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VERISIMILITUDE AND IMPRECISION

IN ATMOSPHERIC AND OCEANIC SIMULATIONS

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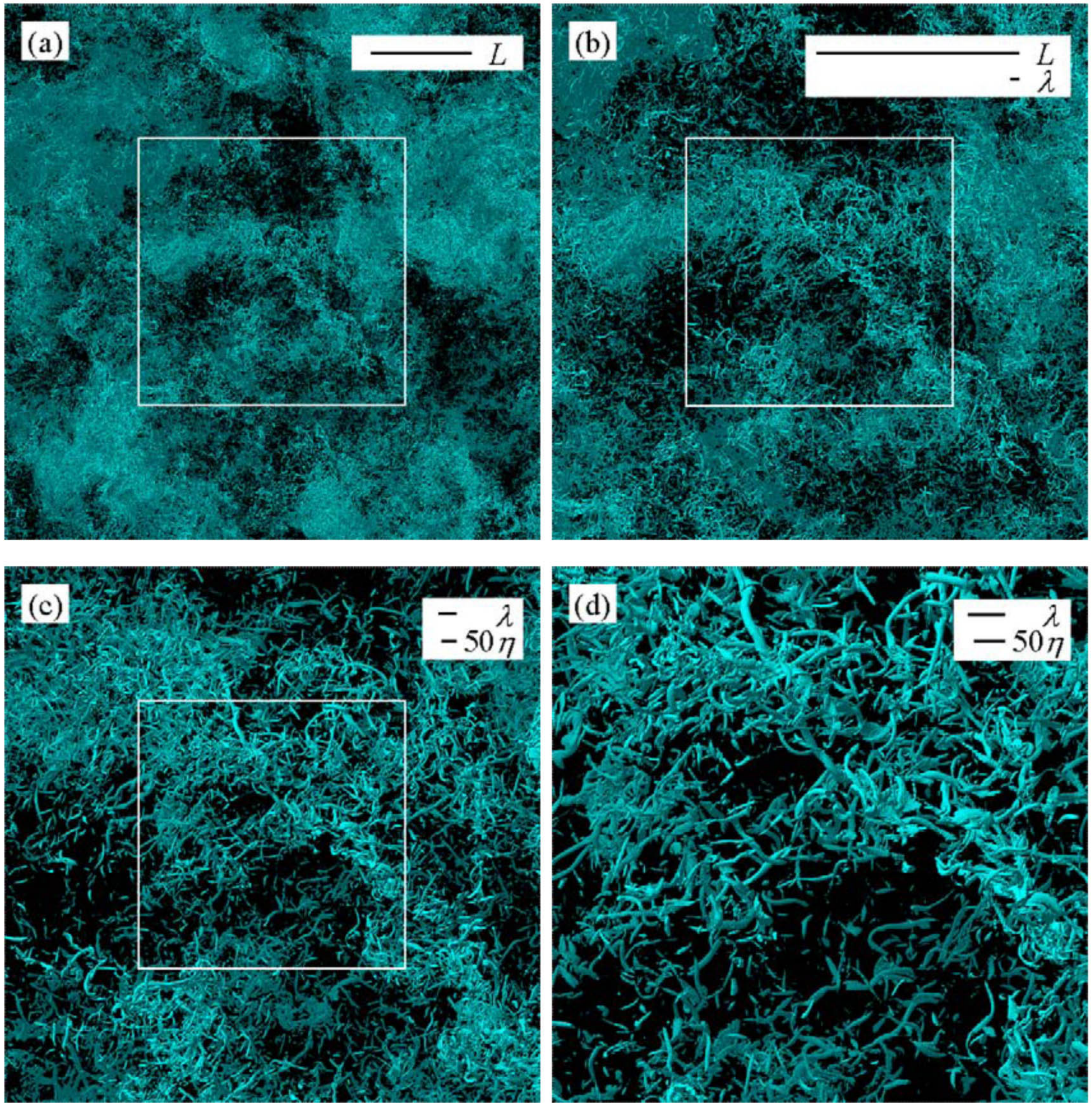
- Emergent structures in fluid dynamics
- Heterogeneous, multi-scale climate dynamics
- Irreducible imprecision

WHY DO WE LIKE CLIMATE MODELS SO MUCH?

For the realism in emergent structures from first-principle fluid dynamics —

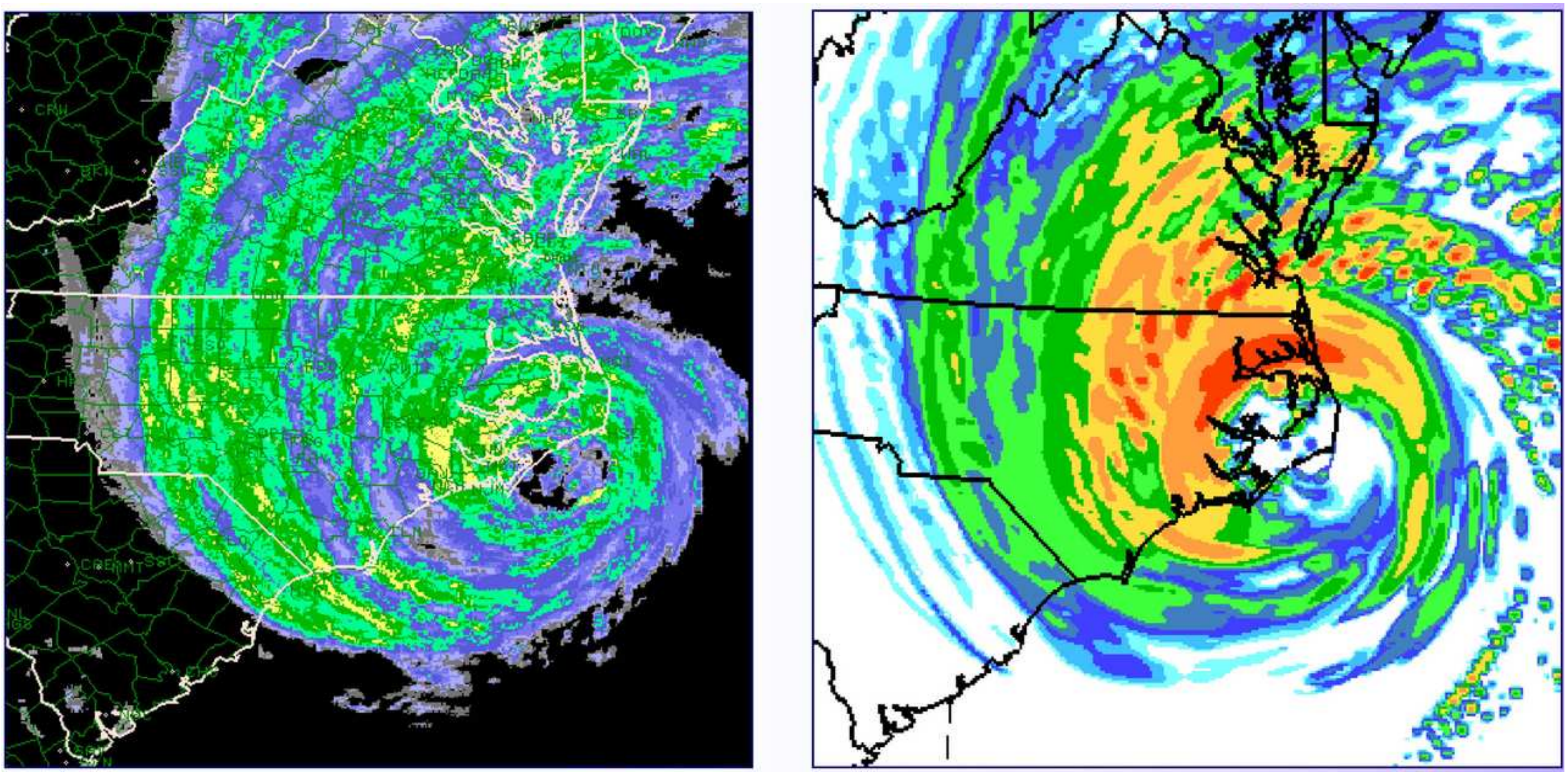
extra-tropical eddies, mean winds and oceanic currents, overturning circulations, seasonal cycle, low-frequency variability patterns, and long-term climate hindcasts & forecasts

— in spite of the fact that crucial micro-scale transports & thermodynamic/radiative energy flows are not fundamentally represented and can be shown to be unrealistic in detail even when tuned to be correct in bulk ways.



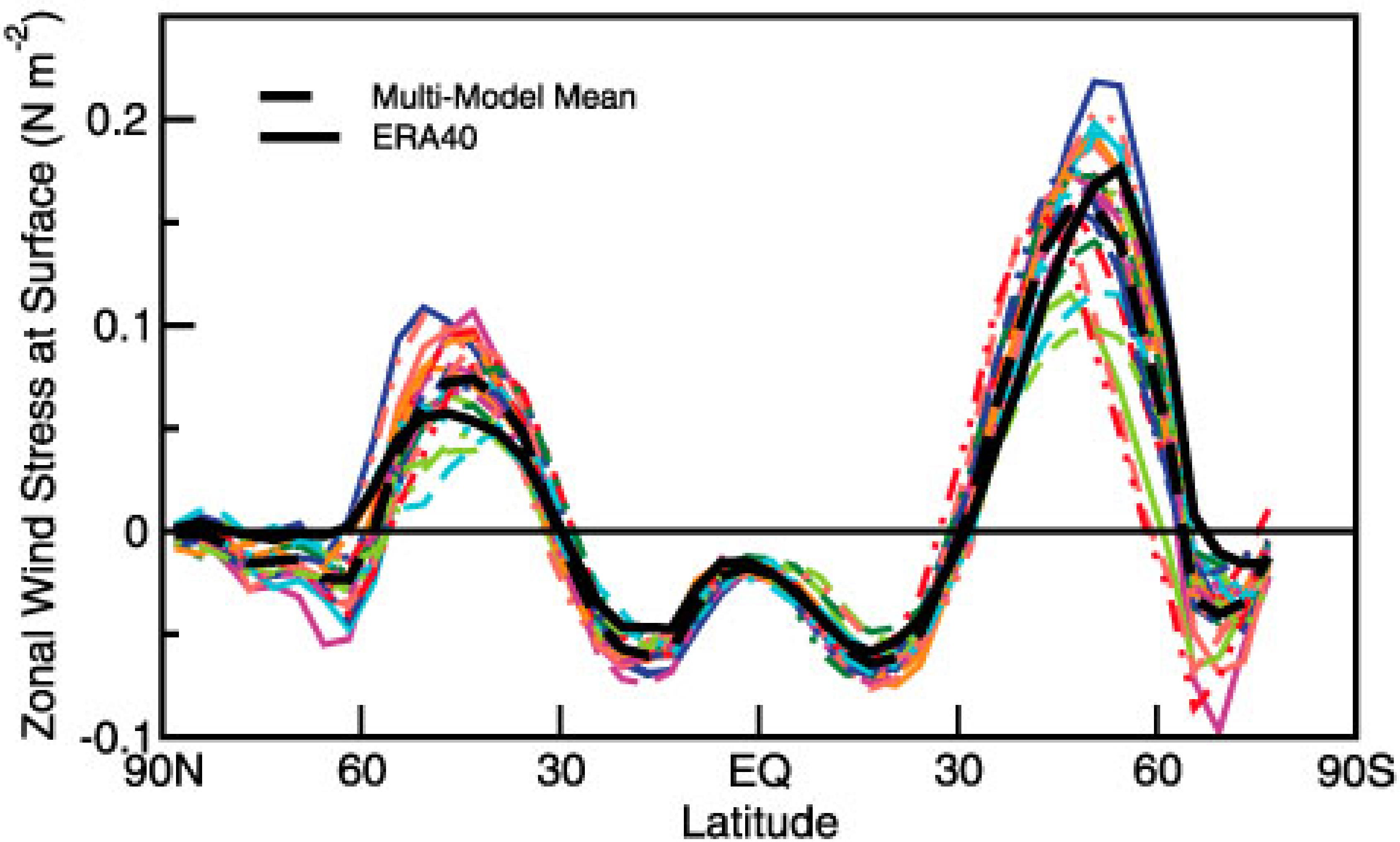
Iso-surfaces of vorticity magnitude at several magnifications in simulated homogeneous turbulence. L, λ, $\eta =$ forcing, Taylor, dissipation scales. (Kaneda & Ishihara, 2005)

Atmospheric Storms



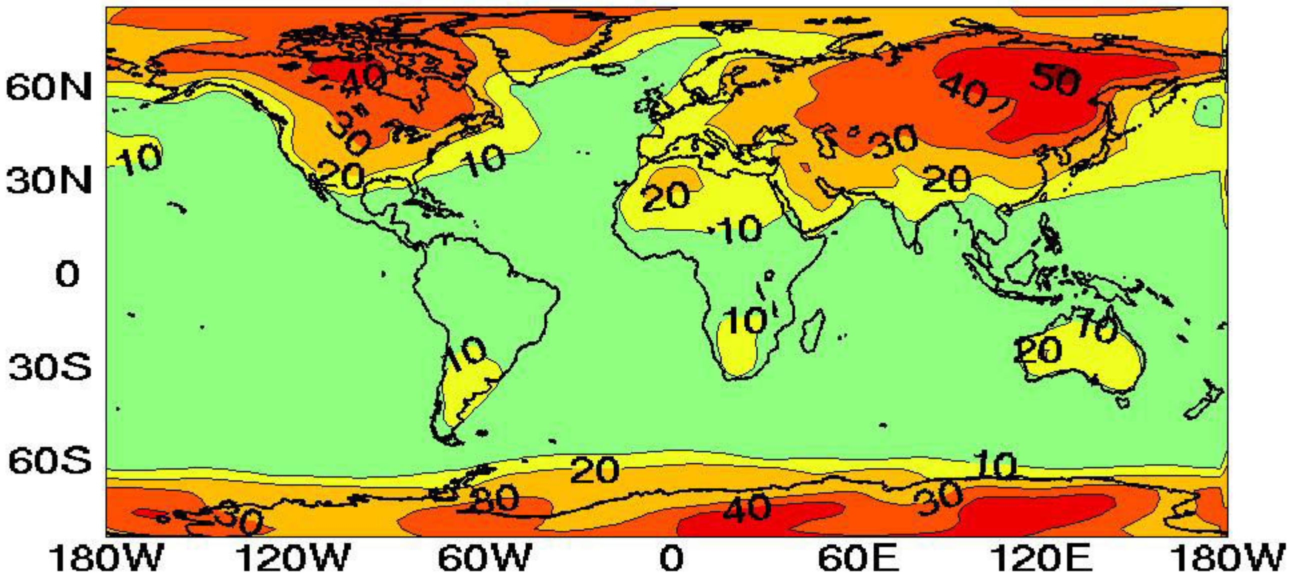
Radar reflectivity in hurricane Isabel on 18 September 2003 (left)
and a 41-hour forecast from a cloud-resolving, regional-simulation model (right).
(Weather Research and Forecast Model: Klemp, 2005)

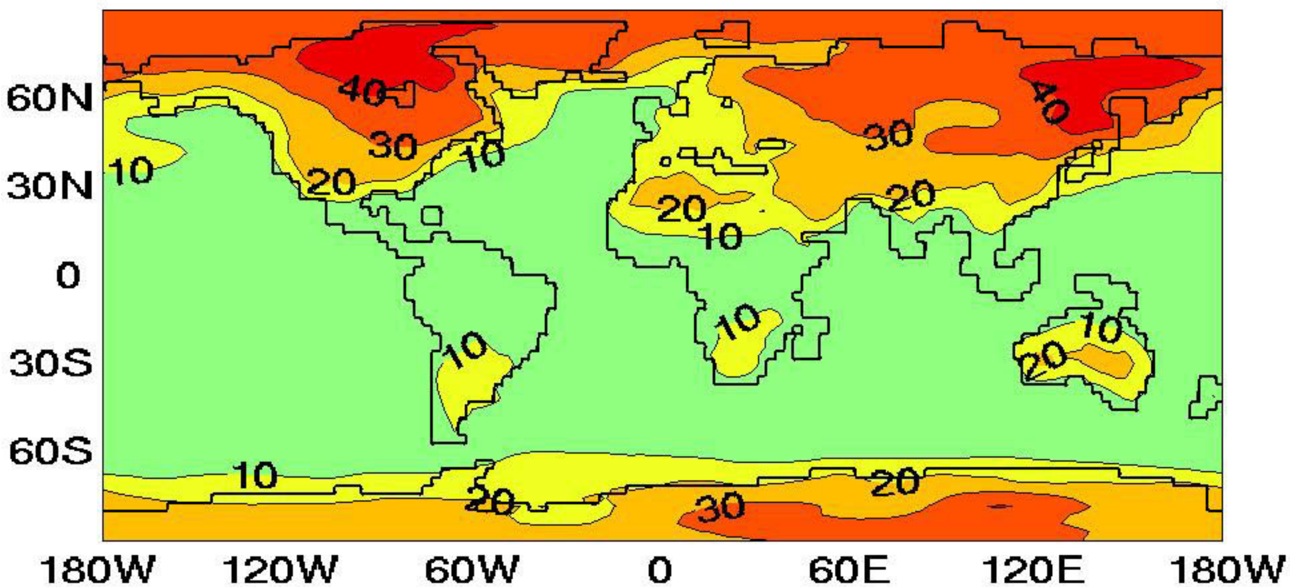
Mean Surface Wind



Mean surface wind *versus* latitude, zonally averaged over the oceans: observed (ERA40) and simulated with different coupled climate models. (IPCC, 2007)

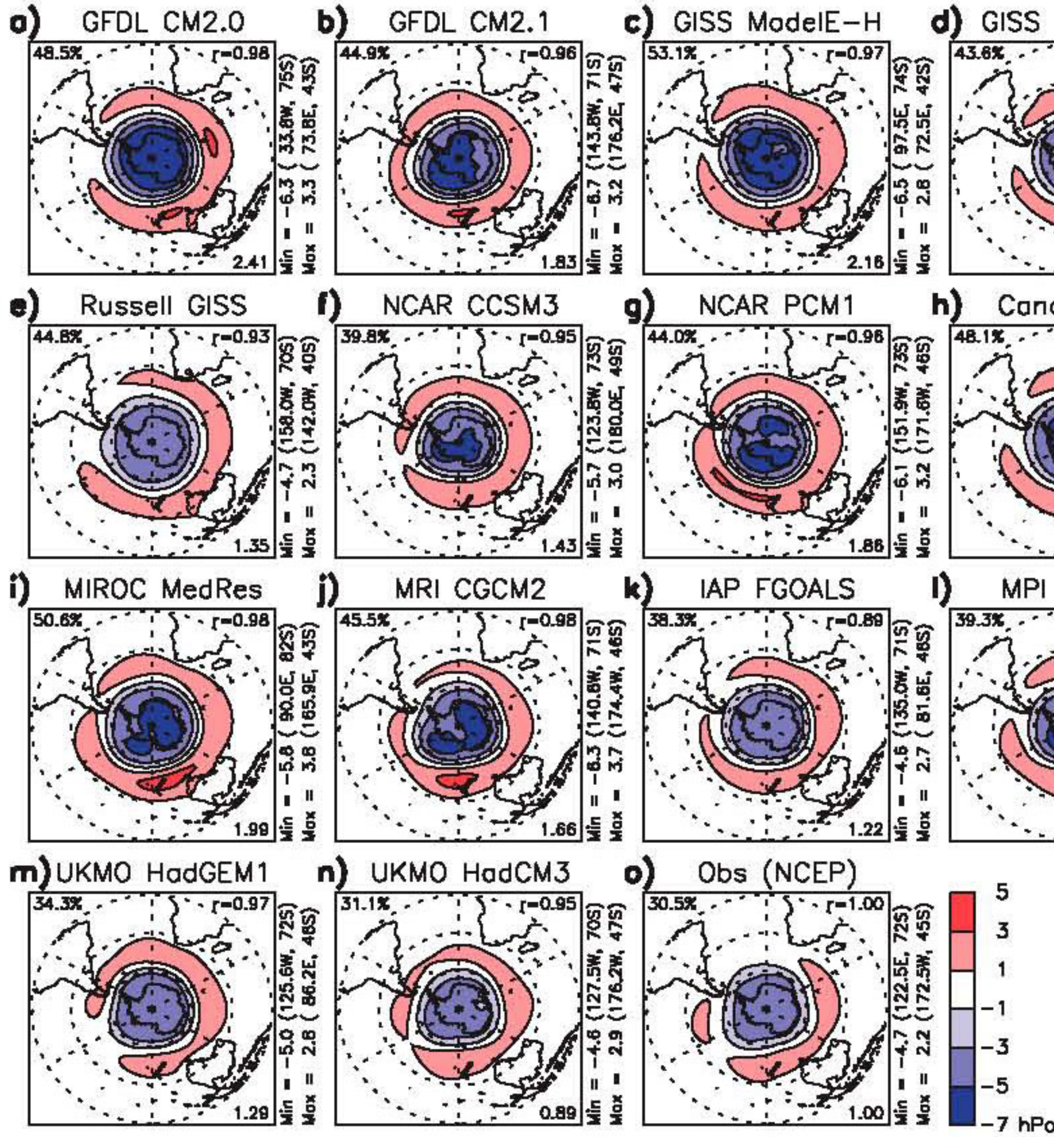
Seasonal Cycle in Surface Temperature





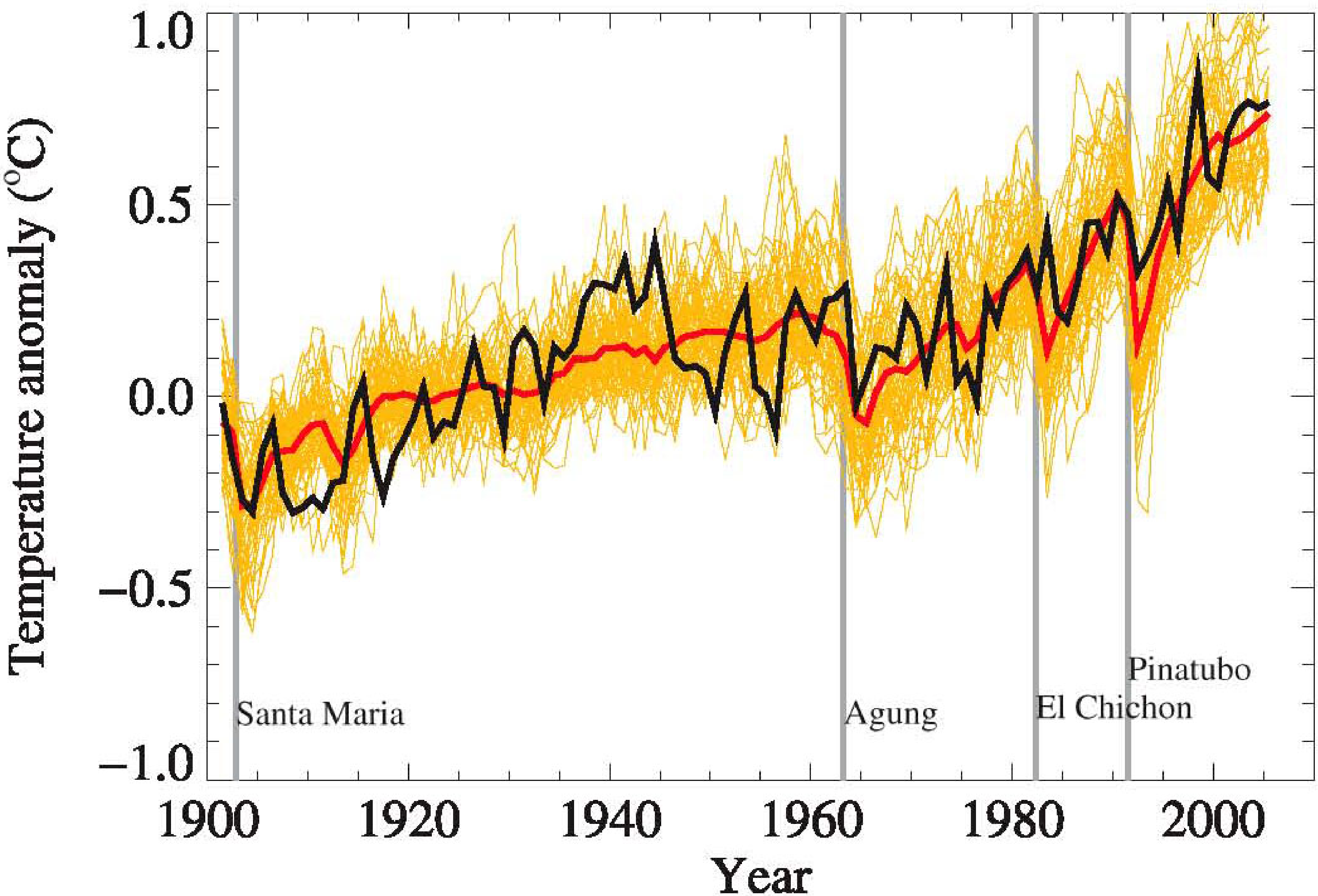
(Top) observed mean-seasonal ΔT [C] from NCEP reanalysis, and (bottom) simulated with the coupled ocean-land-atmosphere model CCSM. (Hall, 2005)

Broad-Band Intrinsic Climate Variability: Arctic Annular Mode



Dominant principal component for summer sea-level pressure variations during 1960-1999:
individual models (a-n) and observed (o). (IPCC, 2007)

Centennial Climate Reconstruction



Global mean surface T: observed (black) and simulated with 58 realizations from 14 different climate models and their ensemble mean (red). Gray lines are volcanic eruptions. (IPCC, 2007)

Sources of Simulation Discrepancy

Why are there discrepancies between observations and simulations and between different simulations?

- Intrinsic variability of simulations and nature

  [dynamical sensitive dependence $\Rightarrow$ predictability limits & sampling errors]

- Model bias and/or phenomenological deficiency

  [model design $\Rightarrow$ *e.g.*, multi-scale computations]

- Irreducible imprecision of simulations

  [dynamical structural instability $\Rightarrow$ model families and solution ensembles]

GLOBAL - REGIONAL CLIMATE DYNAMICS

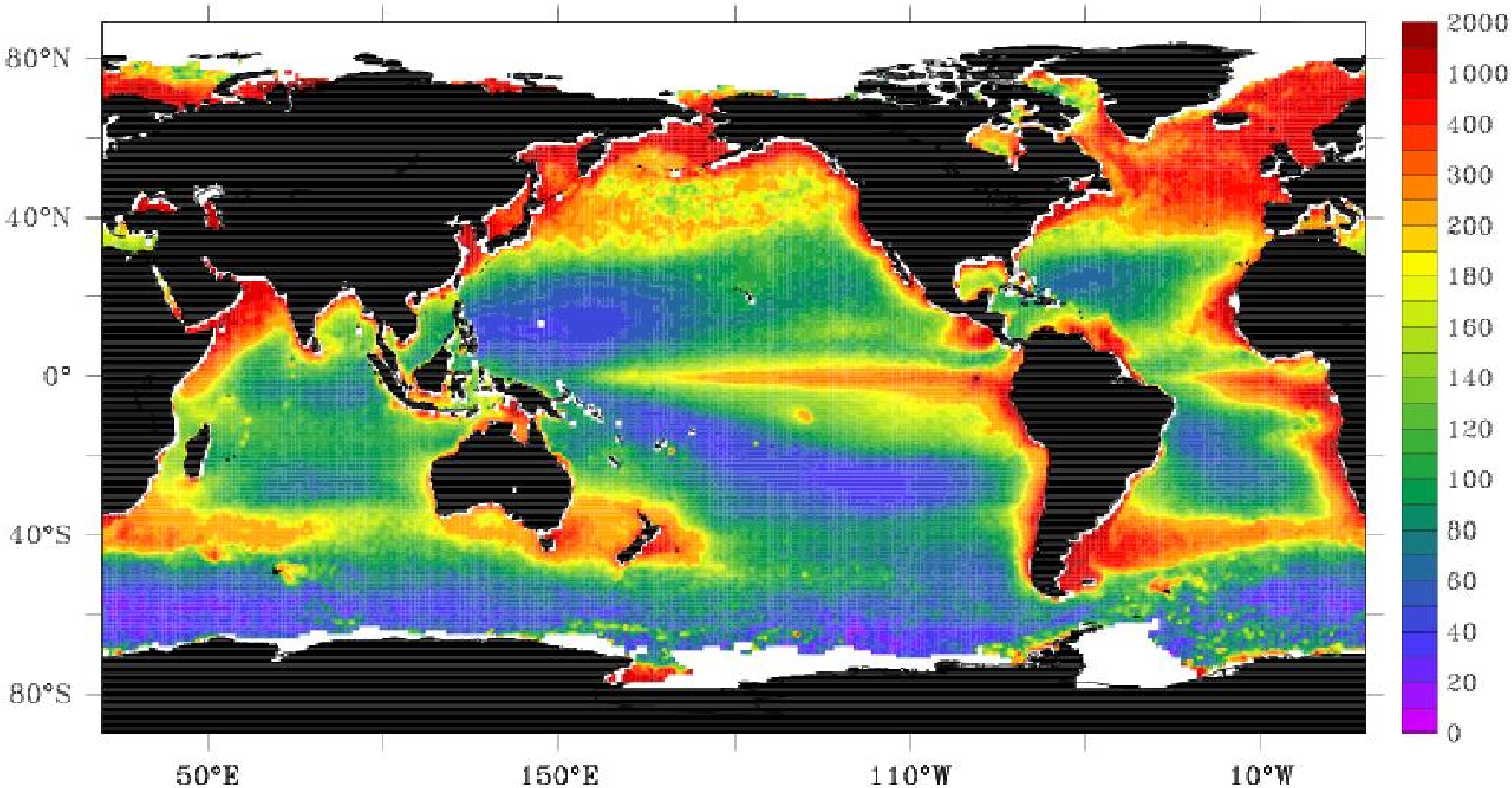
Rationales for statically embedded grid refinement:

- Simulating regional phenomena closer to their natural scales of functioning
- Downscaling global climate signals for detailed local expressions
- Upscaling regional processes for their global influences
- Potency of multi-scale computing for key regional phenomena within global fields

e.g., VOCALS experiment for western South America: overcoming CGCM biases in equatorward winds; Andean orography; stratus clouds and aerosols; desert/cold-ocean border; upwelling currents and eddies; biological fertility.

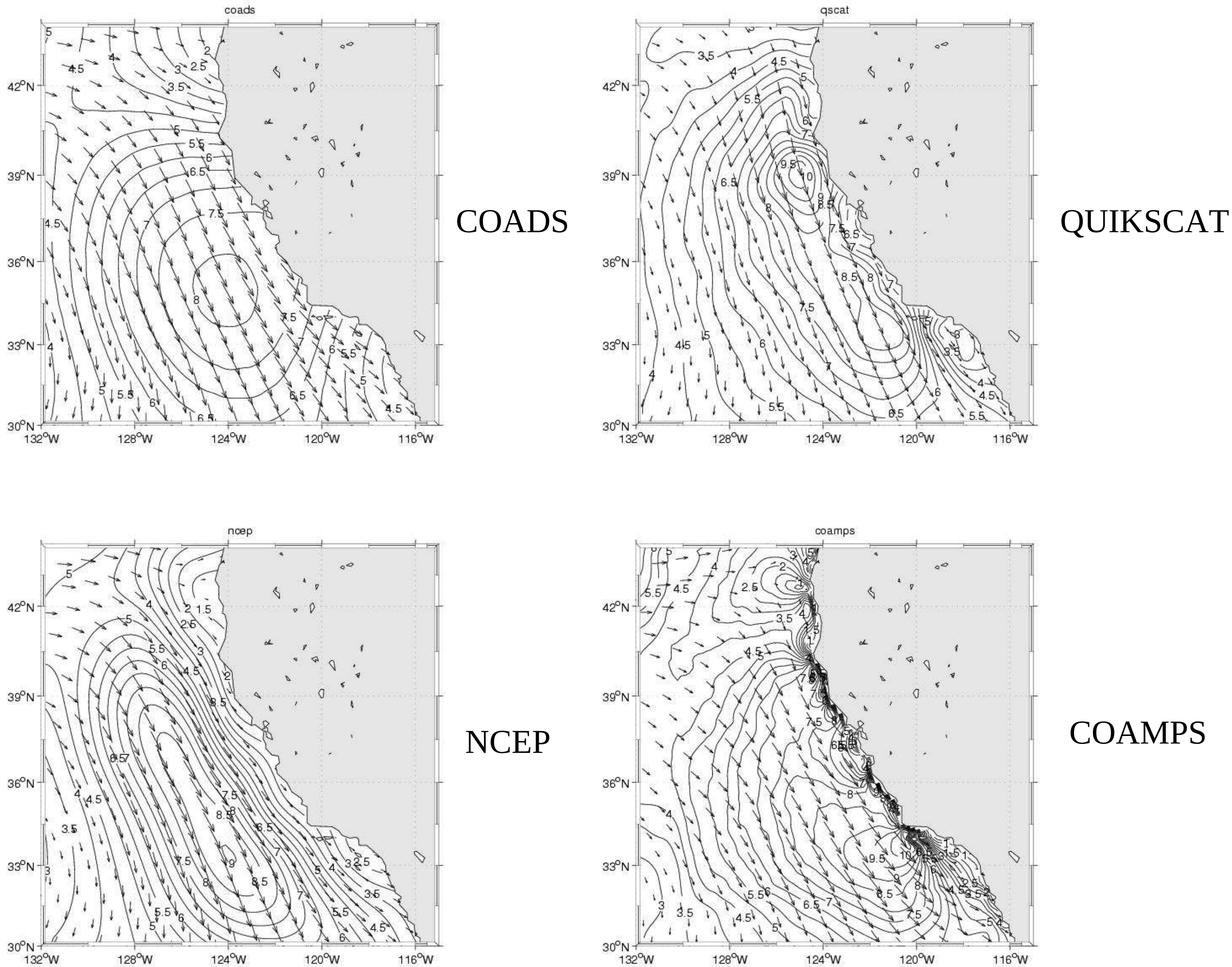
cf., global grid refinement; dynamically-adaptive refinement; unstructured grids; super-parameterization (cummulus convection).

Climate has Regional Structure



Measured mean oceanic **net primary productivity** $[gC/m^2/yr]$, as an indicator of marine ecosystem cycling. Note the coastal enhancements, especially subtropical eastern boundaries. (SeaWiFS)

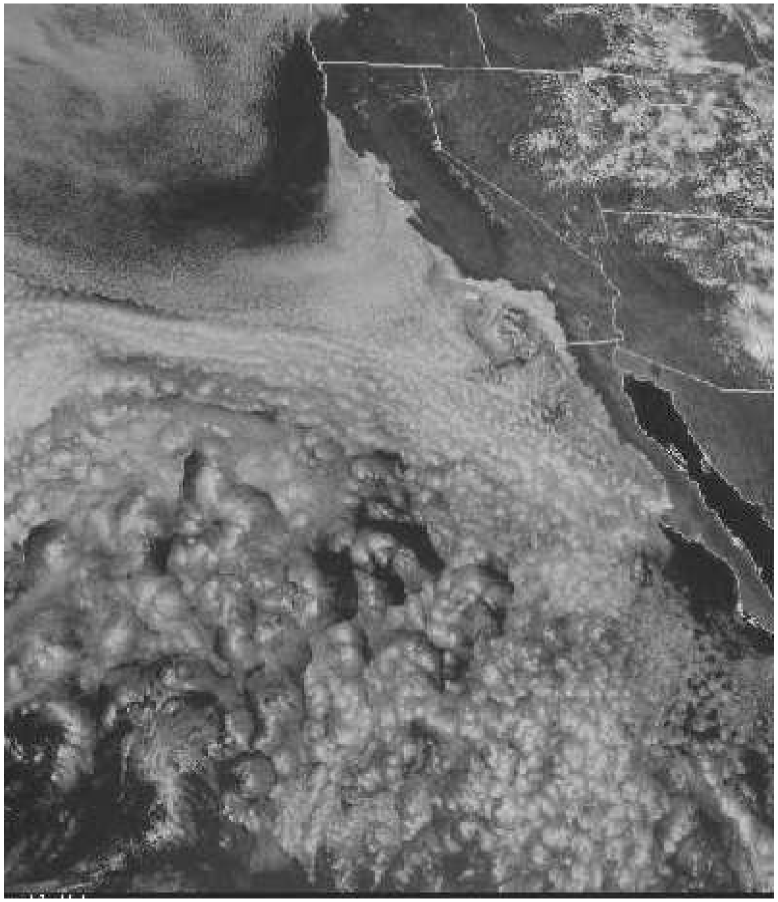
Global Wind Analyses are Inaccurate



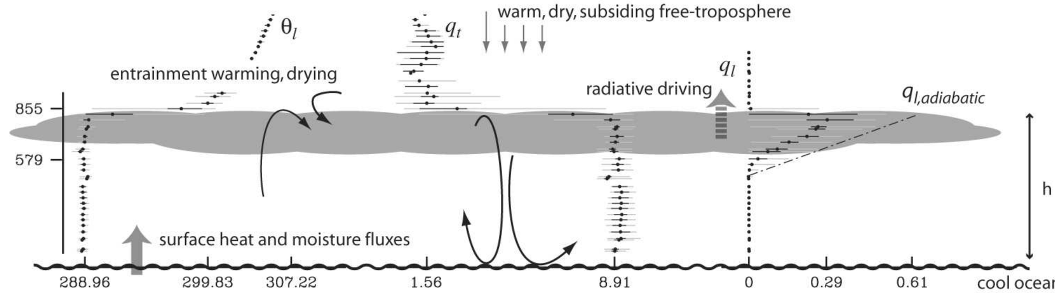
Annual-mean surface wind — arrow for direction & contour for magnitude $[m/s]$ — off the U.S. West Coast in several different model reanalyses.

Stratus Clouds are a Regional Climate Regulator

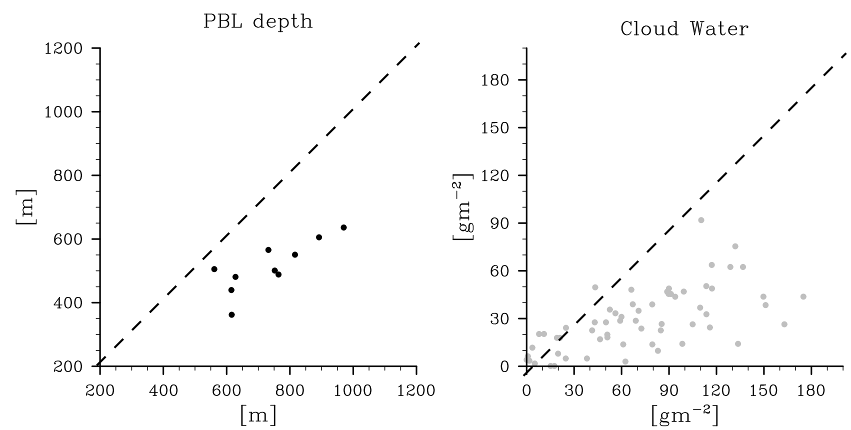
Stratus Snapshot



Stratus Processes and Vertical Profiles



PBL depth and Cloud Water: ECMWF vs. Observations

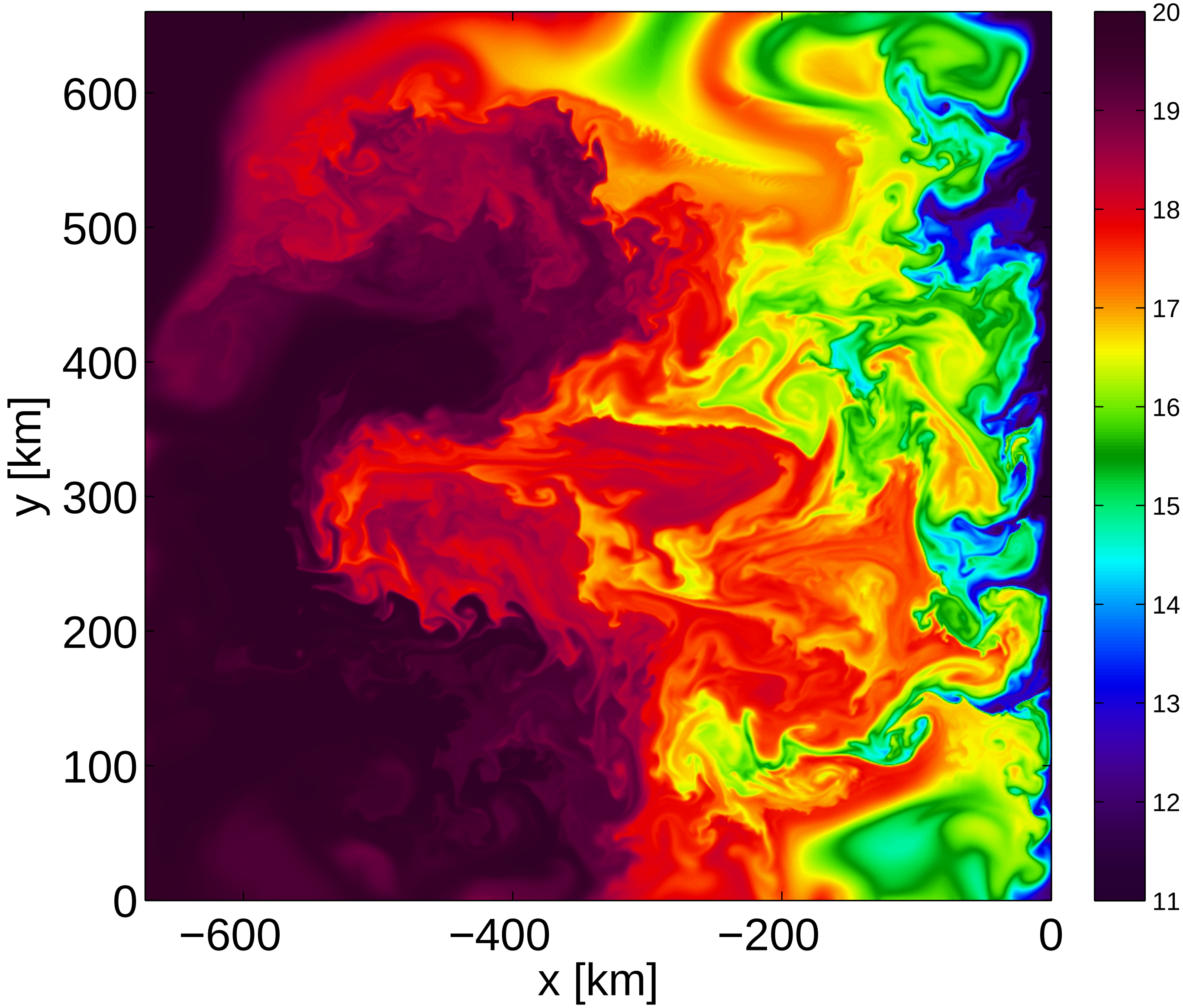


modeled

measured

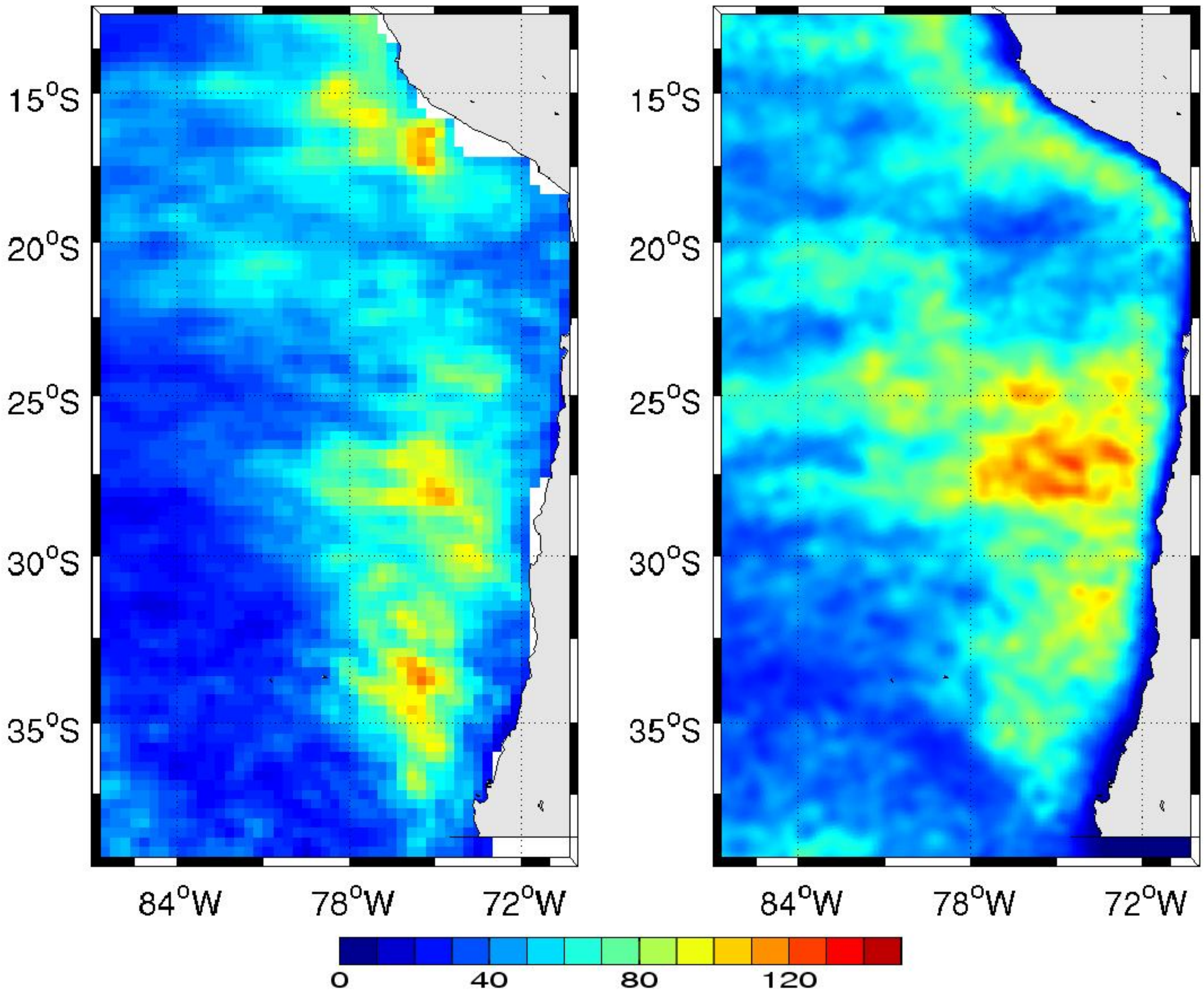
Stratus clouds in the eastern N. Pacific: vertical-column physics (boundary layer, clouds, radiation) in a regional wind and surface-temperature environment. Note the errors in an ECMWF simulation. (Courtesy B. Stevens)

Multiscale SST near a Subtropical Eastern Boundary



Instantaneous SST in a regional oceanic simulation with fine resolution ($dx = 0.75$ km): coastal upwelling, mesoscale filaments & eddies, and unstable submeoscale fronts.
(Capet *et al.*, 2008)

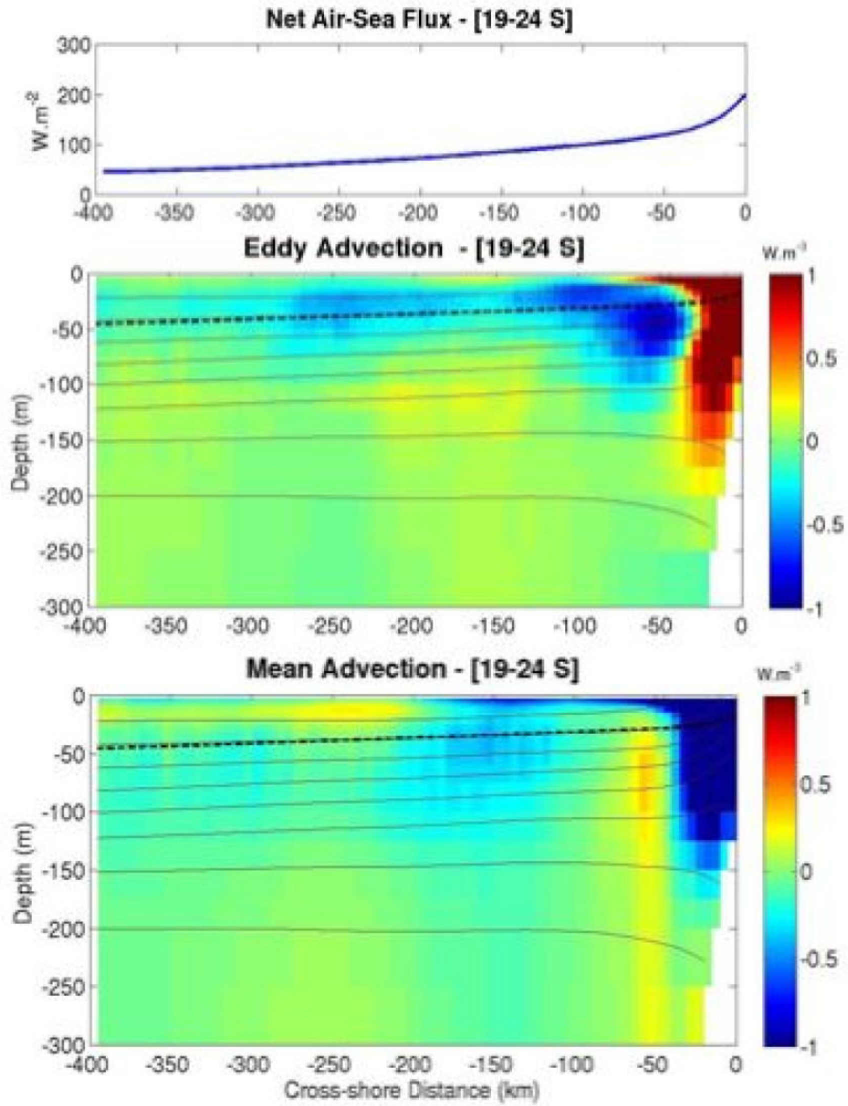
Regional Equilibrium Eddy Kinetic Energy



Mean surface eddy kinetic energy [$cm^2\ s^{-2}$] in the Peru-Chile Current System: measured from the TOPEX-Poseidon and ERS altimeters (left) and simulated (right). (Colas *et al.*, 2008)

Oceanic Heat Balance in the South-East Pacific

ROMS, 5 km x 5 km, 30 levels, QUIKSCAT winds, COADS F & Q



Heat Budget:

$$-adv_{mean} - adv_{eddy} - diff_{vert} = airsea$$

- Net heating by air-sea fluxes over the year
- Cooling needed to balance the airsea heating is provided by:

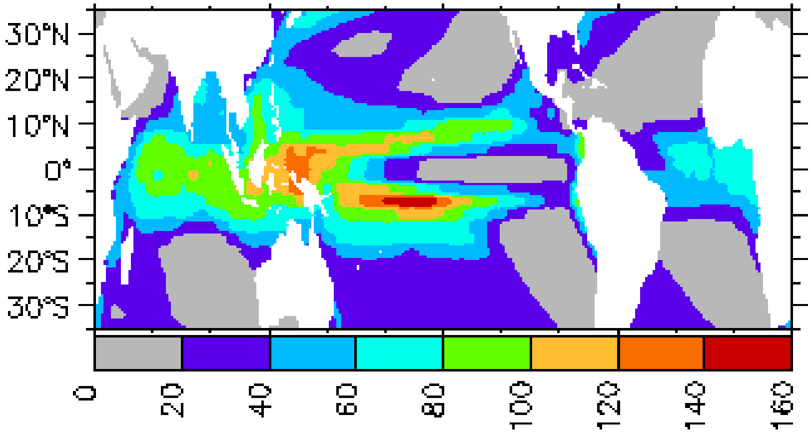
  Nearshore: Mean Advection (upwelling)

  Offshore : Eddy Advection
- Strong role played by eddies everywhere

(Capet, Colas & McWilliams, 2007)

UPSCALING EFFECTS FROM SUBTROPICAL EASTERN BOUNDARY OCEANS

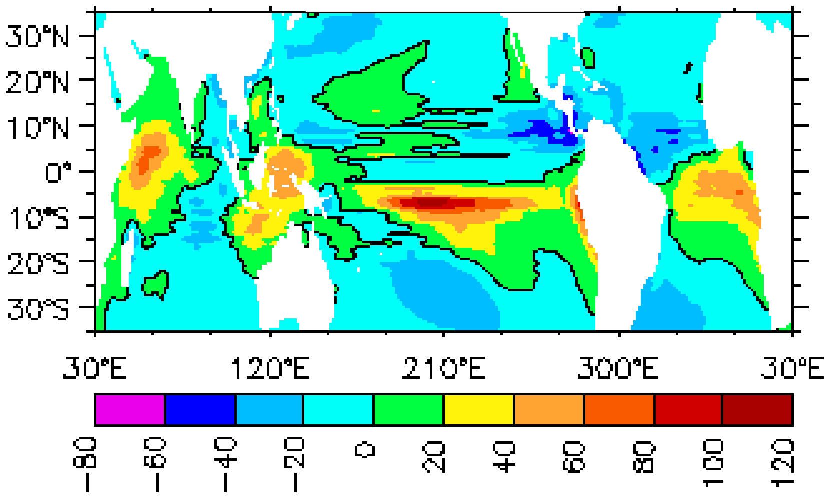
CCSM standard simulation



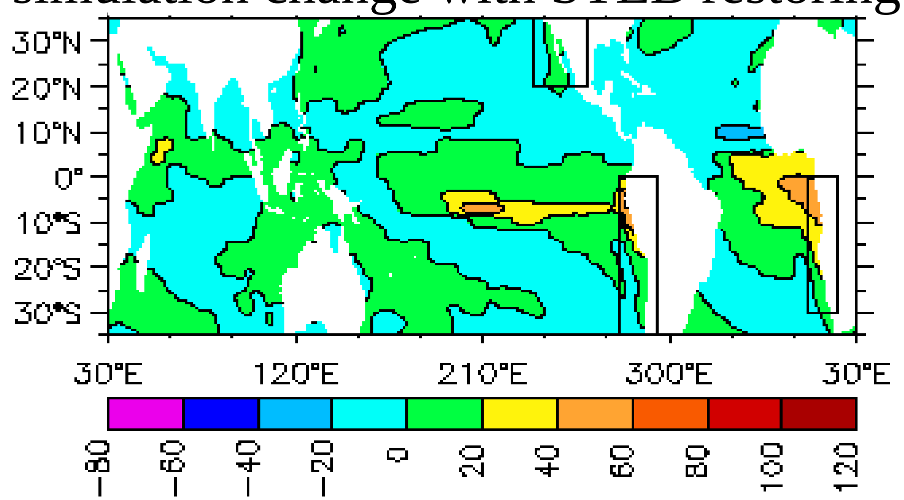
Mean precipitation [$mg/m^2/s$] in coupled model and its change with restoring of T & S in upper subtropical Eastern Boundary regions in N. & S. Pacific and S. Atlantic.

(Large & Danabasoglu, 2006)

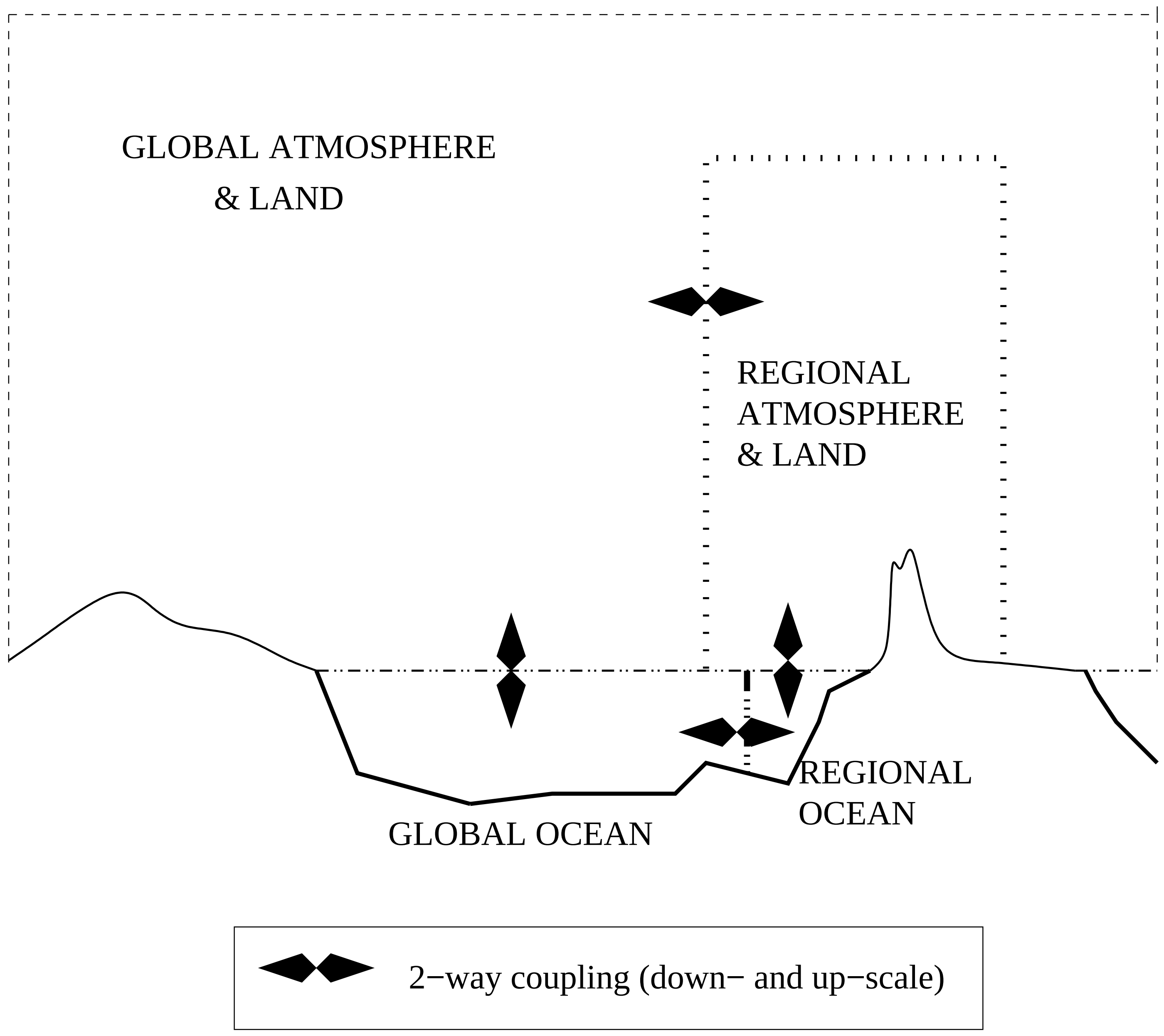
standard simulation error



simulation change with STEB restoring



SCHEMA OF EMBEDDED COUPLED MODELS



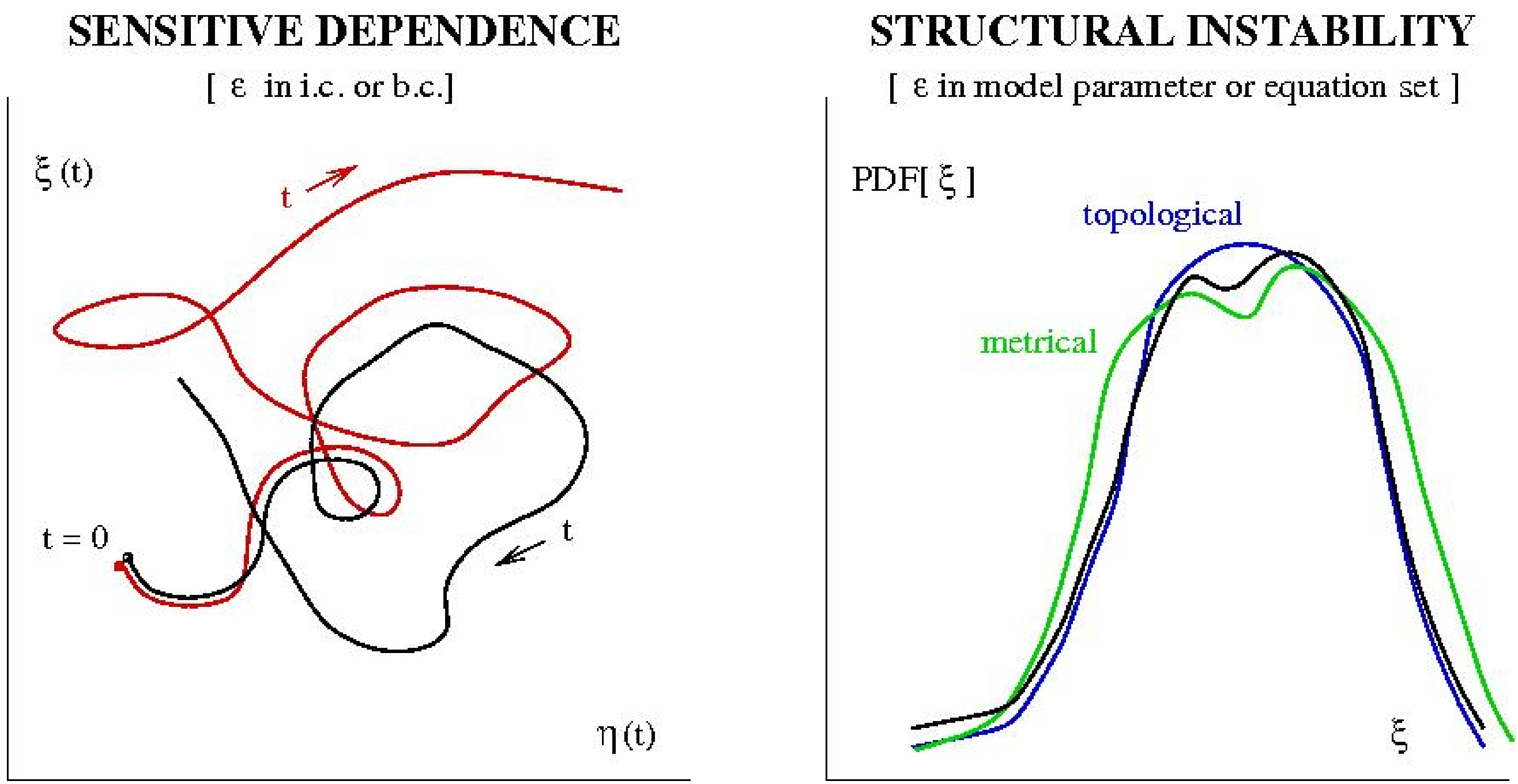
IMPRECISION IN SIMULATIONS

Propositions:

1. Chaotic dynamical systems are (almost always) structurally unstable (*e.g.*, Lorenz, 1963).

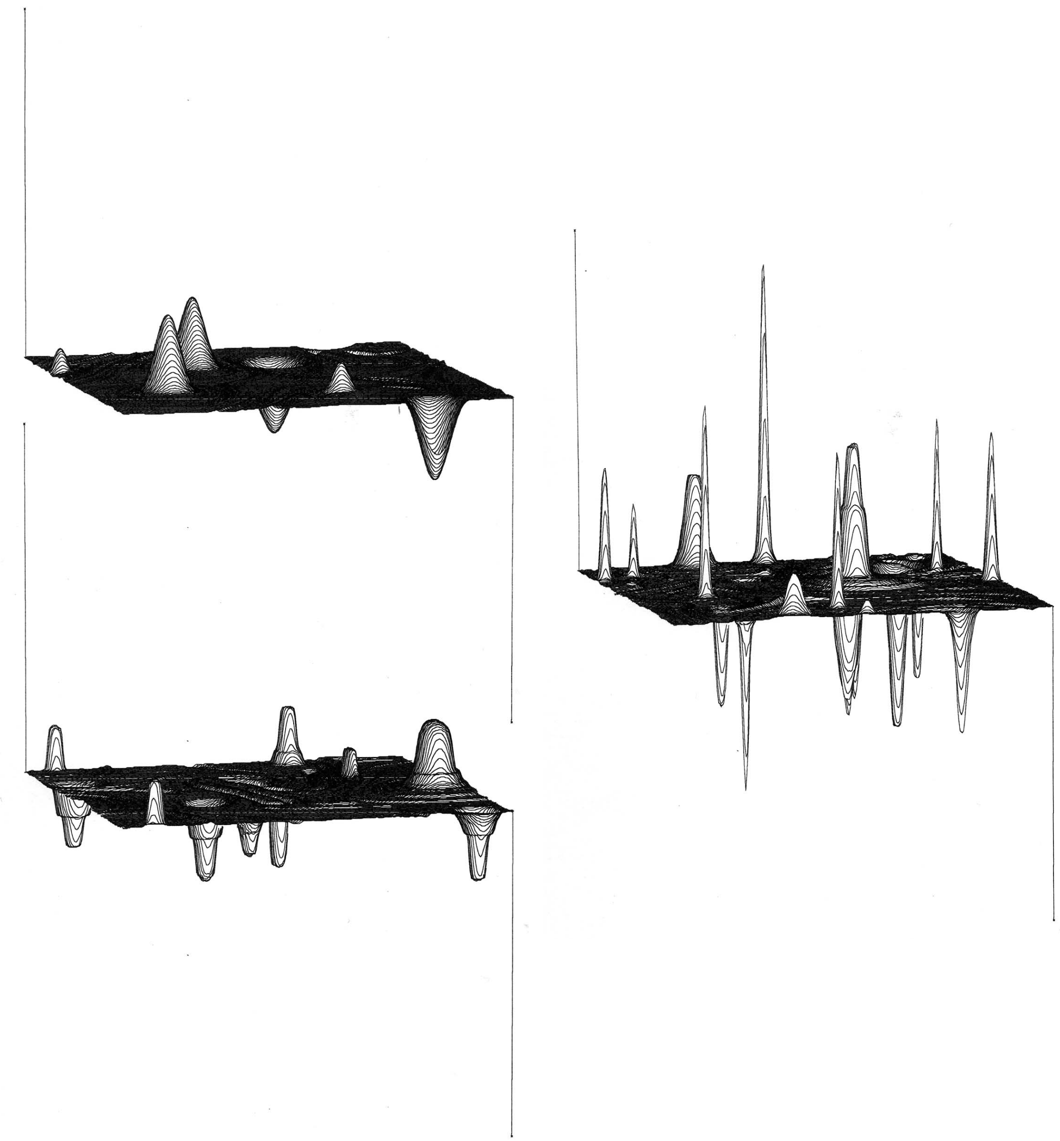
DEFINITION: A small change in a model, either for a parameter value or a functional component, leads to appreciable change in the long-time solution behavior (*i.e.*, the attractor), either topological or metrical.

Generic behaviors for chaotic dynamical systems with dependent variables $\xi(t)$ and $\eta(t)$: (Left) *sensitive dependence*, small changes in initial or boundary conditions imply limited predictability with (Lyapunov) exponential growth in phase differences, and (Right) *structural instability*, small changes in model formulation alter the long-time probability distribution function, PDF (*i.e.*, the attractor).



Fluid Dynamics at High Reynolds Number, Re

With the known Navier-Stokes equation and a well-resolved dissipation range $\Rightarrow$ sensitive dependence but structural STABILITY with respect to Re.



But with alternative choices for "monotone" advection schemes that preserve shape and effect minimal dissipation at a given grid resolution $\Rightarrow$ sensitive dependence & structural INSTABILITY.

Examples of late-time vorticity fields in 2D turbulence using utopia and two varieties of flux-corrected transport (Shchepetkin & McWilliams, *MWR*, 1998).

Numerical algorithms, subgrid-scale parameterizations, and opting for "exciting" (non-smooth) solutions all can induce structural instability of an equation-set and metrical type.

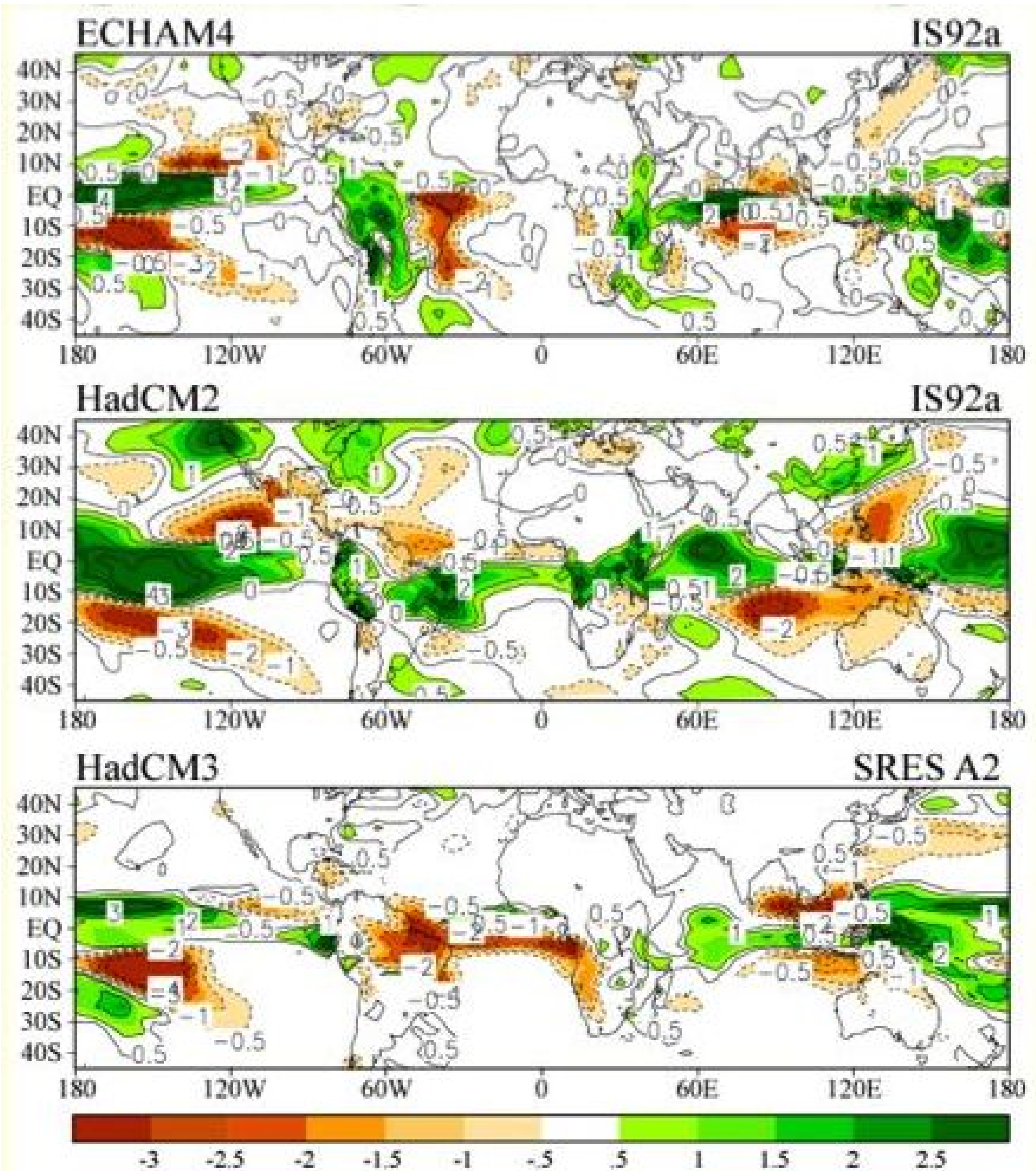
Propositions (cont):

2. Structural instability is untestable in general because there is no meaningful limit for the types of model changes that could be made, only for particular specified types.

3. Atmospheric and oceanic simulation (AOS) models — turbulent fluid dynamics plus ... — are our most potent tool for scientific discovery and prediction now (more so than measurements or fundamental theory), and their interesting solutions are chaotic, hence almost certainly structurally unstable. Thier chaos is essential to the structural pattern emergences that are their greatest success.

$\Rightarrow$ AOS models can teach us about nature and make predictions that can be partially right but will remain partially uncertain.

Precipitation Change Under Global Warming



Predicted average DJF precipitation change [mm day^{-1}] between 1961-1990 and 2070-2090 from different climate models with similar mid-range emission scenarios (from Neelin *et al.*, 2003).

Note agreement in the broadest aspects but substantial disagreement in specific patterns and magnitudes.

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Sources of Irreducible Imprecision

- AOS solution fields are non-smooth near the space-time discretization scales ($i.e.$, the "resolution" of the model) imposed on the known governing principles expressed mostly as partial differential equations.

- AOS models contain essential parameterizations for unresolved or highly simplified processes whose specifications are not at a fundamental level of known governing principles, hence non-unique.

- AOS models are open-ended in their scope for including and dynamically coupling different physical, chemical, biological, and even societal processes.

Inter-model irreproducibility is a common experience for many solution aspects ($e.g.$, $\sim$ 25 years of non-shrinking global warming forecast spreads).

Structural instability — manifested as delicacy of late-time solution measures — is a plausible concept for understanding this behavior.

Model delicacies & irreducible imprecision levels need to be explicitly quantified.

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Coping Strategies

Use models to study processes and phenomena apart from precise comparisons with nature.

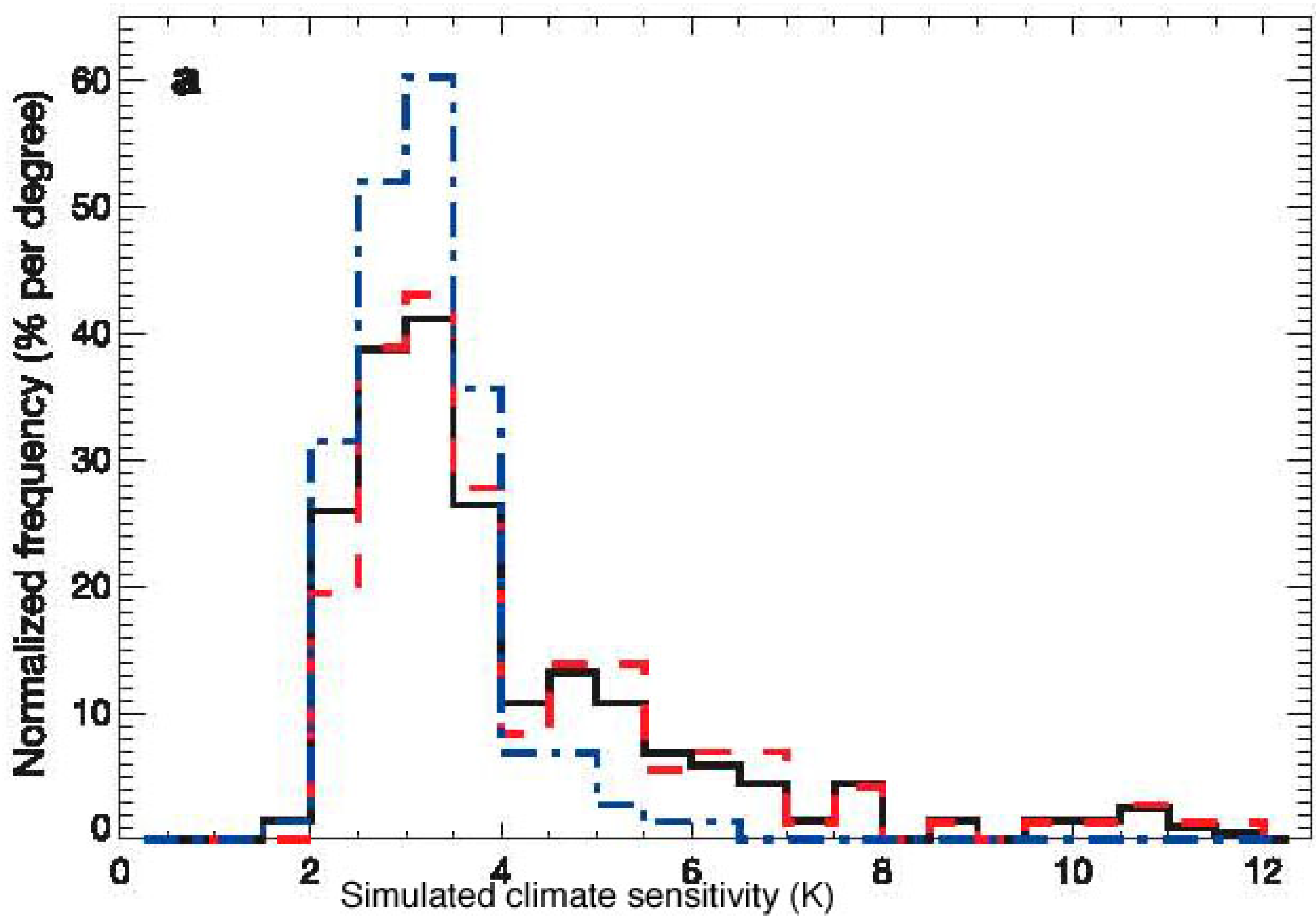
Search for more robust discretization and parameterizations ($e.g.$, differentiable parameterizations?, stochastic PDEs?), as part of the continuing model improvement activities.

Deliberately design model ensembles (not merely inadvertent and opportunistic, as in IPCC, AMIP, CMIP, $etc.$), and document "model tuning" to available observational constraints.

Reframe comparisons with nature and climate forecasts in terms of model-ensemble distributions.

. (McWilliams, 2007)

Climate Sensitivity Distribution Function



Frequency distributions for climate sensitivity (*i.e.*, mean ΔT for doubled atmospheric CO_2) in an atmosphere + ocean mixed-layer GCM with different parameter choices:
(black) all model runs; (red) excluding perturbations to rain threshold;
(blue) excluding perturbations to convective entrainment coefficient.
(Stainforth *et al.*, 2005, based on `climateprediction.net`)

SUMMARY

- Robust patterns emerge out of fluid dyanmics in many climate regimes

- Regional-global, multi-scale computing for bias correction and phenomenological discovery

- Model families and ensembles to expose scope of structural instabilities