A VIEW OF
EARTH-SYSTEM SCIENCE:
OBSERVATIONS, MODELS,
& DATA ASSIMILATION

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. . . a time of great opportunity & responsibility.

Earth Observing Systems

Building on top of existing observing systems for weather, ocean circulation, ice, land-surface conditions, and ecosystems:

- Programs: GCOS, GOOS, COOS. . .
- Satellites: Terra/Aqua/Aura, ICESat. . .
- Sensor Arrays: Neptune, Orion. . .

Will nations make a sustained, multi-decadal commitment?

Earth System Models

Now a very large enterprise with a $\sim$ 50 year history.

Numerical Weather Prediction
$\longrightarrow$ General Circulation (physical climate)
$\longrightarrow$ Earth System (all climate influences)

Components:

- atmosphere: troposphere $\rightarrow$ ionosphere
- ocean circulation
- sea ice
- land surface: soil, hydrology, glaciers
- chemical cycles
- terrestrial and marine ecosystems

. . . an empirically established compromise between computing power, plausibility of answers, and completeness of processes.

. . . widely used and useful but poorly grounded in fundamental principles.

Data Assimilation

ES-DA: fitting data to a "realistic" model,
hence a client of both EOSs and ESMs.

. . . putatively the best state estimates, predictions, data interpretations, and hypothesis tests.

. . . computationally intensive, well beyond the fitted model.

Simple *vs.* complex models in DA?

simple: transparent, mathematically well posed, cheap.

complex: realistic!

Structural Instability

. . . a property of some models, but not others.

General Defn: An $\mathcal{O}(\epsilon)$ change in model formulation $\longrightarrow$ an $\mathcal{O}(1)$ change in solutions.

Defn. for a Chaotic ESM: A seemingly innocuous model change $\longrightarrow$ non-trivial change of solution's statistical-equilibrium PDFs.

. . . a cousin of sensitive dependence on i.c.

Are ESMs structurally unstable?

- we don't know
- it would be hard to prove
- there are good reasons to think they might be: resolution, discretizations, parameterizations, debatable equations.

If so, are there theoretically and/or practically irreducible limits for an ESM's quantitative accuracy? [*cf.*, limits of predictability]

Dynamical Systems Theory

“The main thing for us to do with the equations of mathematical physics is to investigate what may and should be changed in them.”

. . . Poincaré (1905)

Smale (1966):

”Structurally stable systems are not dense”.

The 3-component ODE system of Lorenz (1963) is structurally unstable: $\mathcal{O}(\epsilon)$ parameter changes cause jumps between limit cycles and strange attractors, with a dense intermingling.

$\Rightarrow$ a very instructive model, but not quantitatively reliable about nature.

Computational Simulation

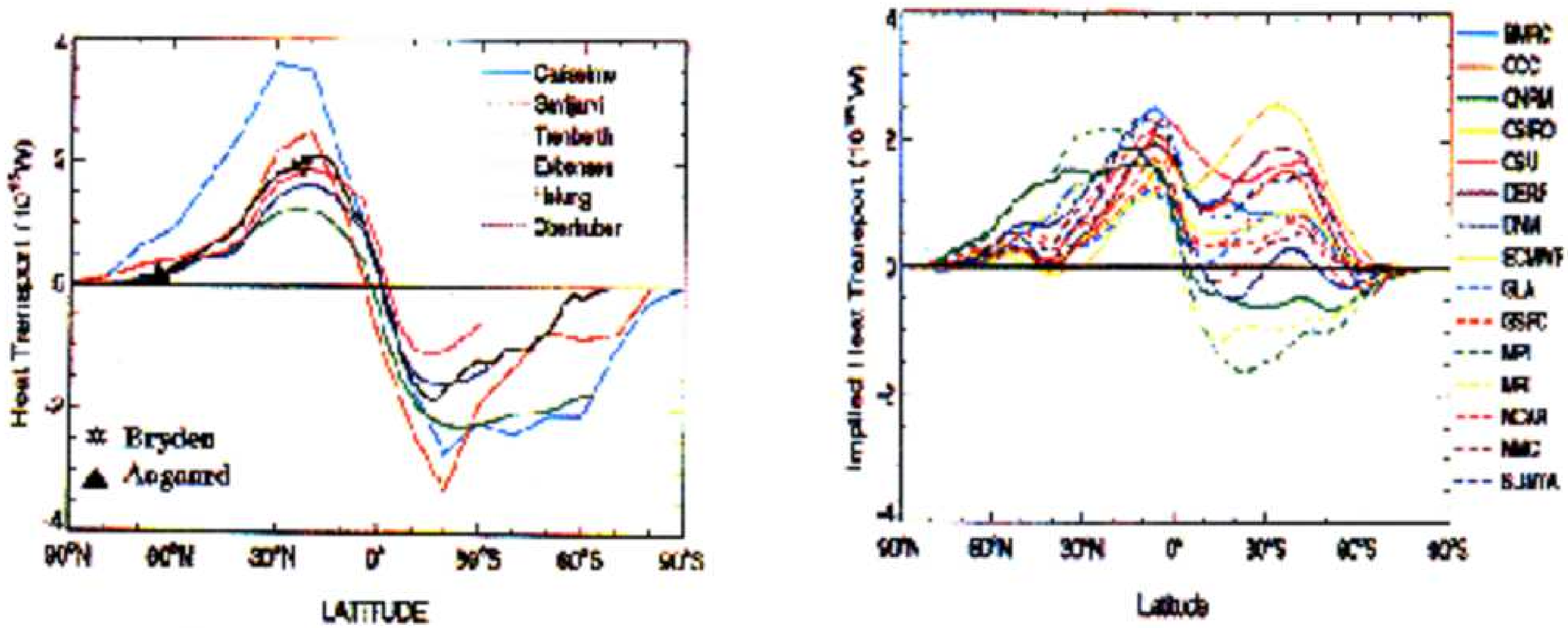
Navier-Stokes equation has unknown and
unproven existence and long-time regularity (*n.b.*, Clay Prize)...but probably OK.

Computational mathematics assures convergence of PDE discretization for *smooth* solutions as $dx \to 0$.

But ESM practice is for *non-smooth* solutions at all dx: small κ_e; stiff or non-differentiable parameterizations & sub-models; artificial regularizations.

cf., conservative CFD practice of limited Re and $dx \ll L \quad \Rightarrow$ convergence to smooth
solutions. (even in chaotic regimes?)

Is ESM convergence achievable? (Richardson: "The coastline of England is infinite.")



Oceanic meridional heat transport: Observed (left) and from AMIP simultaions (right). [Glekler *et al.*, 1995]

ESM Experience

Difficulties of model tuning: parameter adjustments to match a few observational measures.
...everyone does it; no one writes it up.

AMIP: multi-model, atmospheric simulations with specified oceanic T. After tuning to "climate" $\Rightarrow$ wild divergence among implied oceanic heat transports (Gleckler *et al.*, 1995).

Difficulty of $\mathcal{O}(1)$ matching ESM solutions between models even with best efforts to match components, parameters, *etc.* [*e.g.*, NCAR's CAM with spectral & finite-volume methods (Rasch, Boville); NCOM $\rightarrow$ POP (Bryan, Smith).]

I. Held: "...rough fitness landscape of ESMs".

K. Droegemeier, after simulating good patterns of continental squall lines with $dx \ll L$ but low skill scores: "...let's redefine skill".

R. Davis, in 2003 AOSN Monterey mesoscale DA experiment: "...it looks like some ocean, just not the one we measured".

Since Charney's NRC report in 1979, a 25-year failure of ESM community to reduce uncertainties in global warming assessments ($\approx$ 1-5 K in mean surface T for doubled CO_2), despite great efforts and much altered models.

. . . beware of social pressure to tune this away!

Including chemistry and ecosystems in ESMs — if not also sea ice and hydrology — will lead to endless debate about what the governing equations are (unlike fluid dynamics). Which of these will add to structural instability?

. . . is all this convincing?

$\Rightarrow$ a need for constructive demonstrations, yea or nay.

The Glory and Mystery

How can chaotic, fluid-based ESMs produce such gloriously realistic images of nature (patterns) and rough quantitative correspondences, with what seems a socially acceptable degree of parameter tuning, yet perhaps be structurally unstable to a non-trivial degree that precludes ever obtaining reliably precise quantitative simulations?

If structural instability — at least metrical if not topological — is generically true for chaotic ESMs, then how to estimate expected solution variance across a class of ESMs and discover procedures for at least minimizing this variance?

. . . Poincaré's question rephrased, 100 years later.

Implications for Data Assimilation

Posing DA as an optimization problem, it is vulnerable to bad behaviors if the fitted model is structurally unstable:

- model inversion singularity
- iteration non-convergence
- sensitivity to cost function choice
- need for *ad hoc* regularization, compromising the problem as posed

. . . all of which are known to occur sometimes.
(but not always due only to the fitted model)

Conclusions

- Are ESMs structurally unstable?
- How would we prove this?
- Would this imply a limit on their quantitative reliability for nature?
- How could DA methods deal with this?
- How would we explain it to the world?