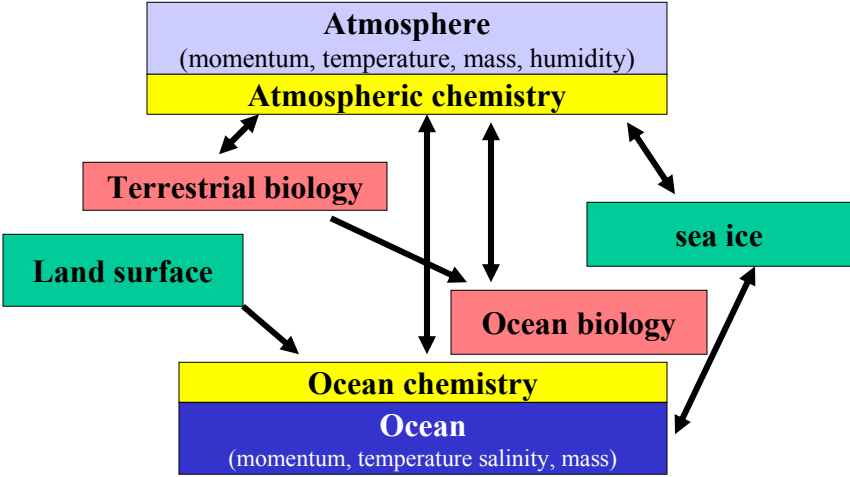


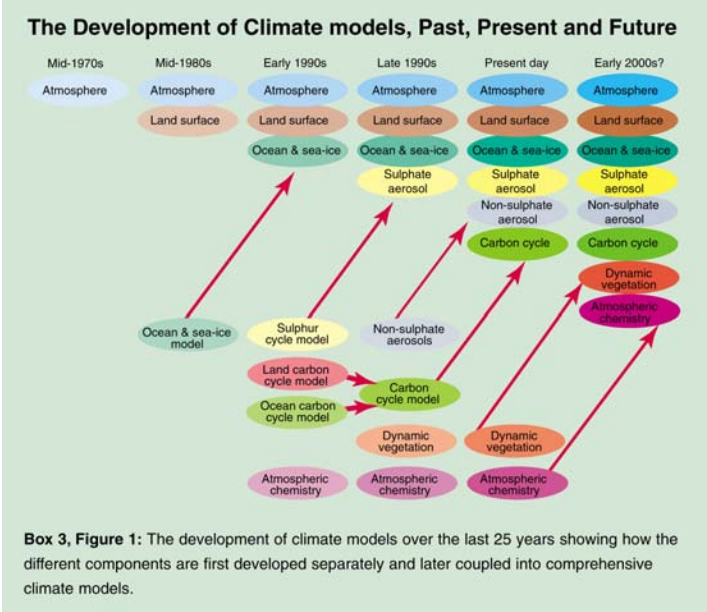
The art of climate and environmental modeling

- "Several sciences are often necessary to form the groundwork of a single art" - *Mills, 1843*
- "Science is knowledge which we understand so well that we can teach it to a computer; and if we don't fully understand something it is an art to deal with it" - *Knuth, 1974*

Climate system models



Evolution of Climate Models



Parts of models

POP QUIZ

- State variables
- Conservations laws
(mass, momentum energy)
- Tendency equations

- Analytic or numerical methods
Discrete solution methods
(finite differences, spectral methods, others)
- Codes to do it

Hierarchy of models

- All do fundamentally the same thing, but different levels of complexity.
- Examples?
 1. Energy balance model
 2. Energy balance model with parameterized heat transport
 3. Energy balance with “physics” transport
(e.g., cyclone model)
 4. Energy balance with explicit transport
(e.g., QG model)

- 5. We built 10 “climate” models

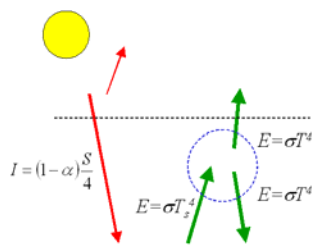
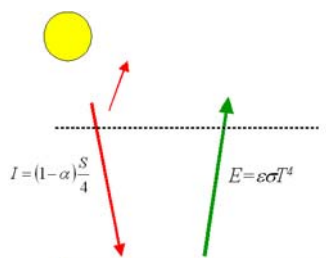
10 steps to making a climate model

1. One-box energy balance model
2. EBM with a greenhouse effect
3. Midlatitude cyclone
4. Advection in one-dimension
5. Advection with Fourier coefficients
6. Soil heat diffusion in one dimension
7. Vorticity and streamfunctions
8. Tracer transport on a sphere
9. Vorticity on a sphere
10. General circulation models (dry)
11. Climate models

Note: 10 steps, plus an initial conditions means 11 models.

Energy balance models

- Simple
- Conservation of energy
- Few parameters
- Can have feedbacks
- Class of models (“box” models)
- ***Solution reaches a steady state.***
- State-of-the-art until 1950
- Important models by Sellers, and Budyko on radiative feedbacks and albedo.
- A model like this lead Arrheneous to realize that CO₂ due to coal burning will rain the earth’s temperature (1886), arguing ever since.

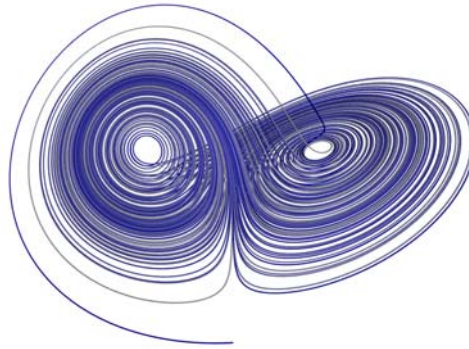


Dynamical models

- Solution does not have a steady state, but there is a quasi-equilibrium
- Nonlinearities important (otherwise simple behavior, e.g., periodic)
- Can show must have 3 variables.
- Difference between “weather” and “climate”

- Important work by Lorenz (1960s-1980) on predictability.
- Also climate low-dimensional “attractors” (which has since lost favor as it appears a consequence of simplicity)

- Similar low dimensional climate models have lead to elegant (but poorly tested) theories for ice sheet dynamics, the role ocean circulation in climate, and the changes in the carbon cycle.

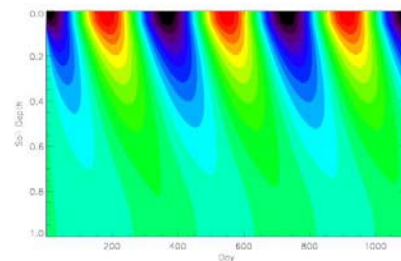
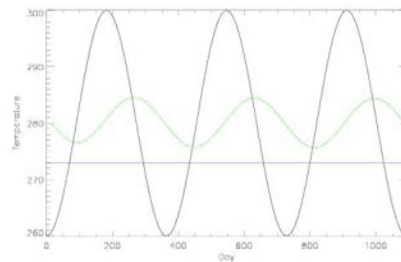


Numerical methods

- Advection and diffusion are basic building blocks of complex models
- Both describe some kind of transport
- Stability issues
- Accuracy issues
- Also, elliptic solvers (common in fluid flow problems)

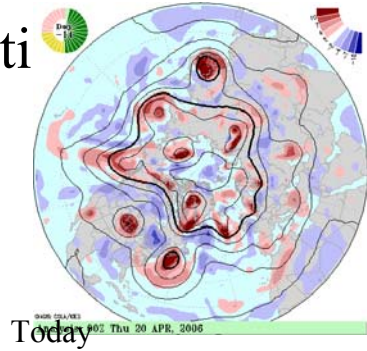
- CFL failure was the main reason that Richardson’s famous first numerical weather prediction (by hand!) failed in 1922.
- (He tried to predict weather for 24 hours over Northern Europe with 6 hour time steps)
- This the most impressive failed model experiment.
- It was Charney 40 years later who worked out why.

- Also wrote:
“*Big whorls have little whorls that feed on their velocity,*
– *and little whorls have smaller whorls and so on to viscosity.*”

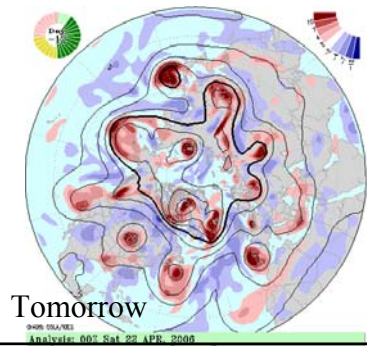


Weather predicti

- Initial value problem
- Limited predictability
- Nonlinear advection (vorticity advects itself)
- Main features well captured, but many details were not

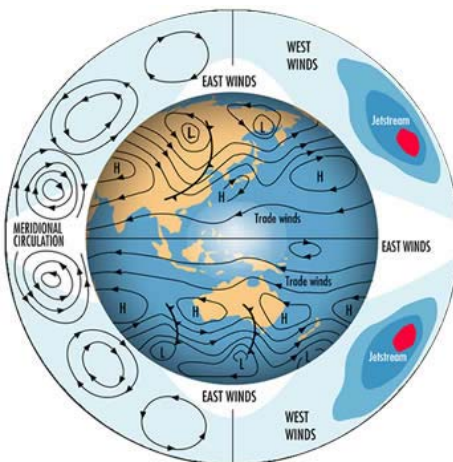


Famous experiment in (Charney et al. 1949), which we reproduced, was one of the first uses of computers. Also demonstrated that weather prediction was possible. Convinced US government to invest in numerical weather prediction, 5 years ahead of Rossby's group in Sweden.



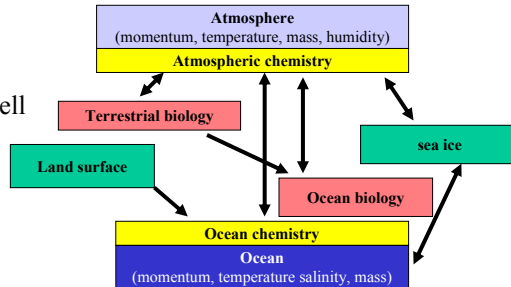
General circulation

- Requirements?
- Heating in tropics, cooling in polar region
- Mechanism for generating eddies
- Multi-layers for baroclinic development
- Conservation of mass, momentum and energy
- Trick, via QG and use of PV, simplifies equations and assists book keeping, but retains 90% of the story.
- Boundary value problem
- Important experiment by Phillips (1956). 2-layer QG on beta-plane, captured main aspects. Essentially what we did, but we used a sphere.
- Also, we used a spectral method, that became popular in the mid-1970s due to accuracy and efficiency.



State-of-the-art climate models

- As complete as possible
- Many individuals and fields of expertise included
- Physics, chemistry biology
- Large scale processes, and small scale process
- Enormous number of parameters
- Match observations exceedingly well
- Used as a centerpiece of climate change studies
- Especially important for understanding linkages
- Trusted by lots of informed non-experts
- Not trusted by skeptics
- Not trusted by expert modelers



Earth-system Models of Intermediate Complexity (EMICs)

- Typically low resolution
- Possibly truncated dynamics
- Simple treatments of physics
- “Small” number of parameters
- Represent main features of climate well, details are not so good
- Runs fast
- Have been used recently for paleoclimate experiments
- Becoming increasingly popular, since full models are too costly to run
- Also, they can be trusted since errors are easier to characterize/understand.

- Typically like state-of-the-art climate models of the 1980s!
- *Very much like our group model.*

Where is the art?

Where is the science?

What you should see on an exam, if
we had an exam.

- Types of problems
(advection, diffusion, wave equations, elliptic equations...)
- Finite differences
(derivations from Taylor series, basics of stability analysis,
existence of non-linear instability)
- Errors – amplitude, phase, dispersion
- Spectral methods (all done with coefficients)
- Spectral-transform methods
(linear parts spectral, non-linear on a grid)
- Reasoning for parameter selection
- Fair use of parameters (not too many, not too few)

Modeling skills

- Fortran basics
- Structured programming
(breaking a complex code into smaller “do-able chunks, possibly in subroutines)
- Debugging strategies
- Strategies for testing and validation
(Is the strange result a bug, bad physics, or a Nobel Prize?)

- Visualization (IDL/Matlab)
(time series, line graphs contour plots, map projections)
- Basic analysis
(means, variance, differences)
- More detailed analysis
(Fourier analysis, EOFs/PCA, statistical tests...)

- *Should have confidence in understanding uses of climate models, and skills to build models of your own.*

Reminder

- Project due 4 pm Monday (paper copy)
- Drop into my office : Ekeley, S234
- Leave in my mail box : 3rd floor, box 151

- Also, please return any books

- Remember also that your report should demonstrate application of what you have learned (this means you should refer to topics covered in the lectures: stability, accuracy, methods, conservation...)