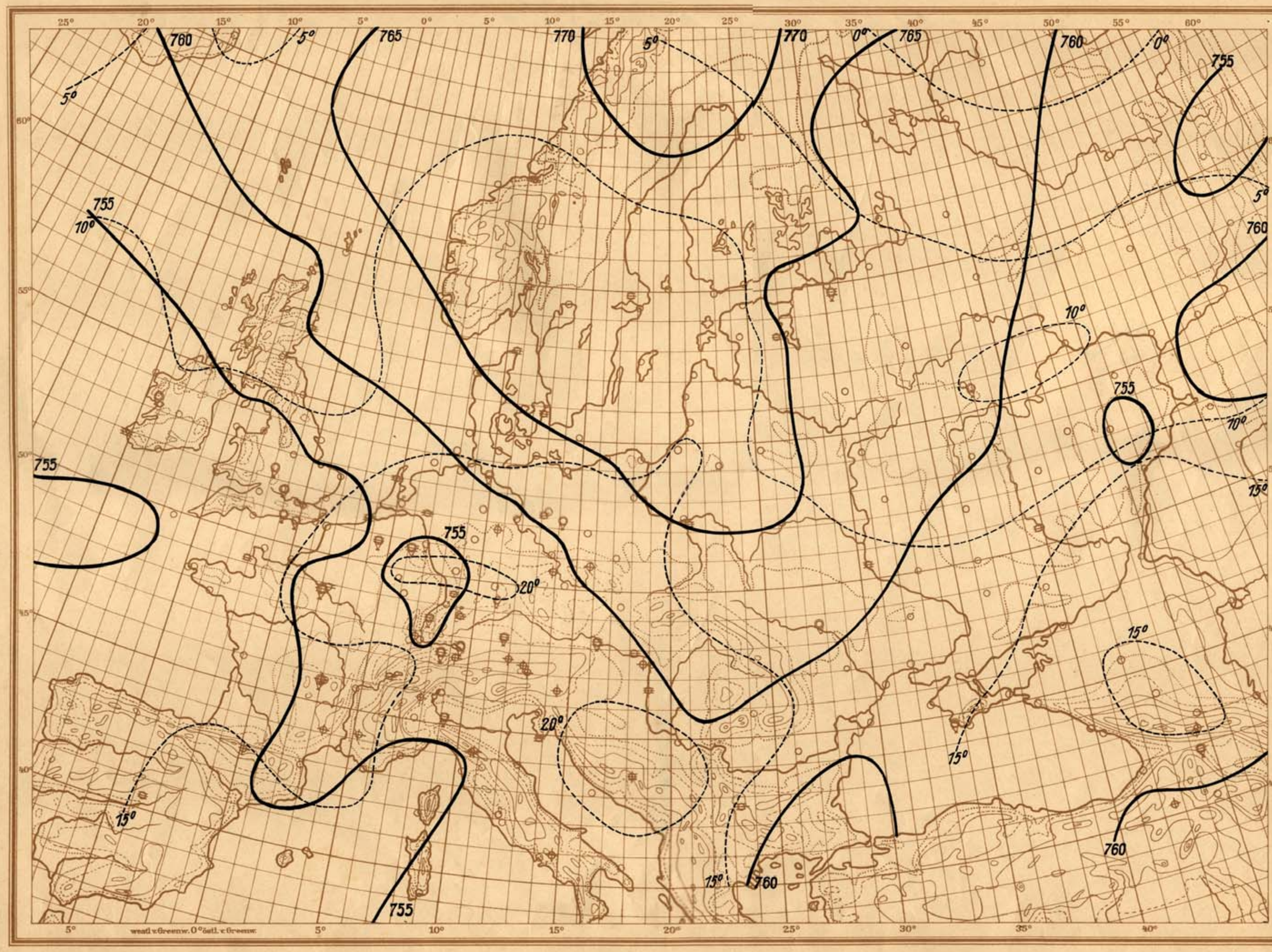
In the beginning

- By the 19th century, the pattern of winds on the globe is mapped and the search for explanations based on our understanding of a heated rotating sphere begins.

- Explanations of climate are little more than story-telling and hand-waving.

- In 1897, Bjerknes constructs the equations that describe a the motion and thermodynamics of a non-homogeneous fluid.

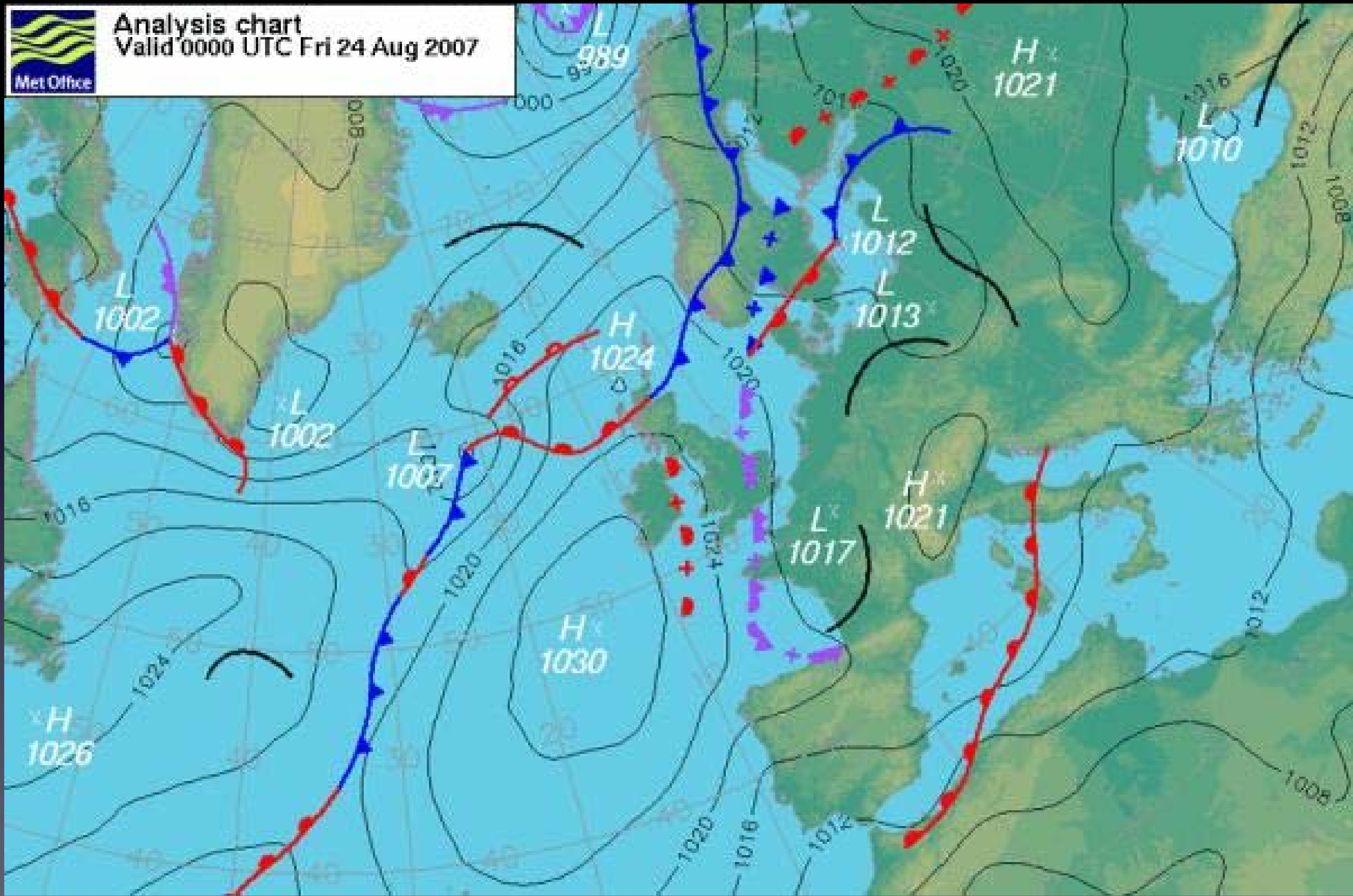
- Bjerknes argues that a physical description of the atmosphere could be used for prediction “Hopefully, the time will also soon come, when a complete statement of atmospheric conditions can be made either daily or on specified dates. At that point, the first condition for scientific weather forecasting will be met.” Published in the Magazine of Meteorology, January 1904(Meteorologische Zeitschrift)



Isobaren im Meeresniveau in mm Quecksilber (ausgezogene Linien).
Isothermen an der Erdoberfläche (gestrichelte Linien).

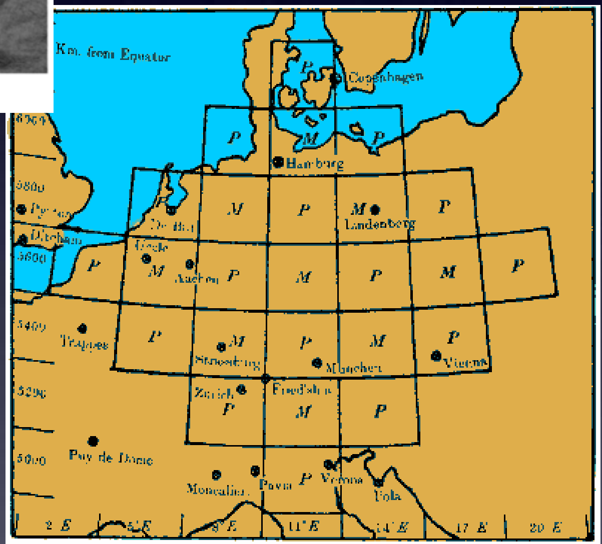
1 : 10 000 000

20. Mai 1910, 7h a. Gr. Z.

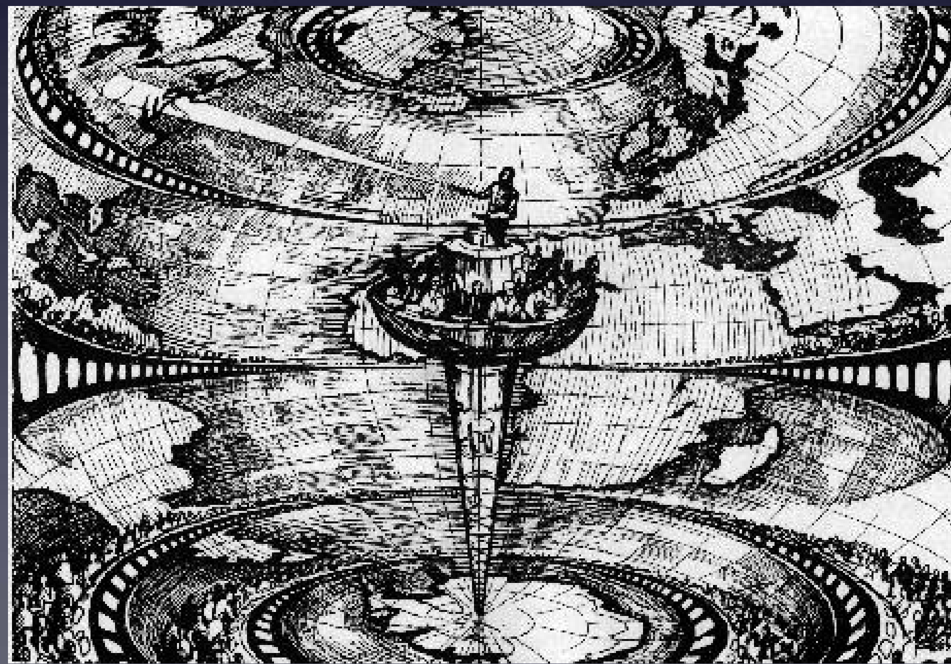

Analysis chart
Valid 0000 UTC Fri 24 Aug 2007
Met Office
L 989
H 1021
L 1010
L 1002
L 1002
L 1007
H 1024
L 1012
L 1013
L 1017
H 1021
H 1030
H 1026
1016
1020
1024
1012
1008

- L.F. Richardson formulates numerical basis for weather forecasts

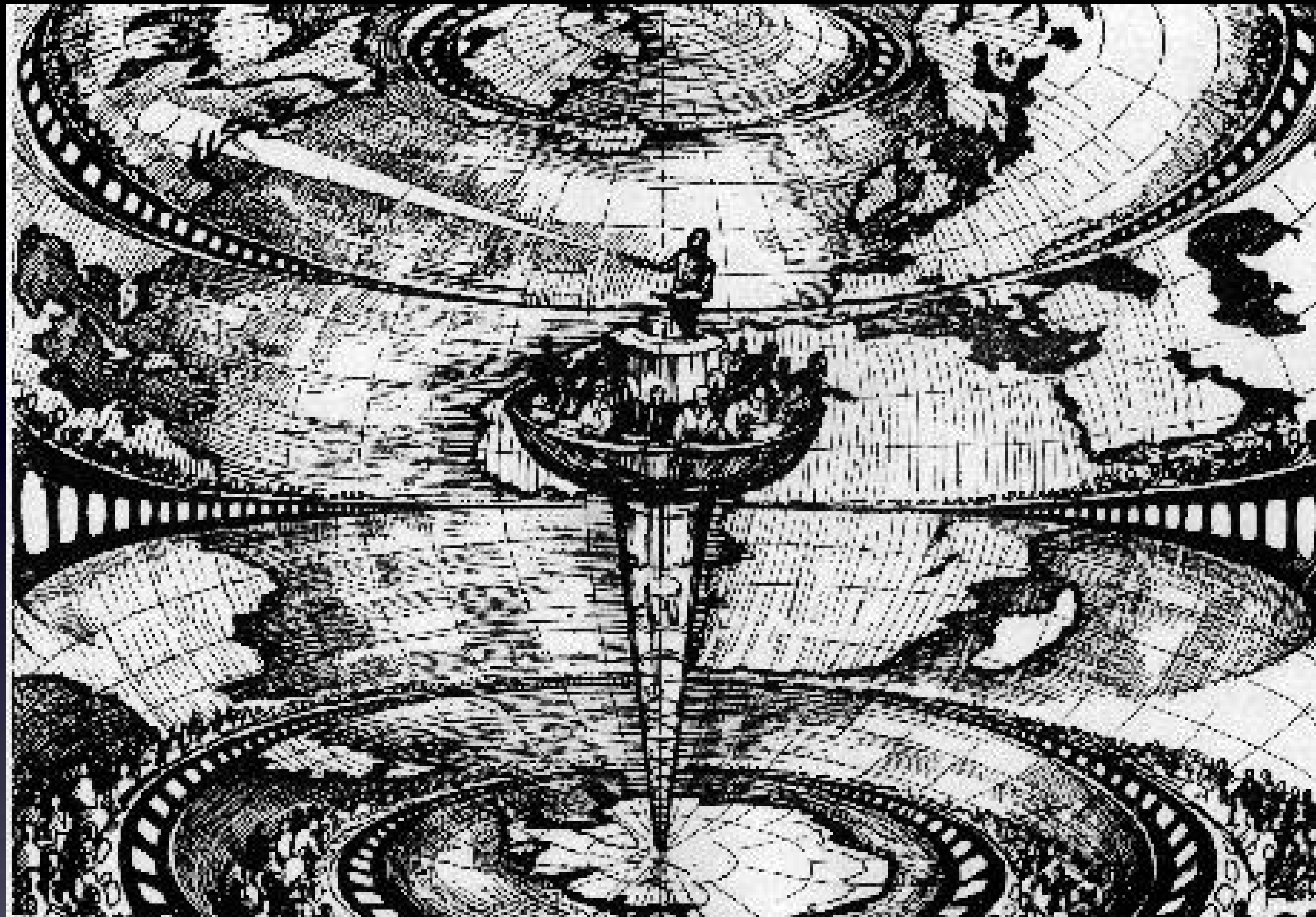
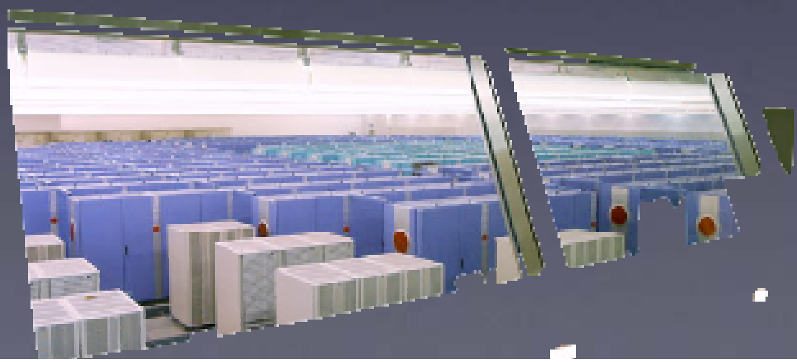
Richardson developed a scheme for numerical prediction of the atmospheric state. His experiment did not produced a realistic result and he concluded that “The scheme is complicated because the atmosphere itself is complicated.



After 6 weeks of pencil work, he wonders if one in the dim future it will be possible to advance the calculations faster than the weather advances.



He envisages a ‘forecast factory’

If you would understand anything, observe its beginning and its development.
— Aristotle

History is the distillation of rumour.
— Thomas Carlyle

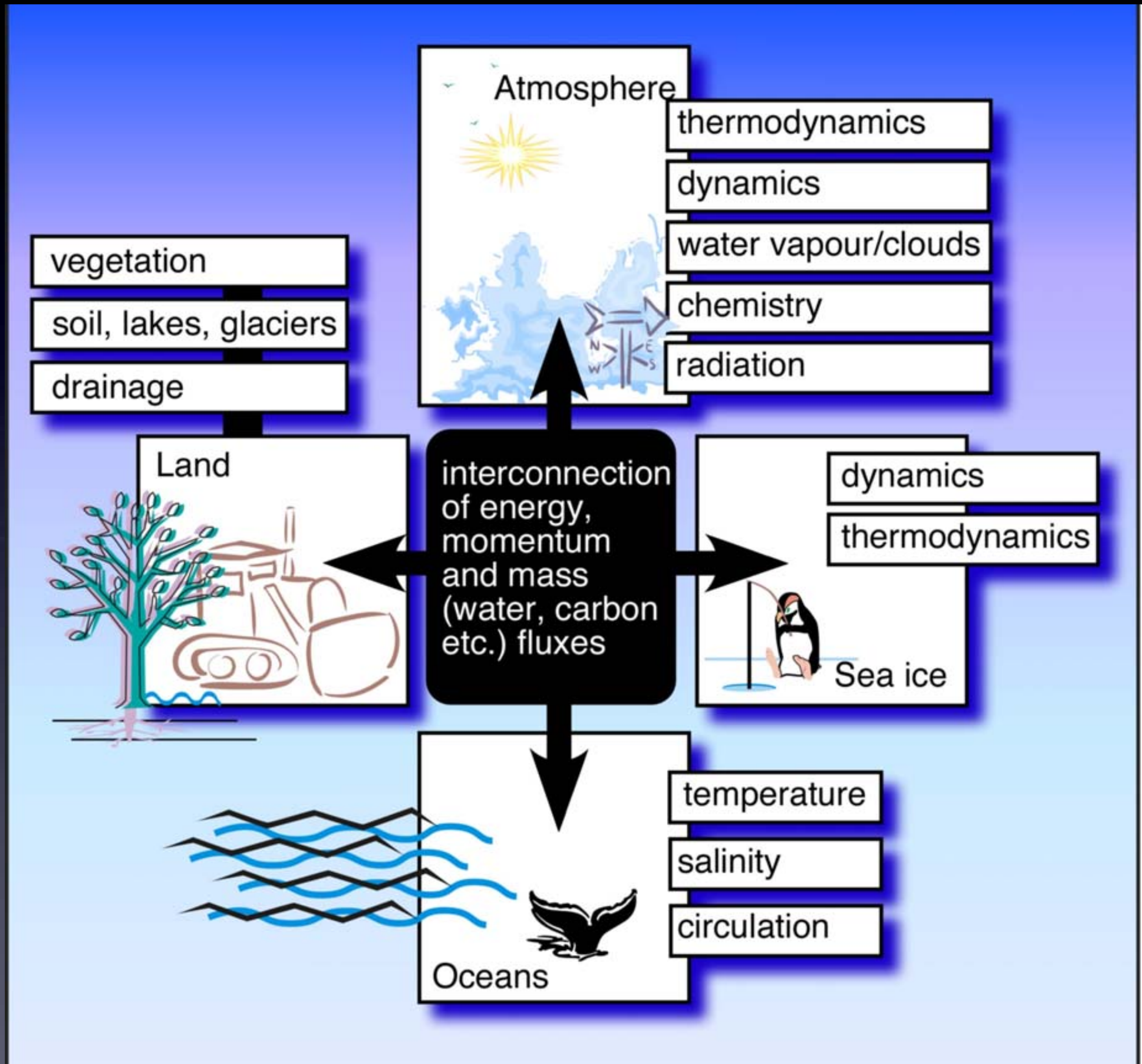
History

- History is, more or less, bunk. — *Henry Ford*
- A chronological record of significant events— *Webster's Dictionary*
- History is indeed little more than the register of the crimes, follies, and misfortunes of mankind — *Edward Gibbon*
- There is properly no history; only biography — *Ralph Waldo Emerson*

For my part, I consider that it will be found much better by all parties to leave the past to history, especially as I propose to write that history myself.
Winston Churchill

History

- History, real solemn history, I cannot be interested in.... I read it a little as a duty; but it tells me nothing that does not either vex or weary me. The quarrels of popes and kings, with wars and pestilences in every page; the men all so good for nothing, and hardly any women at all - it is very tiresome. — *Jane Austen* (from Northanger Abbey)

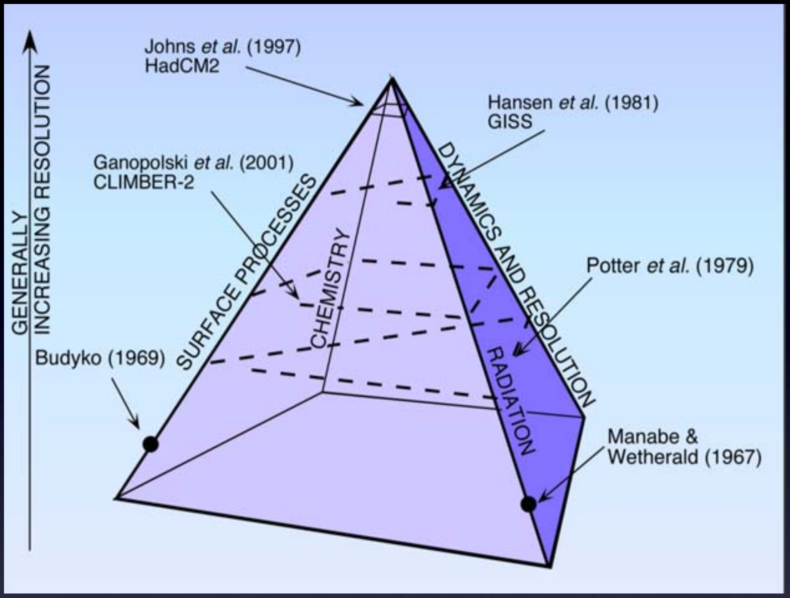


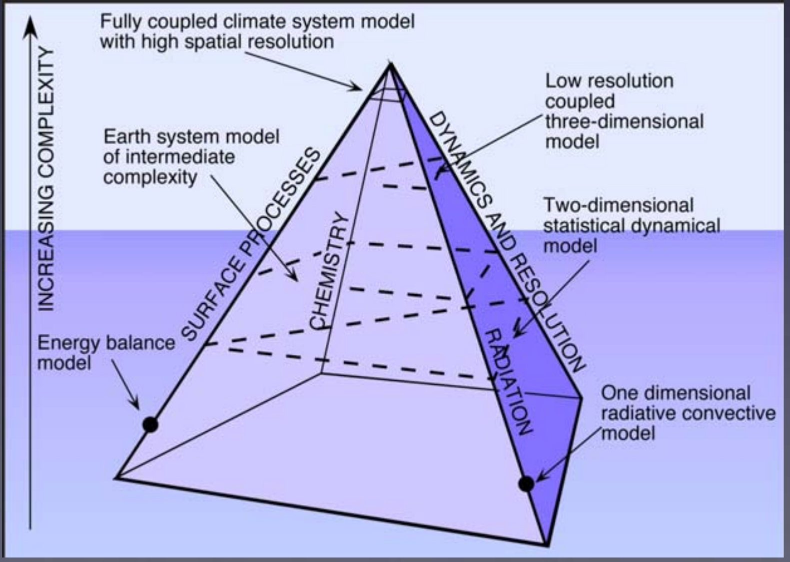
Today we have coupled models incorporating many aspects of the climate system.

How did we get here and how do we use the tools available to go further?

Climate Model Pyramid

- A simple description of climate models is the climate modelling pyramid.
- Simple models are at the base and more complex models at the top.
- Higher means more complex, but not necessarily ‘better’.





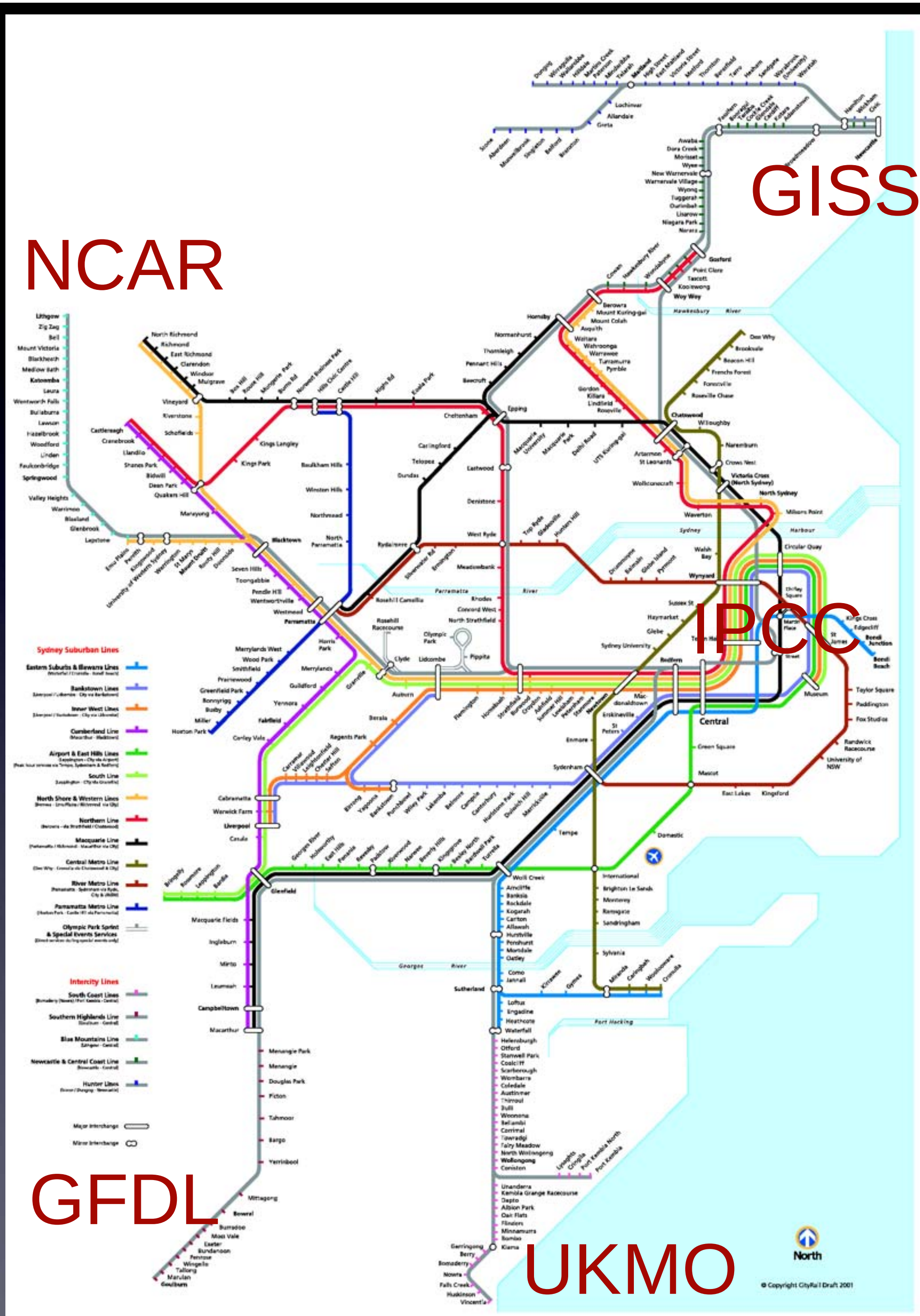
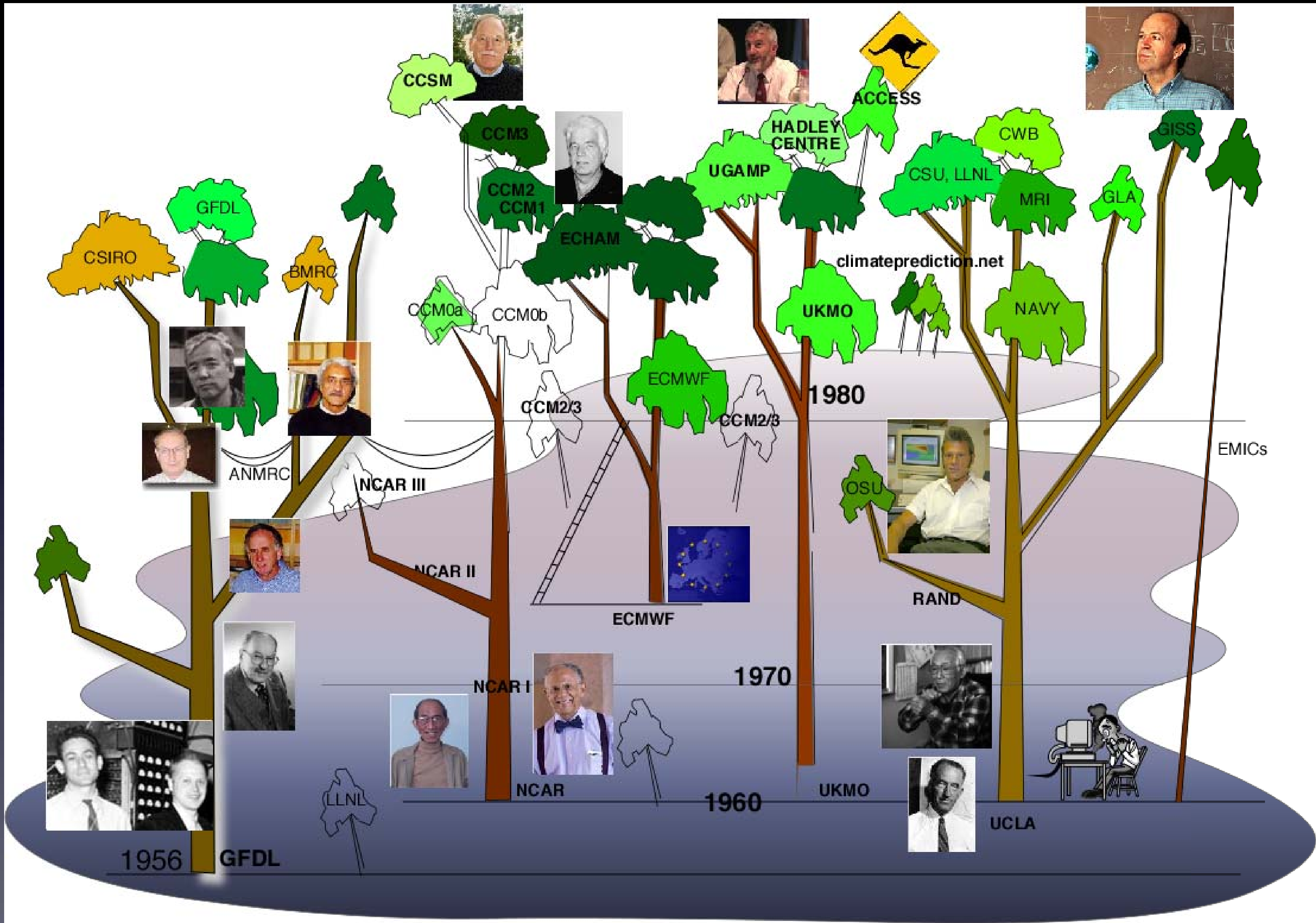


Figure 5.9. Indicative possible train operational patterns on the indicative "ultimate" rail network shown in Figure 5.8.



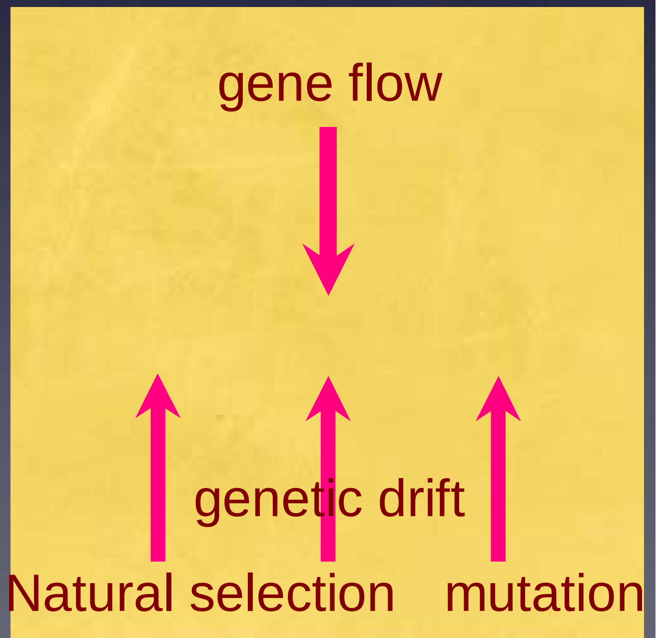
'data' from Spencer Weart's AIP page

Factors affecting population development

- Mutation: a sudden change in genotype caused by a small change in the DNA
- Gene flow: genetic material flows from other populations
- Natural selection: some environments favour certain characteristics and these individuals come to dominate the population
- Genetic Drift: changes due to random chance
- Inbreeding & Inbreeding Depression: a restricted pool of genetic material leads to a reduction in vigour due to expression of deleterious recessive alleles.

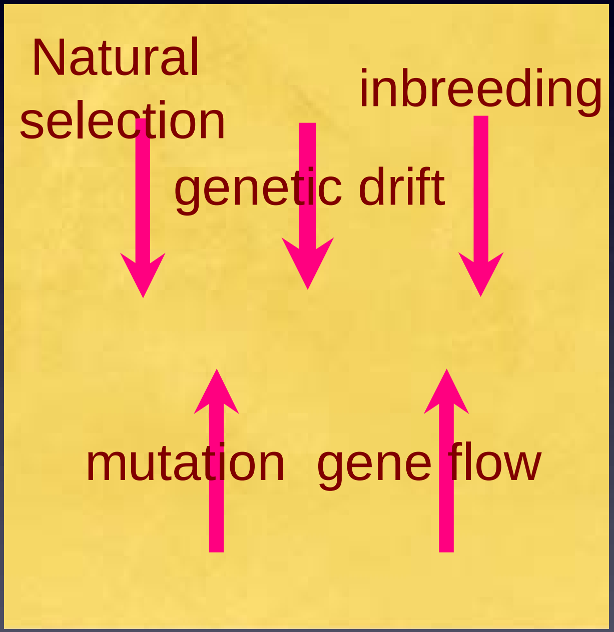
Between population diversity

- populations diverge for a number of reasons
  - natural selection (of parameterisations)
  - genetic drift (modellers get smarter and have lucky breaks)
  - mutations (e.g. funding cuts and increases)
- gene flow: movement of scientists and information reduces inter-population variation



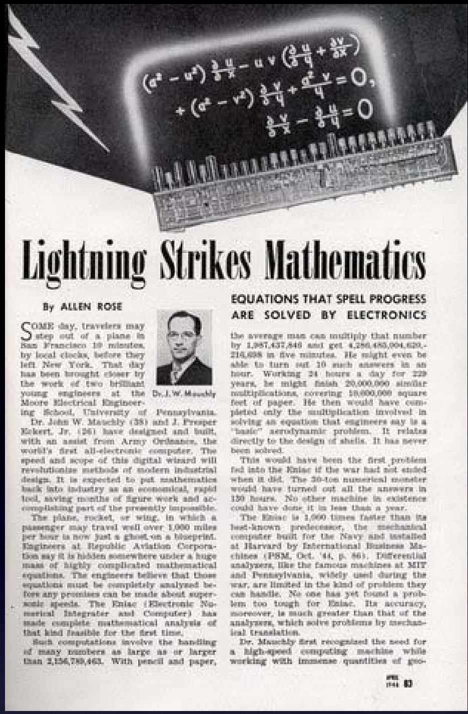
Within population variation

- Variation within a population is controlled (reduced) by
  - natural selection (the best individuals dominate)
  - genetic drift
  - inbreeding (leads to reduced vigour)
- increased by gene flow and mutation (new model versions created)



beginnings

- Fast-tracked development in WW2 means that computers are now available for scientific problems
- Spurred by possibilities of weather weapons, work on computerized forecasts begins
- Exact solution is impossible, so numerical schemes are developed



Lightning Strikes Mathematics

By ALLEN ROSE

EQUATIONS THAT SPELL PROGRESS ARE SOLVED BY ELECTRONICS

Dr. J. W. Mauchly

SOME day, travelers may step out of a plane in San Francisco 10 minutes, by local clocks, before they left New York. That day has been brought closer by the work of two brilliant young engineers at the Moore Electrical Engineering School, University of Pennsylvania.

Dr. John W. Mauchly (38) and J. Presper Eckert, Jr. (26) have designed and built, with an assist from Army Ordnance, the world's first all-electronic computer. The speed and scope of this digital wizard will revolutionize methods of modern industrial design. It is expected to put mathematics back into industry as an economical, rapid tool, saving months of figure work and accomplishing part of the presently impossible.

The plane, rocket, or wing, in which a passenger may travel well over 1,000 miles per hour is now just a ghost on a blueprint. Engineers at Republic Aviation Corporation say it is hidden somewhere under a huge mass of highly complicated mathematical equations. The engineers believe that those equations must be completely analyzed before any promises can be made about supersonic speeds. The Eniac (Electronic Numerical Integrator and Computer) has made complete mathematical analysis of that kind feasible for the first time.

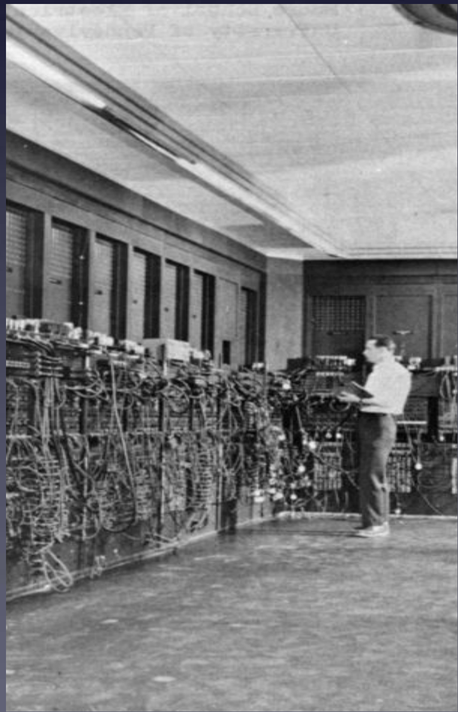
Such computations involve the handling of many numbers as large as or larger than 2,156,789,463. With pencil and paper, the average man can multiply that number by 1,987,437,846 and get 4,286,485,004,620,-216,698 in five minutes. He might even be able to turn out 10 such answers in an hour. Working 24 hours a day for 229 years, he might finish 20,000,000 similar multiplications, covering 10,000,000 square feet of paper. He then would have completed only the multiplication involved in solving an equation that engineers say is a "basic" aerodynamic problem. It relates directly to the design of shells. It has never been solved.

This would have been the first problem fed into the Eniac if the war had not ended when it did. The 30-ton numerical monster would have turned out all the answers in 150 hours. No other machine in existence could have done it in less than a year.

The Eniac is 1,000 times faster than its best-known predecessor, the mechanical computer built for the Navy and installed at Harvard by International Business Machines (PSM, Oct. '44, p. 86). Differential analyzers, like the famous machines at MIT and Pennsylvania, widely used during the war, are limited in the kind of problem they can handle. No one has yet found a problem too tough for Eniac. Its accuracy, moreover, is much greater than that of the analyzers, which solve problems by mechanical translation.

Dr. Mauchly first recognized the need for a high-speed computing machine while working with immense quantities of geo-

APRIL 1946 83



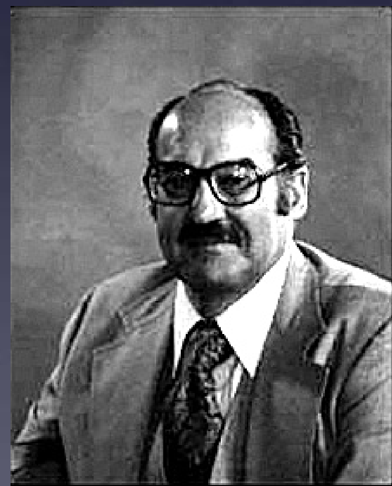
Popular Science, April 1946

Forties and Fifties

In 1952 Bert Bolin concluded that "there is very little hope for the possibility of deducing a theory for the general circulation of the atmosphere from the complete hydrodynamic and thermodynamic equations.

Already Von Neuman had started working on numerical computations of the atmosphere

Smagorinsky



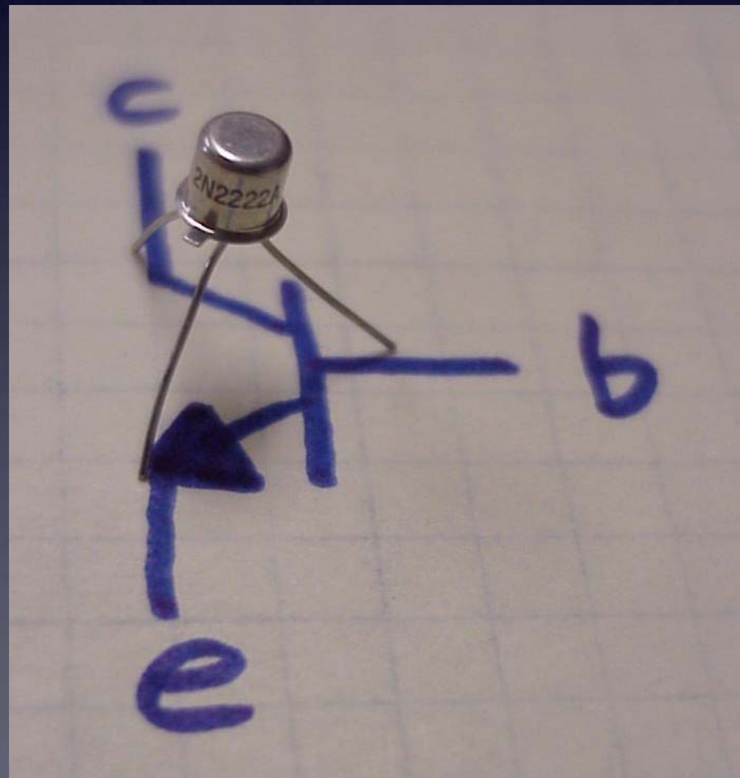
Charney

"the machine will give a greater scope to the making and testing of physical hypotheses"

by 1949, results were looking fairly realistic.

Arakawa, Manabe, Phillips, Wetherald, Mintz,

Milestone1. The Transistor



Early years: the invention of a machine

- Formulation of models
- Direct programming of hardware by a few individuals
- Dealing with new paradigms poses problems (what is status of model output)
- Computers still barely able to do the job required

Early highlights

- Von Neuman sees parallels between explosion simulations and weather predictions and advocates the use of computers
- Jules Charney is invited to head a new meteorology group and by 1950 has a 24 hour forecast that takes 24 hours to produce a 24 hour forecast (700km grid over USA)
- Charney's success sparks further action. By 1958 Smagorinsky has employed a young Japanese physicist (Manabe) who goes on to build one of the longest lasting GCM programmes.
- Manabe studies all aspects of the climate system and by 1965, the lab has a nine level model of the global atmosphere (no geography)
- Meanwhile at UCLA, a young Arakawa has been recruited and by 1964 has a 2 layer, global model with geography, moutains, oceans and ice (representations anyway)

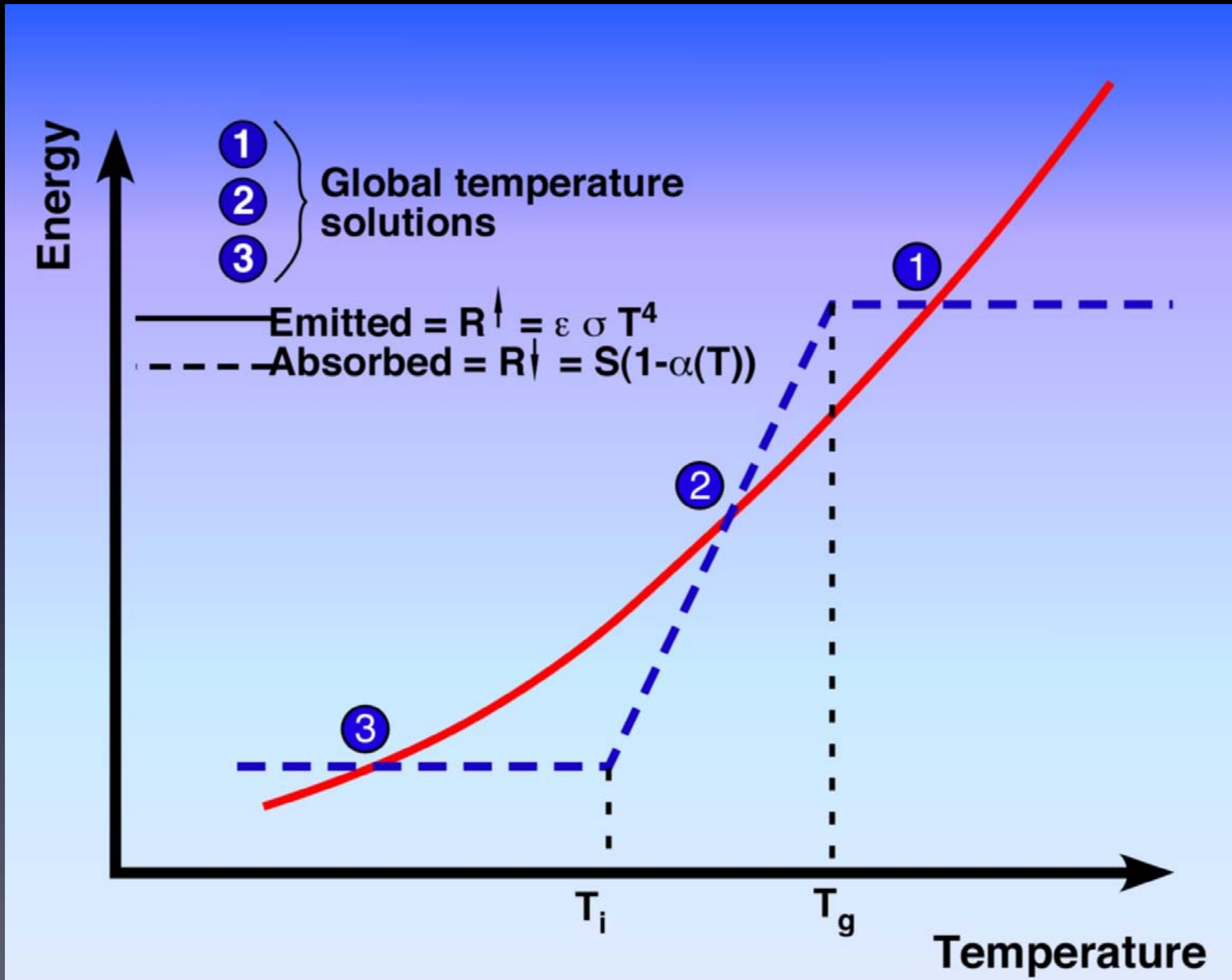
Milestone 2: FORTRAN

1960s and FORTRAN

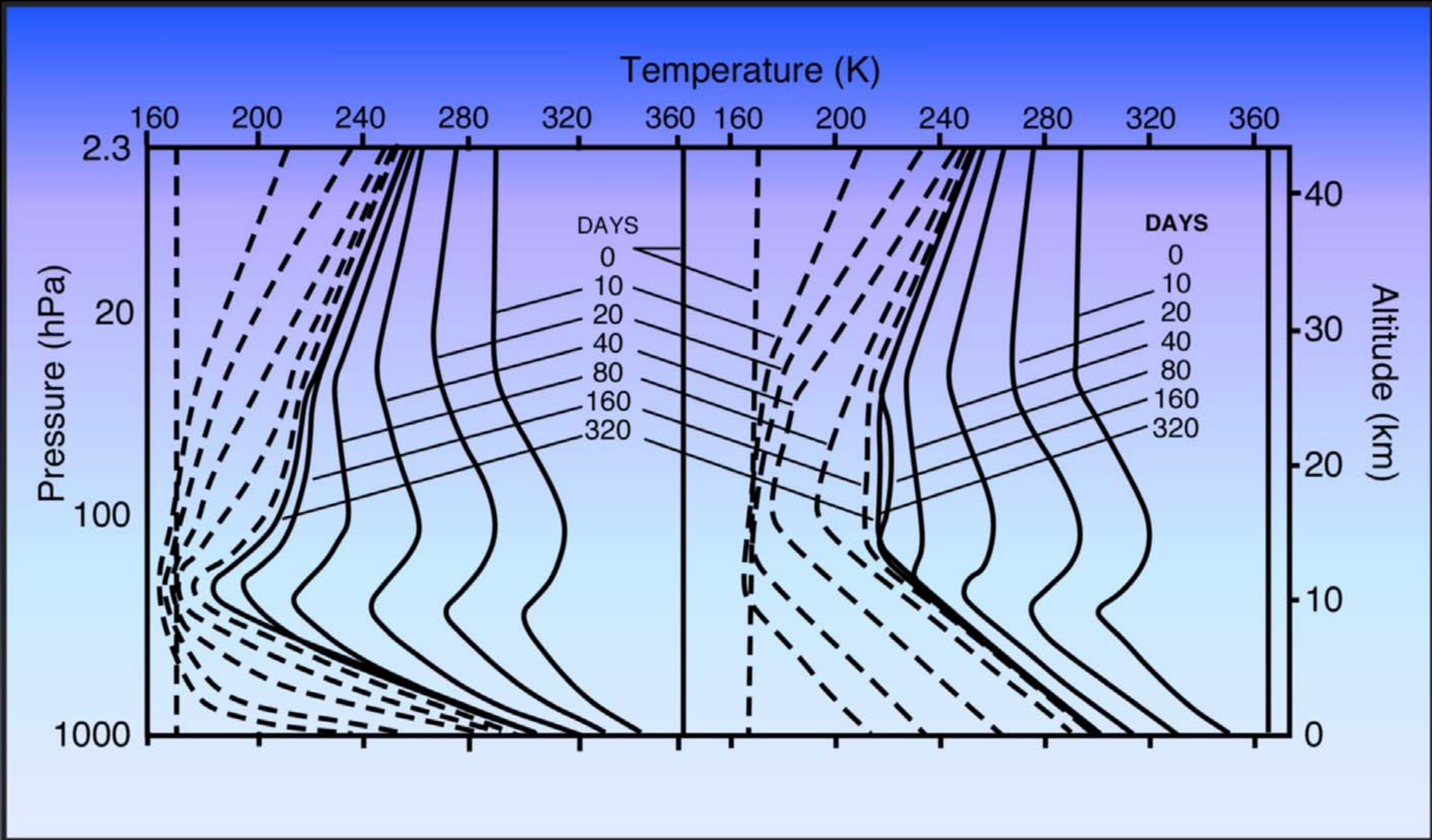
- High level languages and ‘programmers’ are invented. Scientists can now focus on science.
- Modelling at this point is a secret society. Programming is a complex task, heavily machine dependent. Higher level languages are primitive compared to today and storage capacity is minimal.
- At this point, models begin to emerge around the world as computers improve and knowledge spreads. Gene flow increases but mutations and genetic drift dominate.

1960s

- Decent simulations of climate (e.g. Smagorinksy, 1963; Leith, 1965)
- Development of ocean model (Bryan, 1969; Manabe & Bryan, 1969)
- 1D RC simulations (Manabe & Wetherald, 1967)
- Role of the surface hydrology (Manabe, 1969)
- Energy Balance Models (Budyko 1969; Sellers, 1969)
- Credibility established and conceptual aspects being explored



Energy
1
2
3
Global temperature solutions
Emitted = R↑ = ε σ T⁴
Absorbed = R↓ = S(1-α(T))
1
2
3
T_i
T_g
Temperature


Temperature (K)
160
200
240
280
320
360
160
200
240
280
320
360
2.3
20
100
1000
Pressure (hPa)
Altitude (km)
40
30
20
10
0
DAYS
0
10
20
40
80
160
320
DAYS
0
10
20
40
80
160
320

60s

- Basic building blocks are constructed and modellers begin to expand their horizons
- Implementation is ‘basic’ at best
- Computers are getting better but still a rare and expensive resource
- ...enter Seymour Cray

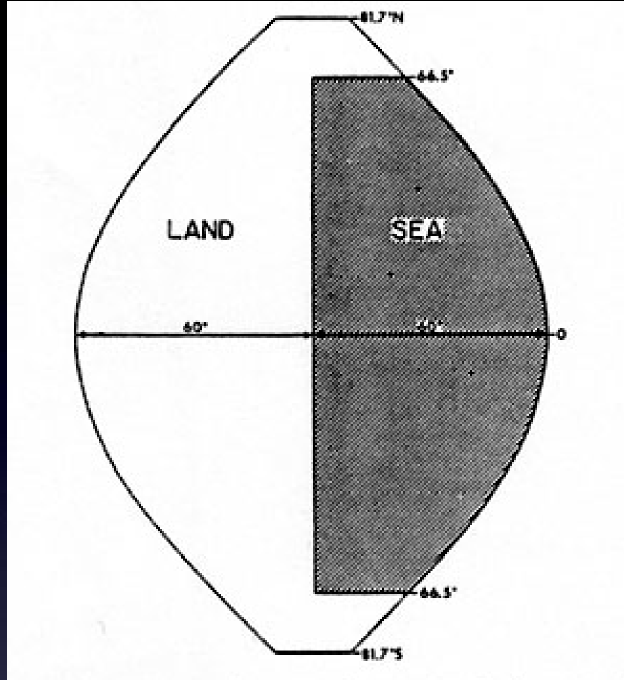
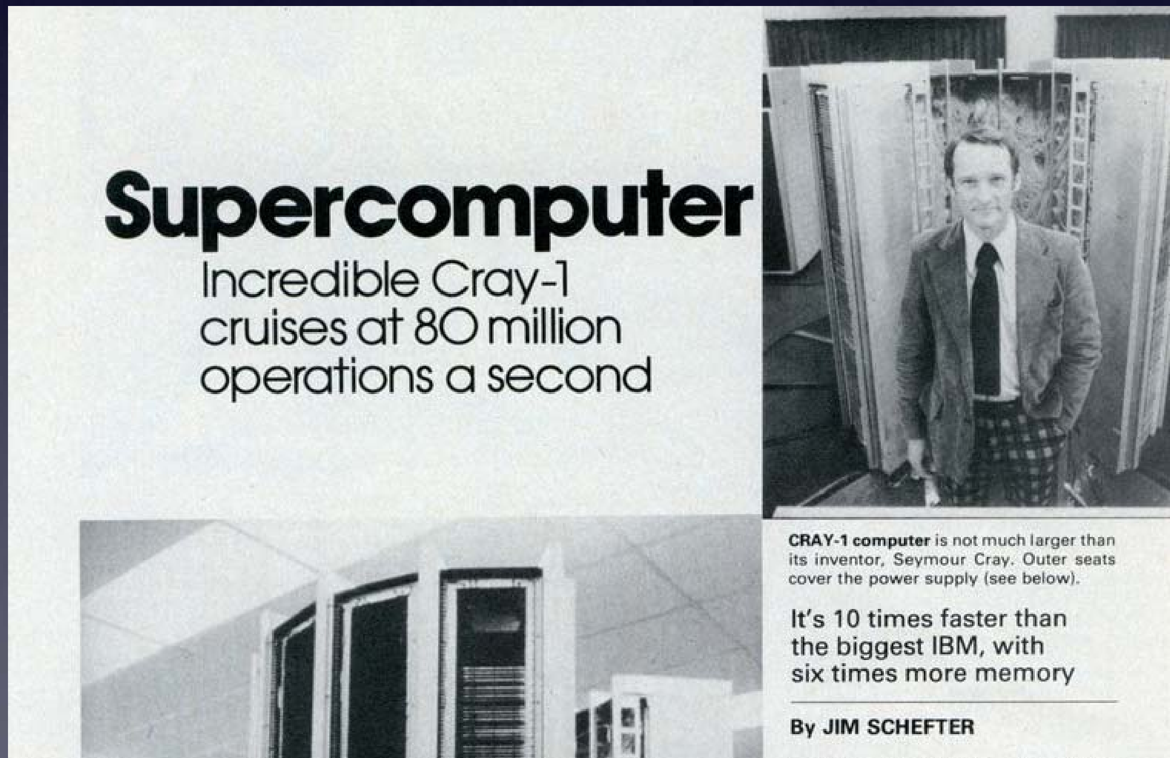


FIG. 1. Ocean-continent configuration of the model.

Milestone 3: Supercomputer



Supercomputer

Incredible Cray-1 cruises at 80 million operations a second

CRAY-1 computer is not much larger than its inventor, Seymour Cray. Outer seats cover the power supply (see below).

It's 10 times faster than the biggest IBM, with six times more memory

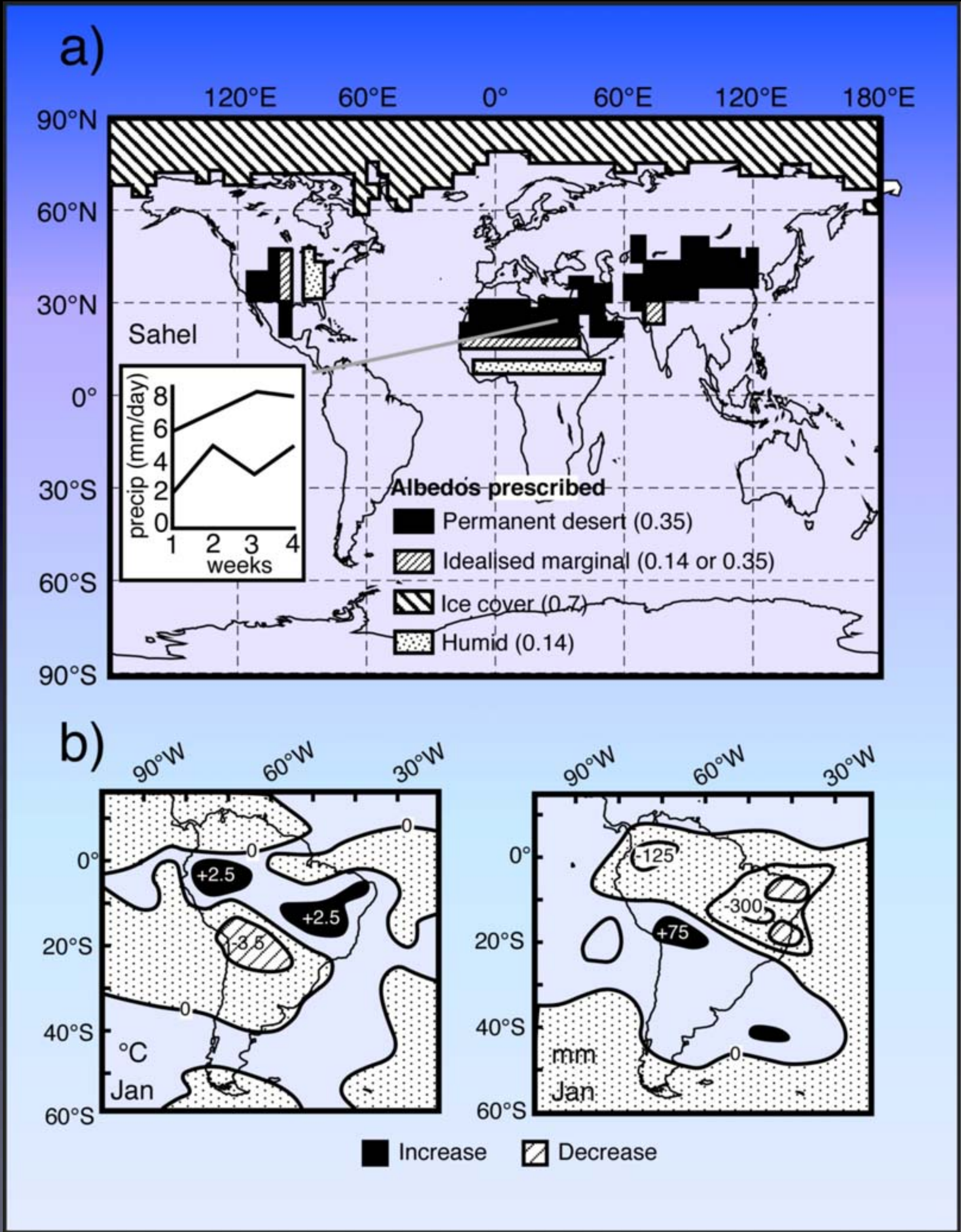
By JIM SCHEFTER

1970s

- Computers keep getting bigger, storage improves, understanding improves
- Modellers start to catalogue their tools
- Recognition of a lack of knowledge about the real atmosphere spawns GARP and FGGE (1979)
- Modelling begins to develop different schools of thought that continue to this day

Classifying modellers

- Seers & formalists emerge as genres
  - Seers: Model’s simulated climate has many characteristics of the real climate the important features are included (ocean, atmosphere, surface hydrology)
  - Formalists pursue detail
- In the 70s, a heirarchy begins to emerge (e.g. Schneider and Dickinson) and modelling continues to develop.



At this time, we see the emergence of 'model experiments' and a framework for analysis of these experiments

70s classics

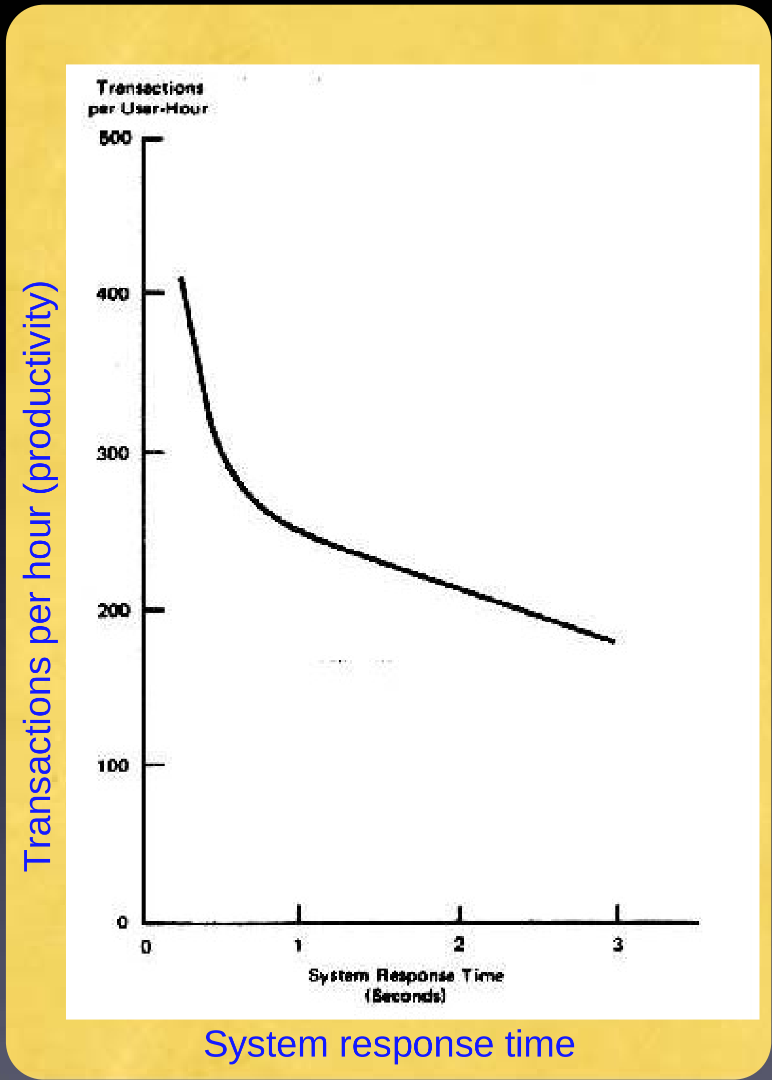
- Manabe & Wetherald 1975; Effects of CO_2 doubling
- Chervin et al 1976; On determining statistical significance
- Bourke et al., 1977 Modelling using spectral methods
- Schneider and Dickinson, 1974, Review of Climate Modelling
- GARP 1975

Milestone 4: Sub-second response

1980s

- The arrival of sub-second response and interactive desktop computing

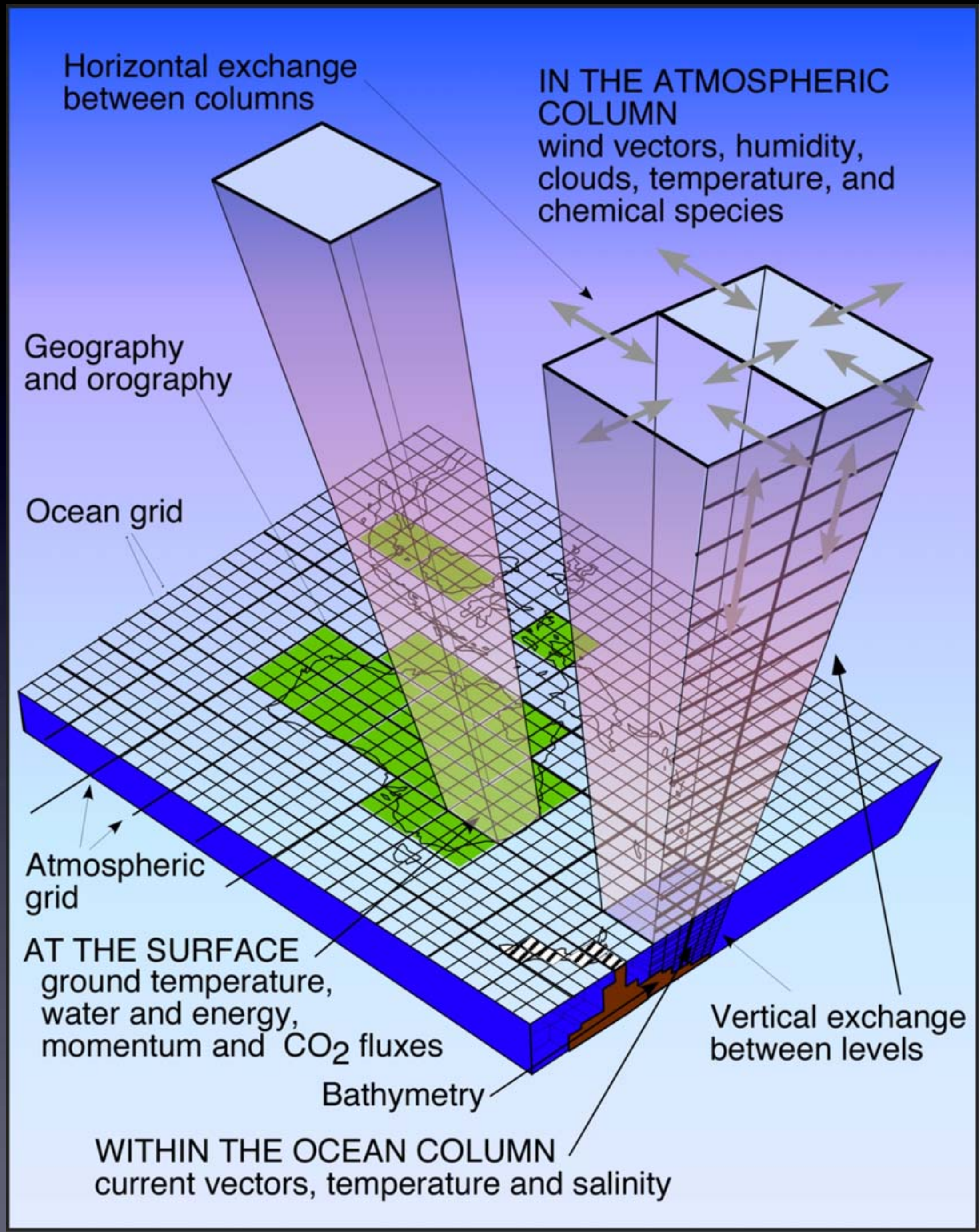
- The Economic Value of Rapid Response Time November, 1982 W. J. Doherty, A. J. Thadani, “*When a computer and its users interact at a pace that ensures that neither has to wait on the other, productivity soars, the cost of the work done on the computer tumbles, employees get more satisfaction from their work, and its quality tends to improve*”.

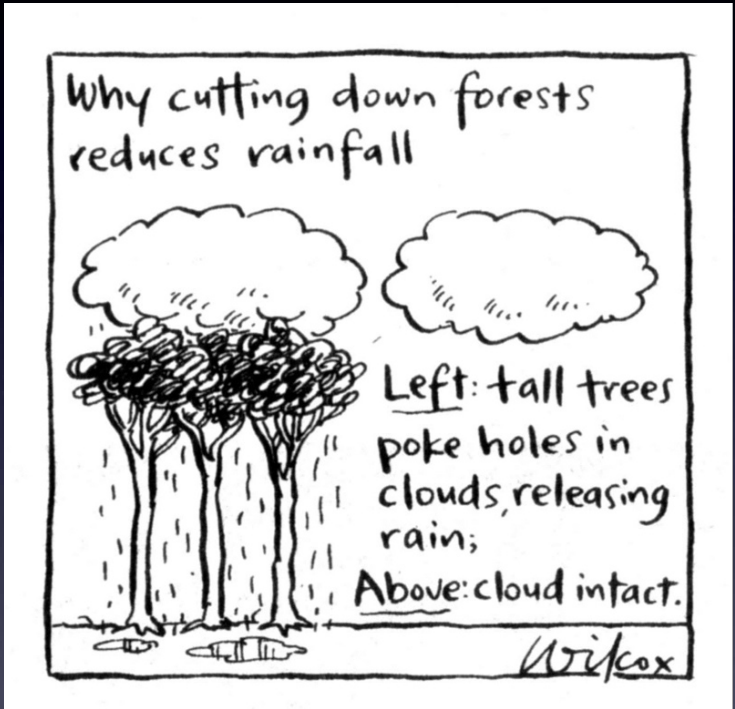


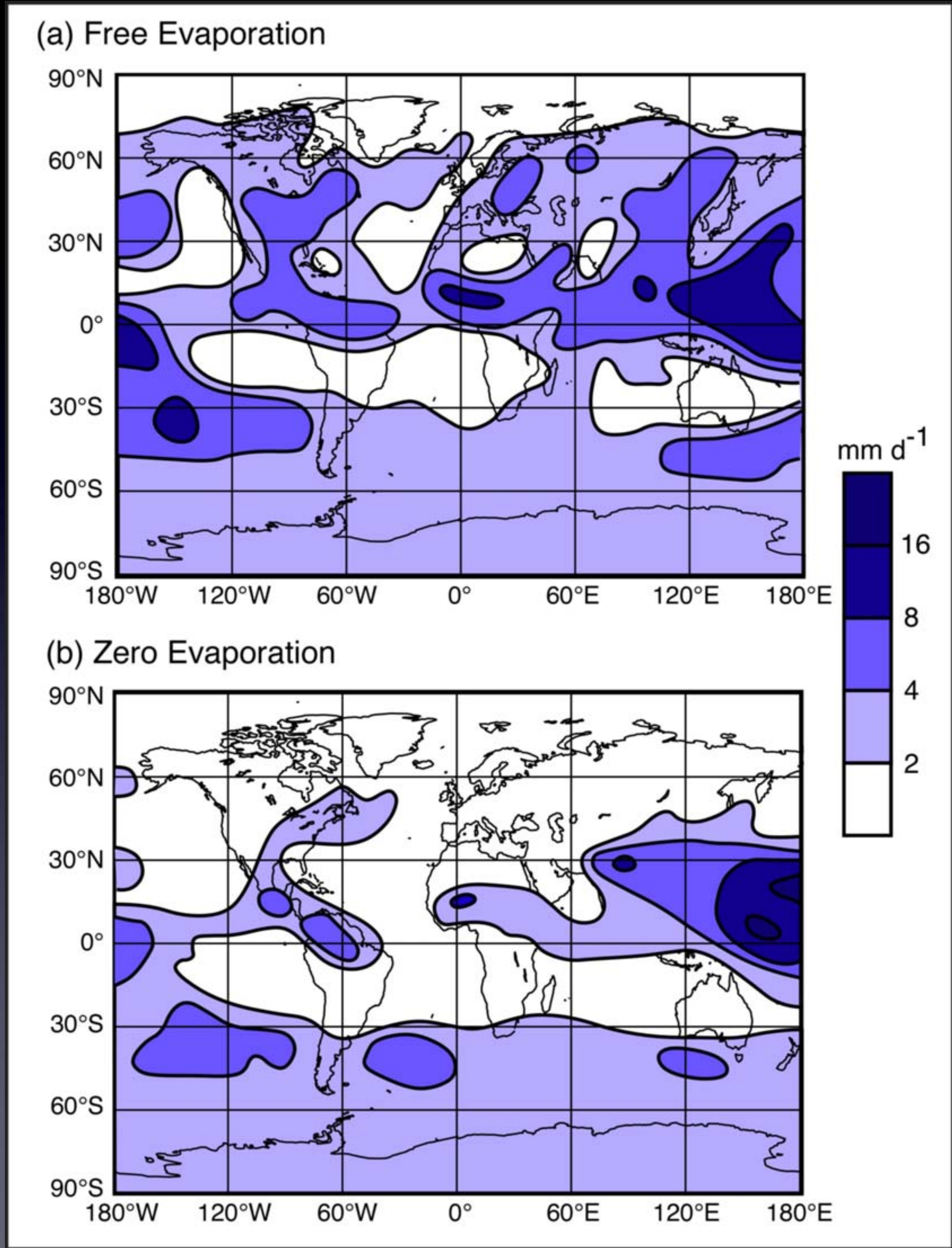
The rise of the formalists

- You can never have too much detail
- push to higher resolution
- push to longer simulations
- push for more processes (soil layers, stomates, crops, trees, rivers, sea ice etc.)
- the model is an end in itself

The formalists begin to dominate as the balance of external forces changes

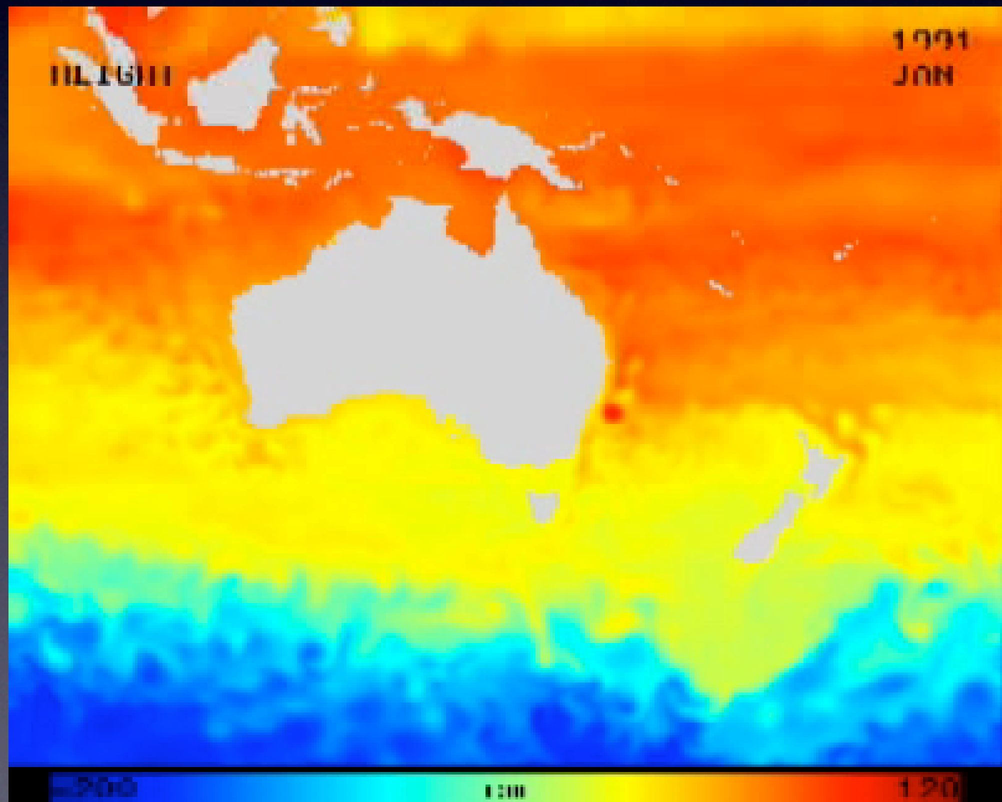



Why cutting down forests reduces rainfall
Left: tall trees poke holes in clouds, releasing rain;
Above: cloud intact.
Wilcox

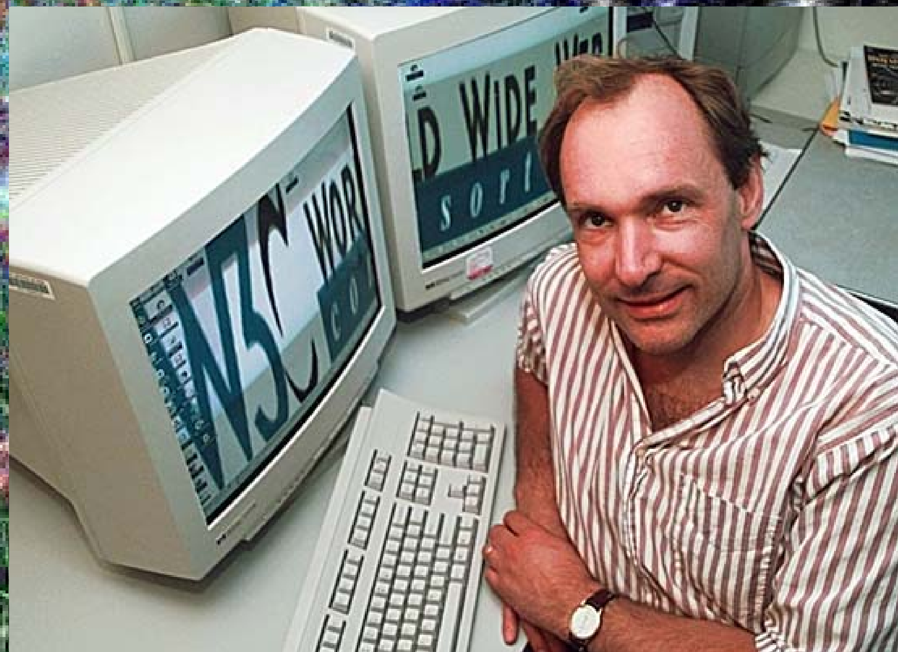

(a) Free Evaporation
90°N
60°N
30°N
0°
30°S
60°S
90°S
180°W
120°W
60°W
0°
60°E
120°E
180°E
(b) Zero Evaporation
mm d^{-1}
16
8
4
2

80s classics

- Semtner & Chervin, 1988
- Sellers et al., 1986 (SiB)
- Henderson-Sellers & Wilson 1983
- Washington et al., 1980

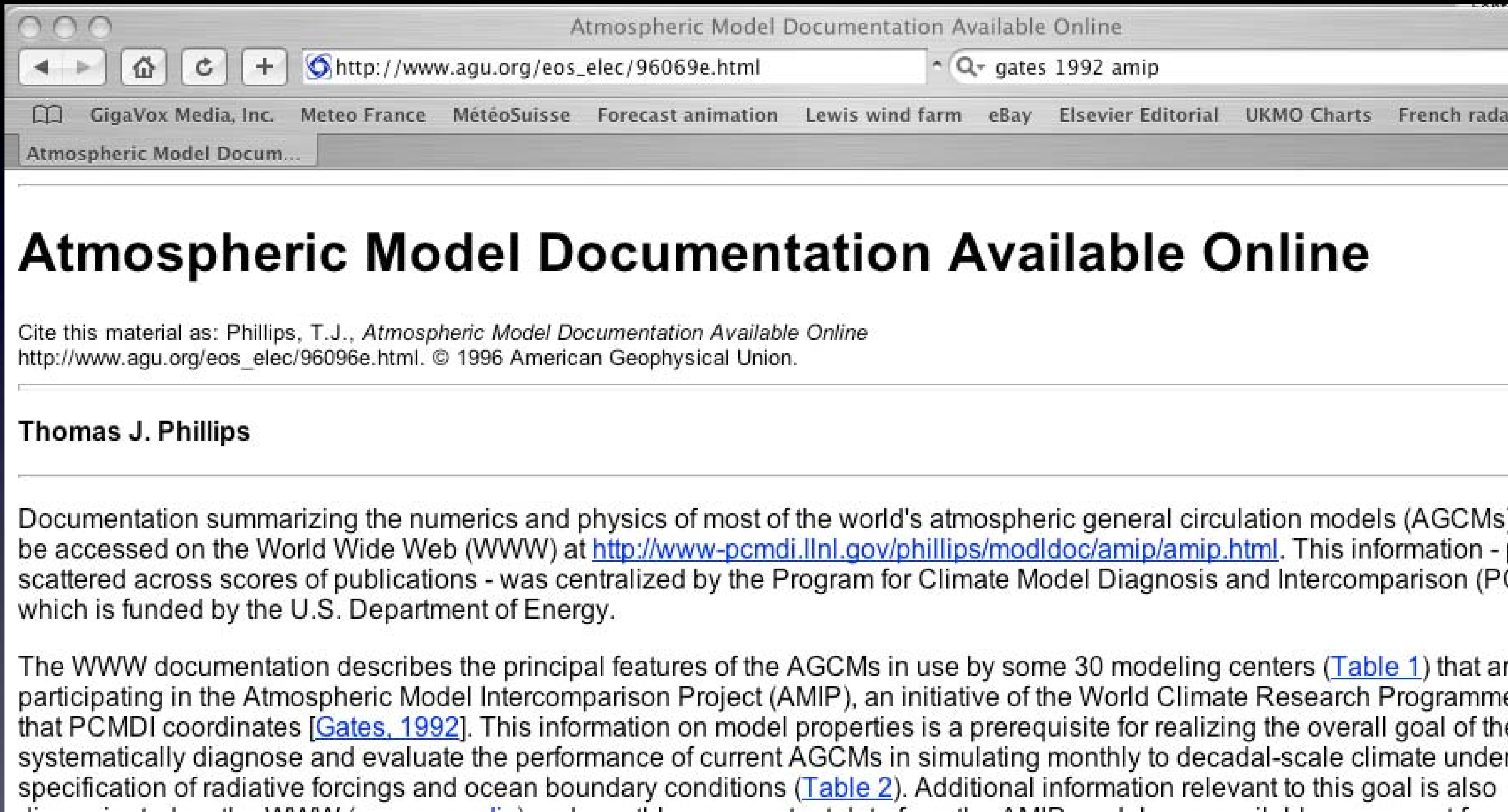


5. WWW



1990s: Intercomparisons and Assessments

- New communications spurs better documentation and sharing of data
- New generation of code sharing
- Model intercomparison projects abound
- IPCC begins to influence community



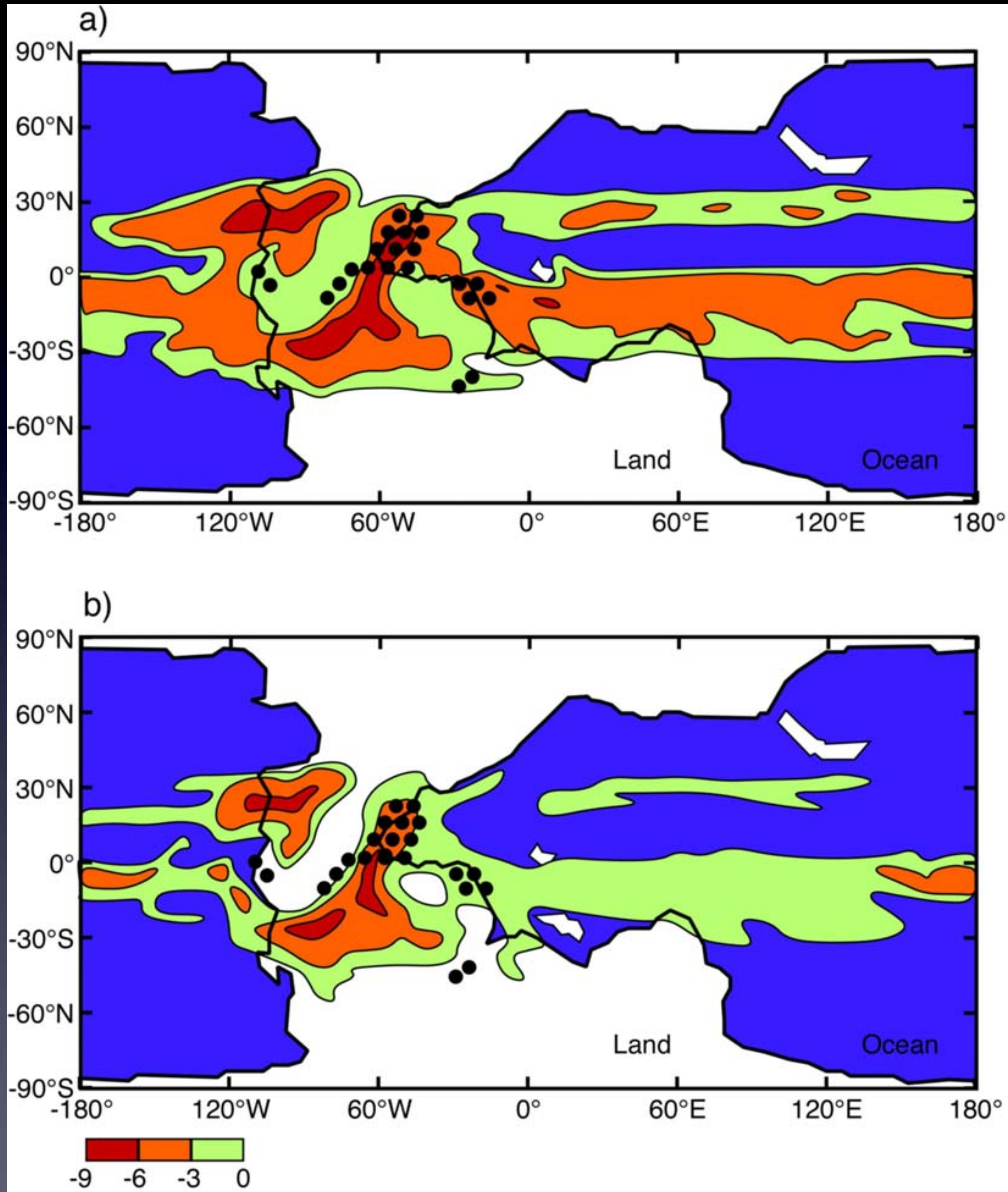
Atmospheric Model Documentation Available Online

Cite this material as: Phillips, T.J., *Atmospheric Model Documentation Available Online*
http://www.agu.org/eos_elec/96096e.html. © 1996 American Geophysical Union.

Thomas J. Phillips

Documentation summarizing the numerics and physics of most of the world's atmospheric general circulation models (AGCMs)
be accessed on the World Wide Web (WWW) at http://www-pcmdi.llnl.gov/phillips/modldoc/amip/amip.html. This information -
scattered across scores of publications - was centralized by the Program for Climate Model Diagnosis and Intercomparison (PC
which is funded by the U.S. Department of Energy.

The WWW documentation describes the principal features of the AGCMs in use by some 30 modeling centers (Table 1) that ar
participating in the Atmospheric Model Intercomparison Project (AMIP), an initiative of the World Climate Research Programme
that PCMDI coordinates [Gates, 1992]. This information on model properties is a prerequisite for realizing the overall goal of the
systematically diagnose and evaluate the performance of current AGCMs in simulating monthly to decadal-scale climate under
specification of radiative forcings and ocean boundary conditions (Table 2). Additional information relevant to this goal is also



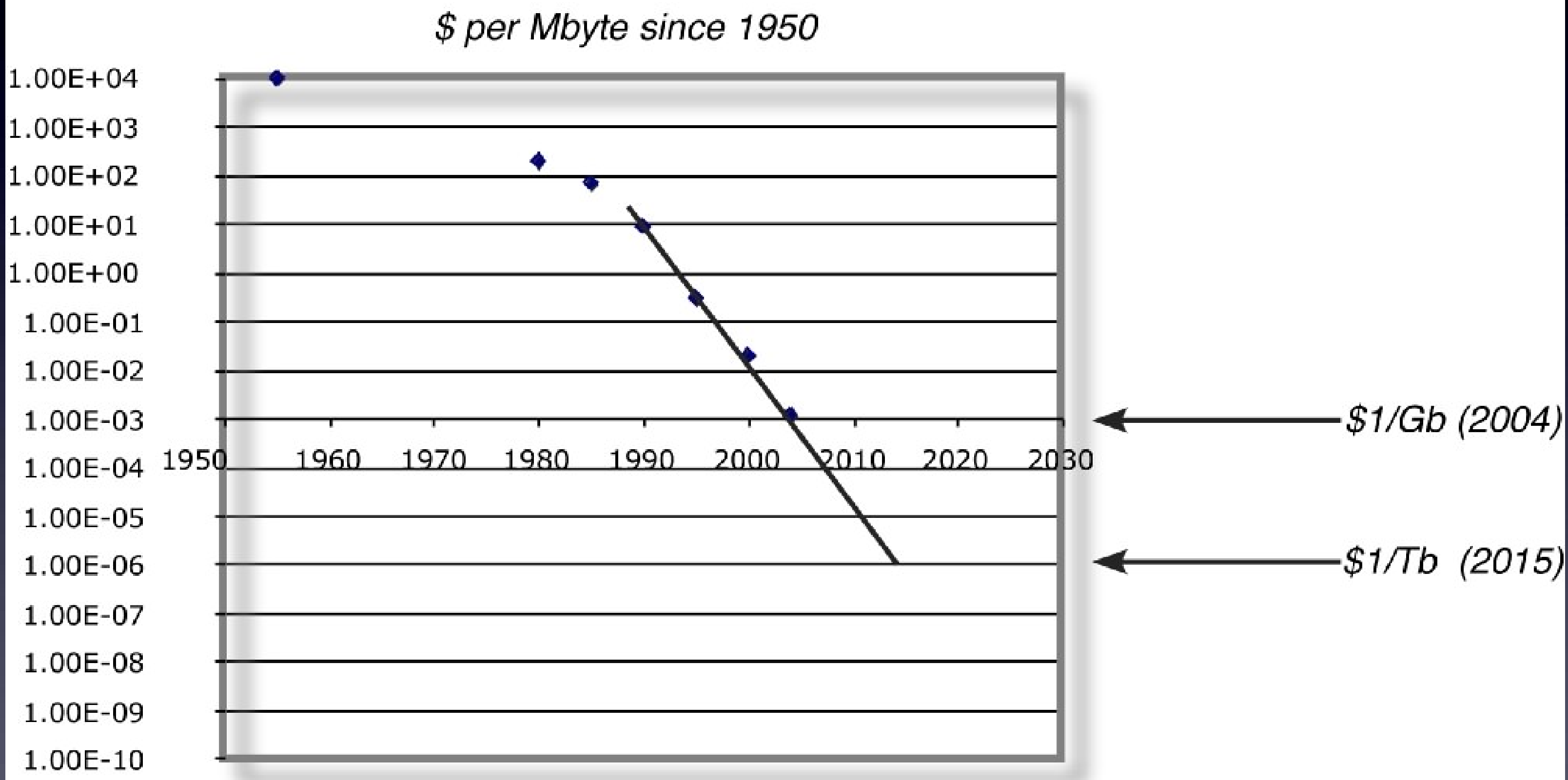
a)
90°N
60°N
30°N
0°
-30°S
-60°N
-90°S
-180°
120°W
60°W
0°
60°E
120°E
180°
Land
Ocean
b)
90°N
60°N
30°N
0°
-30°S
-60°N
-90°S
-180°
120°W
60°W
0°
60°E
120°E
180°
Land
Ocean
-9
-6
-3
0

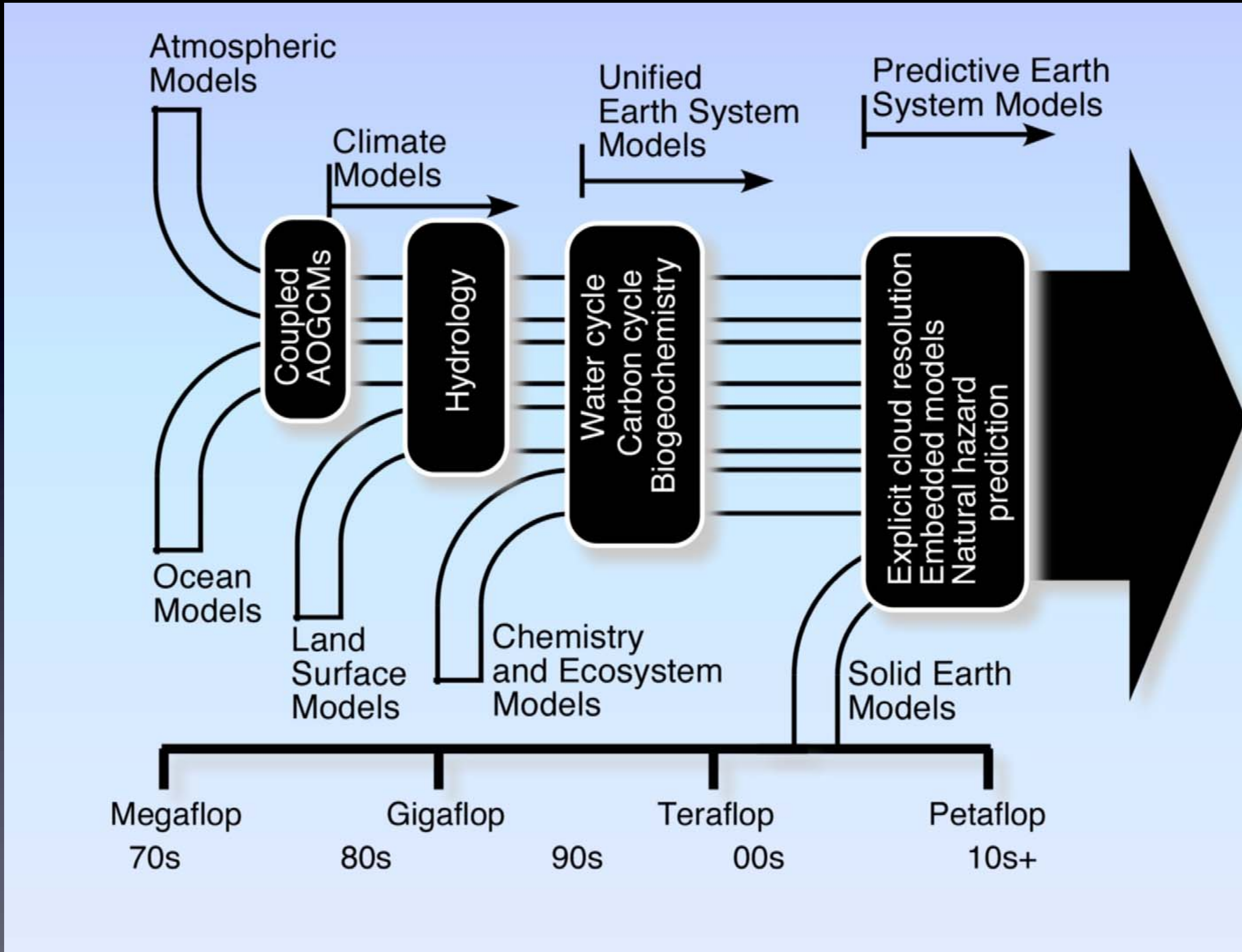
90s classics

- Cess et al., 1989 (FANGIO)
- Cess et al., 1991 (Snow-Climate Feedback analysis and intercomparison)
- Gates, 1992, AMIP
- IPCC Assessment reports begin to frame progress

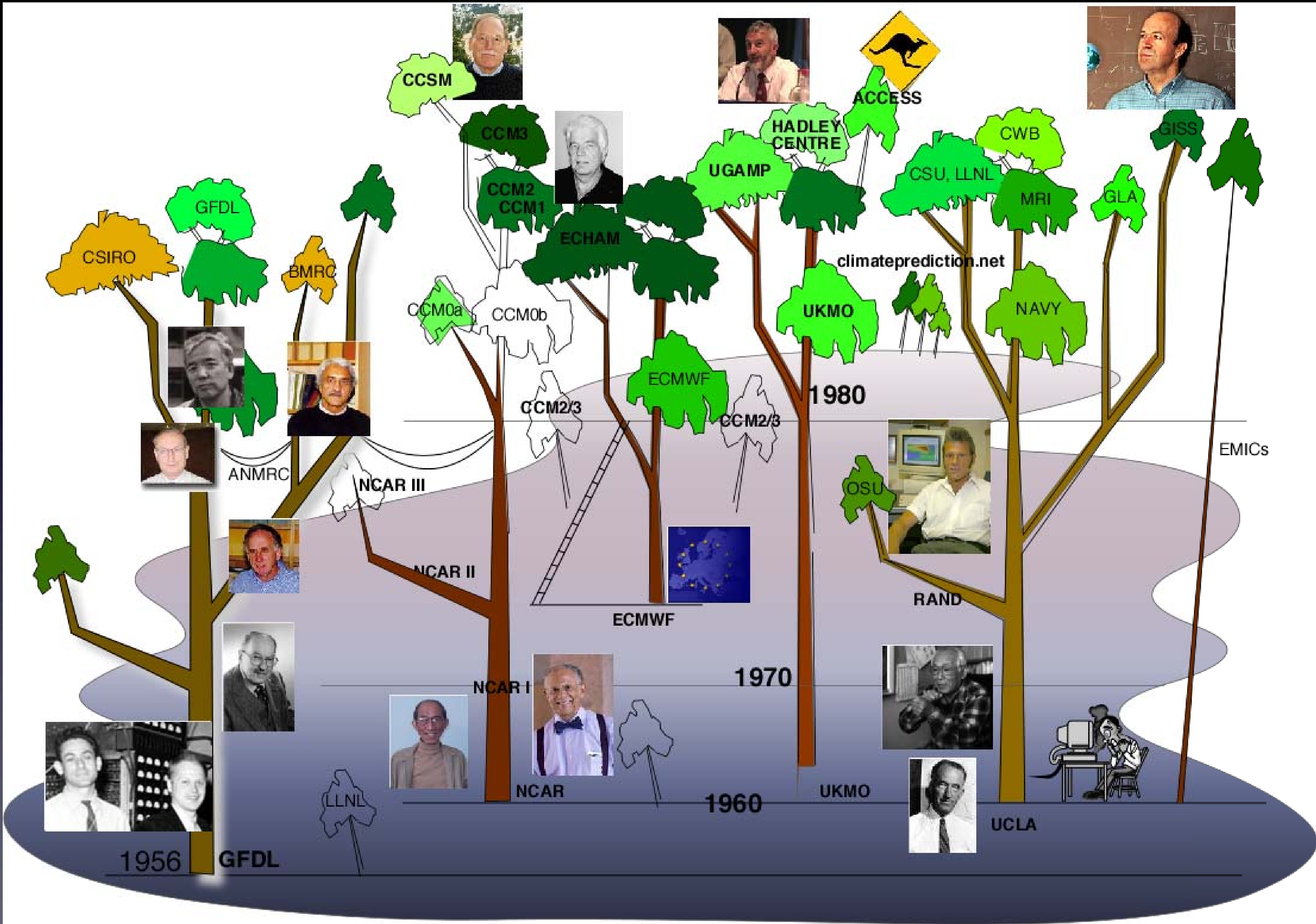
6. Giant Magneto-resistance

Non-volatile storage costs: 1950 — 2015





Atmospheric Models
Climate Models
Unified Earth System Models
Predictive Earth System Models
Coupled AOGCMs
Hydrology
Water cycle
Carbon cycle
Biogeochemistry
Explicit cloud resolution
Embedded models
Natural hazard prediction
Ocean Models
Land Surface Models
Chemistry and Ecosystem Models
Solid Earth Models
Megaflop
Gigaflop
Teraflop
Petaflop
70s
80s
90s
00s
10s+


CCSM
CCM3
CCM2
CCM1
ECHAM
UGAMP
HADLEY CENTRE
ACCESS
CWB
CSU, LLNL
MRI
GLA
GISS
GFDL
CSIRO
BMRC
CCM0a
CCM0b
climateprediction.net
UKMO
NAVY
ECMWF
1980
CCM2/3
CCM2/3
EMICs
ANMRC
NCAR III
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RAND
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1970
NCAR I
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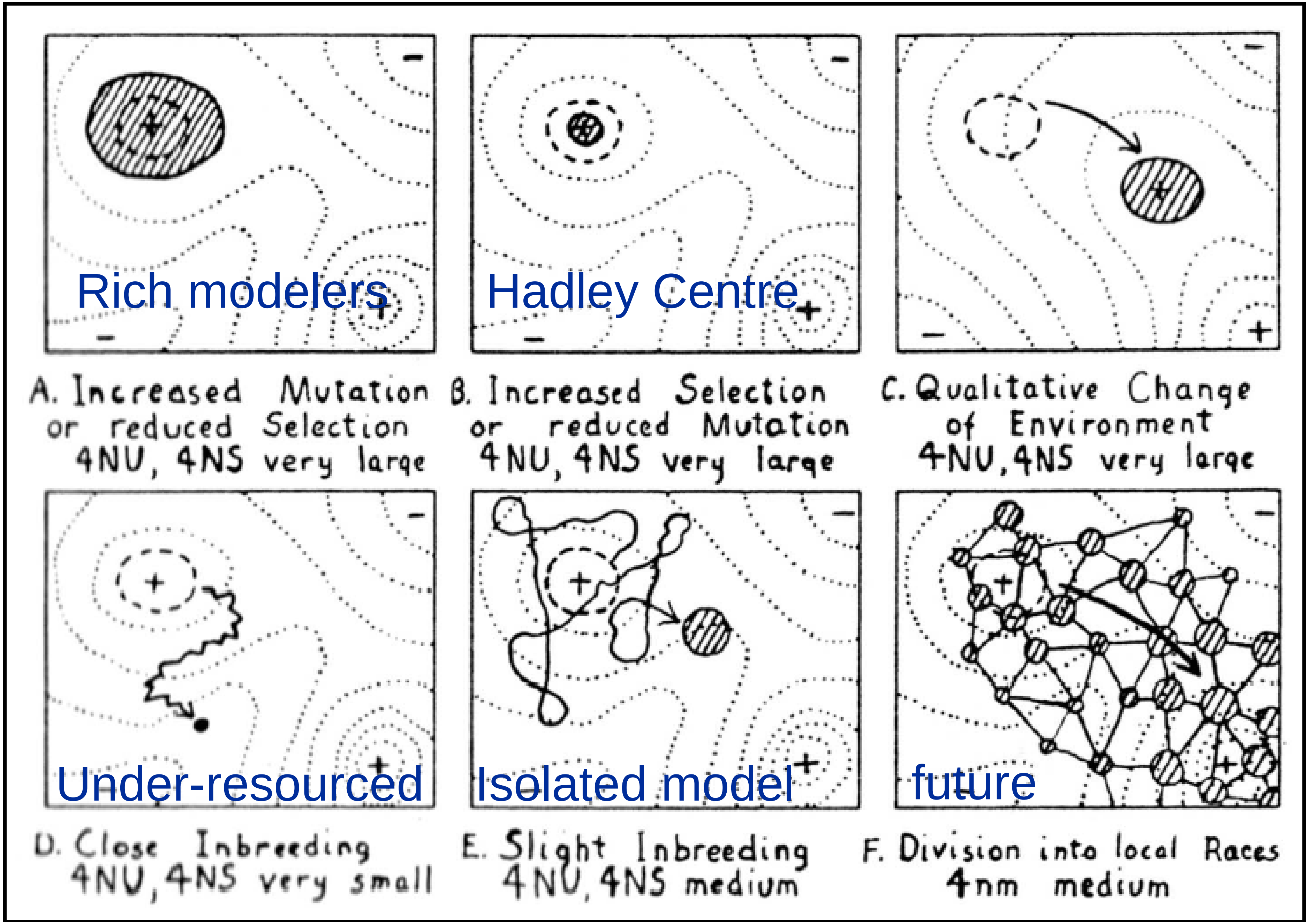
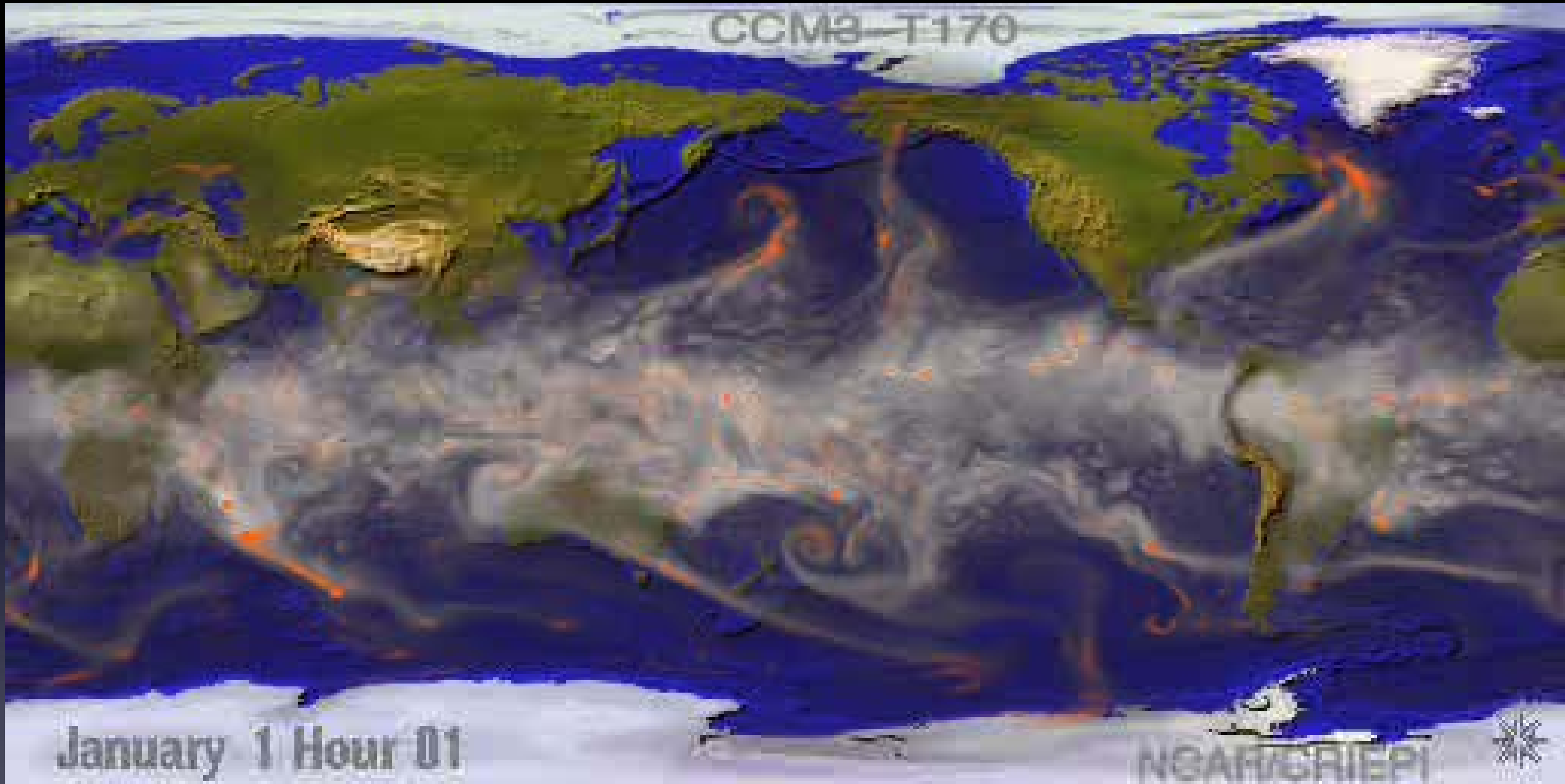
1960
LLNL
UCLA
1956
GFDL



- Greene, M.T., 2006, Looking for a General for some Modern Major Models, Endeavour, 30, 55–59.


CCM3 - T170
January 1 Hour 01
NCAR/CRIEPI

Six key milestones

- 1947: the transistor. Makes reliable computer possible.
- 1956: the first FORTRAN manual. The secret society of computer programming is opened
- 1976: the super computer is born (first Cray 1 installed)
- 1980: sub-second response and the dawn of interactivity. Rapid expansion in analysis of results
- 1990: html and WWW interchange of documentation and model results
- 2000: GMR (Nobel Physics Prize 2007) means that data density on disk continues to expand.
- Modelling moves forward because of ALL of these.

END OF PRESENTATION