# The Important Role of Physics-Dynamics Coupling

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# To Consider:

- We are modeling complex systems, which requires complex models.
- Still, the models are simple compared to the natural systems we are trying to understand and predict.
- Even if we know an equation which describes, exactly, the balance of forces (mass, energy, … ), we have to rely on approximations to the solution of that equation.
- We rarely know an exact equation.
- Hence, we are faced with the problem of building complex systems with building blocks, none of which are quite right.
- How do we connect these building blocks?

# It Might Be Like Building a Stone Wall

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- There are many ways to cut the stones (or not).
- There is the choice to hold the stones together with mortar (or not).
- All choices can lead to functional and attractive walls, of a certain height, thickness, and length.
- There is benefit of design.

# Choices

- Some people think that mortar is important. Some do not.
- Some applications require mortar. Some do not.

# What is coupling?

- In this example I have used mortar in a stone wall as a metaphor for coupling.
  - The stones can touch each other directly.
  - The stones can be connected by mortar.
  - The stones can be shaped, cut, to fit together very well without mortar.
    - There still might be requirements or benefit of mortar.

# What is coupling?

- There is not a unique definition of coupling.
- In design and architecture, there are evolving definitions of what happens at interfaces of components.
- There is increasing attention to the taxonomy, description, and development of coupling.
  - In our field, often restricted to connecting component models, e.g., atmosphere, ocean, land, ice
  - In our field, some equate coupling to process splitting and time splitting
  - Based largely on history, not comprehensive design.
- I will be talking, simplistically, about the scientific attributes of coupling.

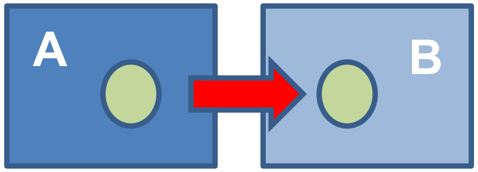
# Coupling: More Precisely

- Here we define “coupling” as any transfer of information between distinct processes.
- It can be as simple as calling a subroutine and passing unchanged values (direct exchange).
- It can involve a separate coupler that performs interpolations, temporal averages, field merges, unit transformations, computations of derived fields, etc. (mediated exchange).

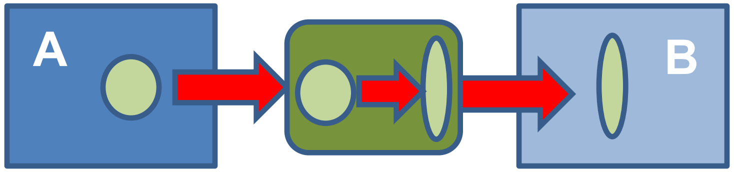
Thanks to Cecelia DeLuca

# Direct and Mediated Exchanges

- Direct exchange does not require operations outside of the context of the processes involved (here A and B).




- Mediated exchange introduces a separate design element with operations that are not part of the context of the processes involved.




- In a mediated exchange there is a "place" for handling the disparities between the outputs of one process and the inputs of another.
- Mediated exchange offers the possibility of generalizing the code in the mediating element to handle multiple implementations of the components (say B1 or B2), and to support complex multi-component transformations (e.g. mergers where A and B create a derived quantity that is sent to C).

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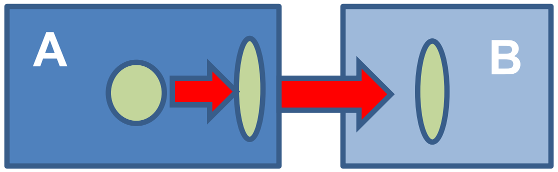
Thanks to Cecelia DeLuca

# “API” Approach

- In an Application Programming Interface or physics interface approach, each component writes to a prescribed interface, and then there is a direct exchange:




- This pushes any exchange transformations into the context of the components in the exchange.
- It tends to discourage reuse of the design elements involved in exchange transformations.
- This approach also limits the ability to perform transformations that may involve multiple processes (e.g. mergers).

Thanks to Cecelia DeLuca

# Coupling and Design

- Gamma et al. Design Patterns (1995)
  - Describes the mediator design pattern: An object that encapsulates how a set of objects interact. Mediator keeps objects from referring to each other explicitly, and it lets you vary their interaction independently

Thanks to Cecelia DeLuca

# Choices

- Some people think that mortar is important. Some do not.
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- Some people think that coupling is important. Some do not.
- Some applications require coupling to be done well. Some do not.

# My History: Chemistry, positivity

- I came at coupling problem, first, through chemistry-transport modeling.
- If the transport algorithm provides the chemical solver with a value that is less than zero, then the solver simply fails.
- If the transport algorithm provides the chemical solver with a value that is larger than any value in the field being transported, then the solver is using values that are non-physical.
- The point: the solver brings a set of requirements to the dynamical core.
  - Likewise, the dynamical core might have requirements for the solver.

# For example: Lin & Rood (1996) Advection of a pulse (square wave)

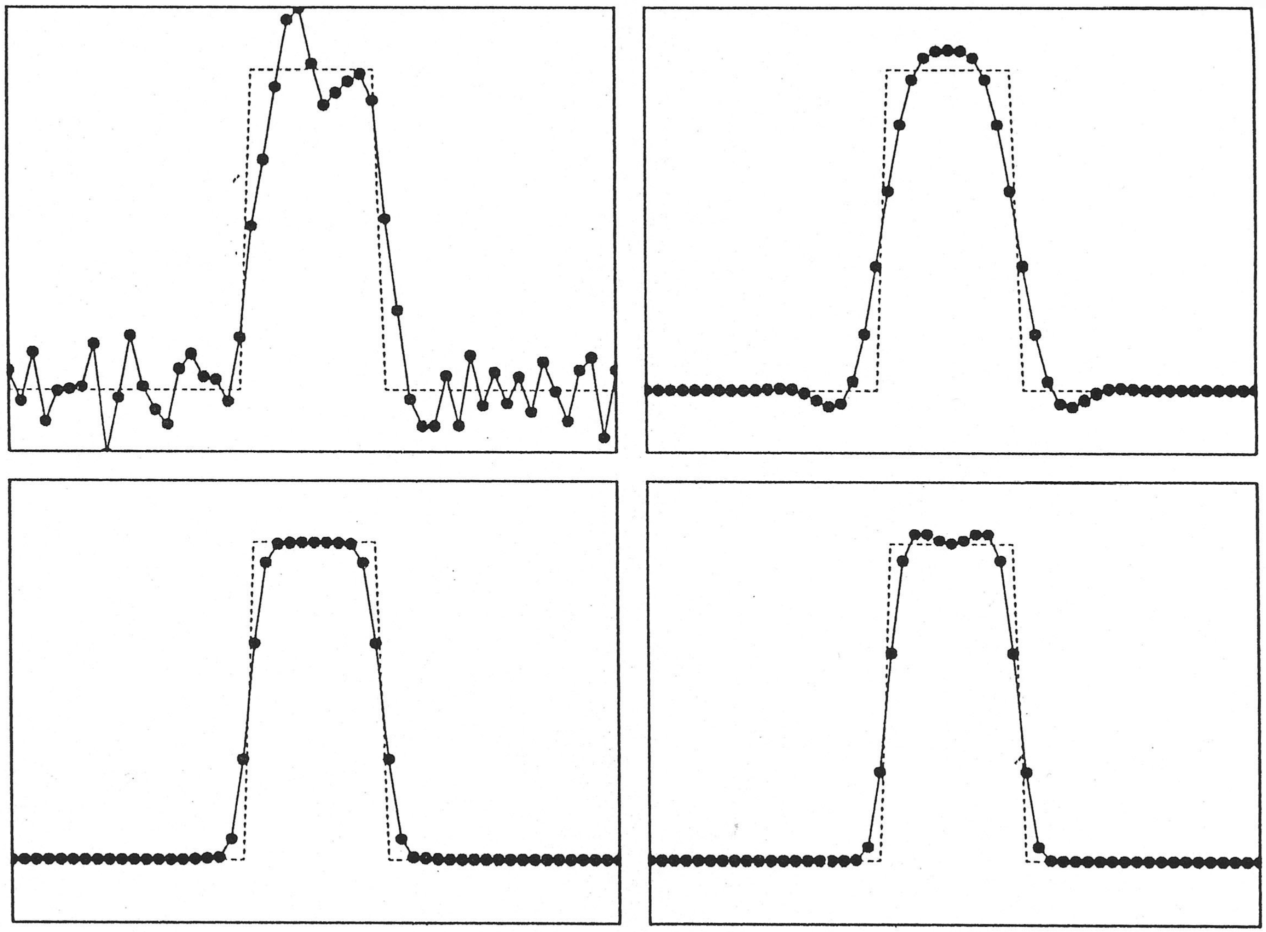


Fig. 4 center differencing scheme (CD4, upper left panel), (b) semi-Lagrangiann scheme based on the cubic interpolation (SL4, upper right panel), (c) modified monotonic PPM (FFSL-3, lower left panel), and (d) modified positive definite PPM (FFSL-5, lower right panel). Courant number is 0.5. Dashed line is the analytic solution.

# My History: Chemistry, correlation

- In multi-constituent flows, the chemical equations lead to correlated behavior between constituents.
  - There are multiple time scales.
- If the transport scheme, say, creates a negative value in one constituent, which is corrected in some way, then correlated information is compromised. Consistent treatment is required.
- The point: If I start to hand the solver information from different solvers, I am likely to hand inconsistent, not correctly correlated, non-conserving, etc., to the solver.

# Two attributes of coupling here

- We are working in discrete systems.
- We solve that systems in discrete steps.
- We need to assure that parameters are passed across these steps that meet the physical, chemical, and biological requirements,
- We need to assure that information from discrete parts behaves in proper correlated fashion.
- We are managing data and information to assure adherence to physical, chemical, and biological principles.

# My History: Precipitation

- Providing moisture to convection parameterizations.
  - Numerical overshoots can trigger numerical convection.
  - Diffusion and filtering to prevent overshoots can underrepresent convection.
  - Negative water is unphysical.
  - Numerically induced rippling of, for example, water vapor and temperature fields can cause precipitation and clouds far away from where they should be.

# To Consider, Again:

- Chain only as strong as its weakest link.
  - Advantages that are developed in specific components can be lost if the connection of those components cannot use that information and propagate that information to the end product.

Amdahl’s law, Rate-limiting reaction, Nutrient-limited growth.

# We Are Building Systems

- The performance of our modeling systems, measured by excellent forecasts or quantitative understanding, depends on the system as a whole.
  - Depends on the quality of the pieces of the model
  - Depends on how well those pieces are connected (coupled)
  - Is limited by weak components and poor coupling
- Coupling is important.

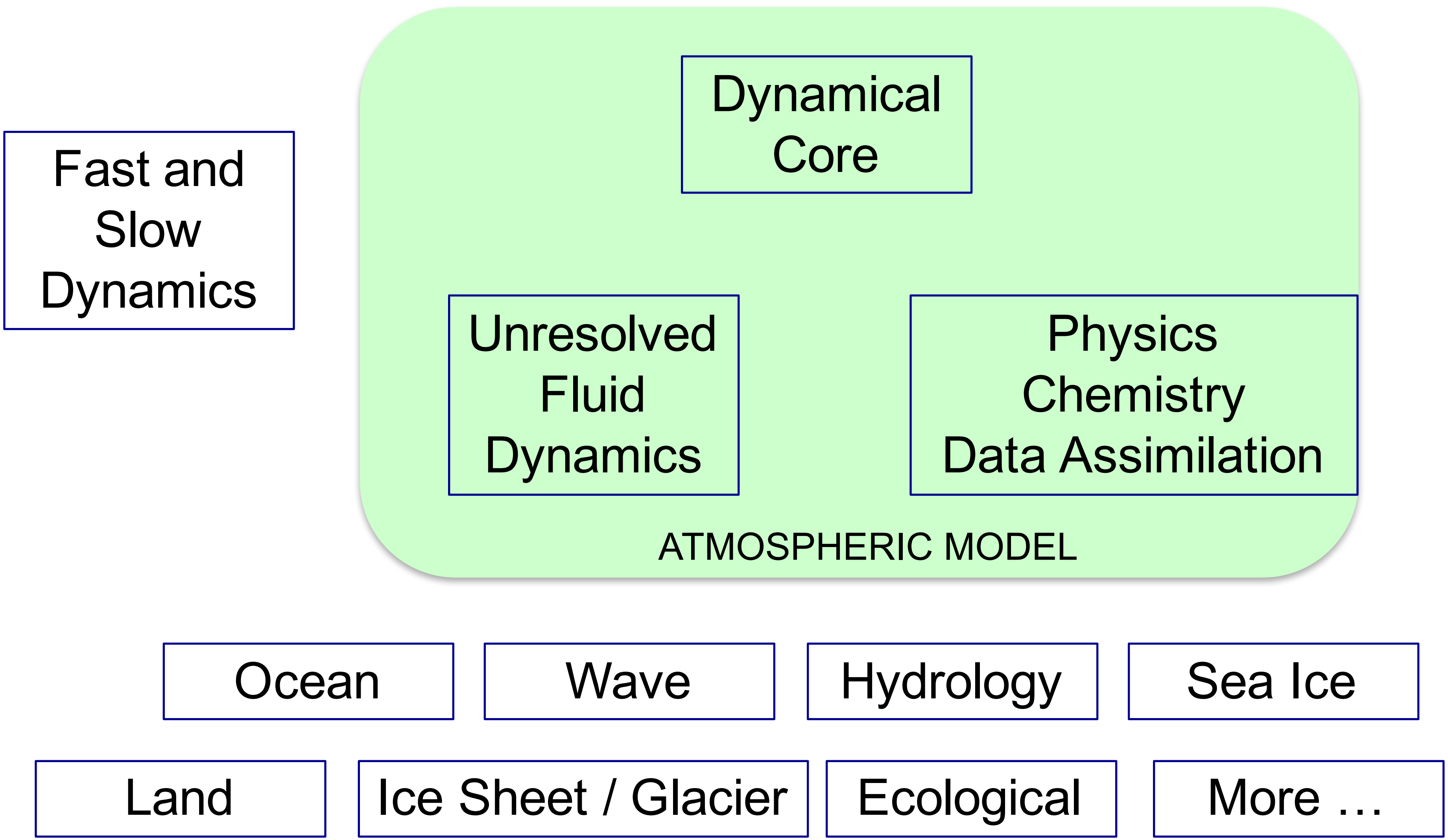
# Coupling is important

- There are scientific aspects of coupling.
- There are computational aspects of coupling.
- Coupling depends on the components of the system.
  - Coupling changes in time. That is as components change.
- Coupling depends on the application of the system.
- Coupled systems require coupled diagnostics and coupled evaluation.
- Coupling needs to be considered a part, a component, of the modeling system.

# Some references

- Staniforth et al. (2007):Aspects of unified dynamical core.
- Staniforth et al. (2006):Analysis of numerics of coupling.
- Staniforth et al. (2002):Comparison of coupling methods.
- Williamson (2002): Process split and time split comparison.
- Gassman et al. (2006): Time splitting and divergence damping.
- Dubal et al. (2006): Physics-dynamics coupling.
- Termonia et al. (2007): Stability and analysis of coupling
- Rood (1987): Some basic definitions and ancient references

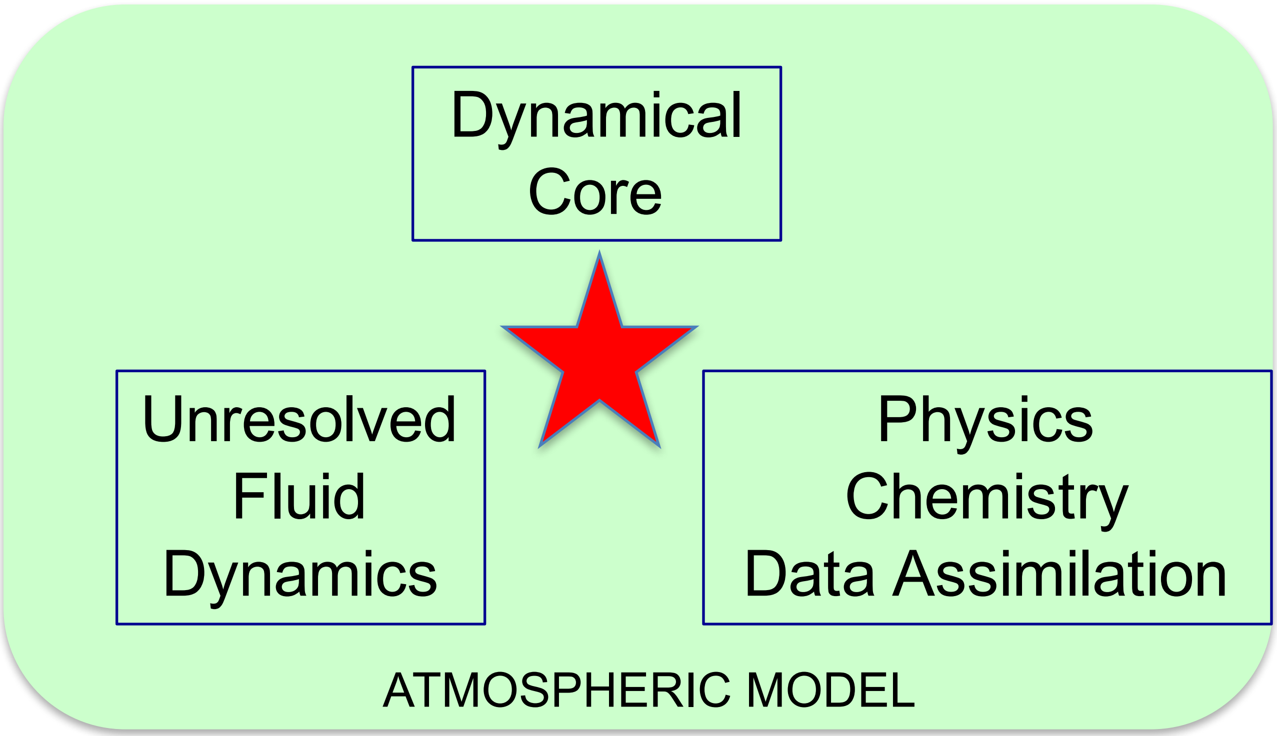
# Coupling in Atmospheric Models



# More attributes of coupling

- In addition to the previous requirements about the physical robustness of a variable and correlated information, consideration of coupling brings in the possibility of the need for other information.
  – Grid transfers
  – Filtering and fixers
  – State transformations
  – Time management
  – Sub-grid information

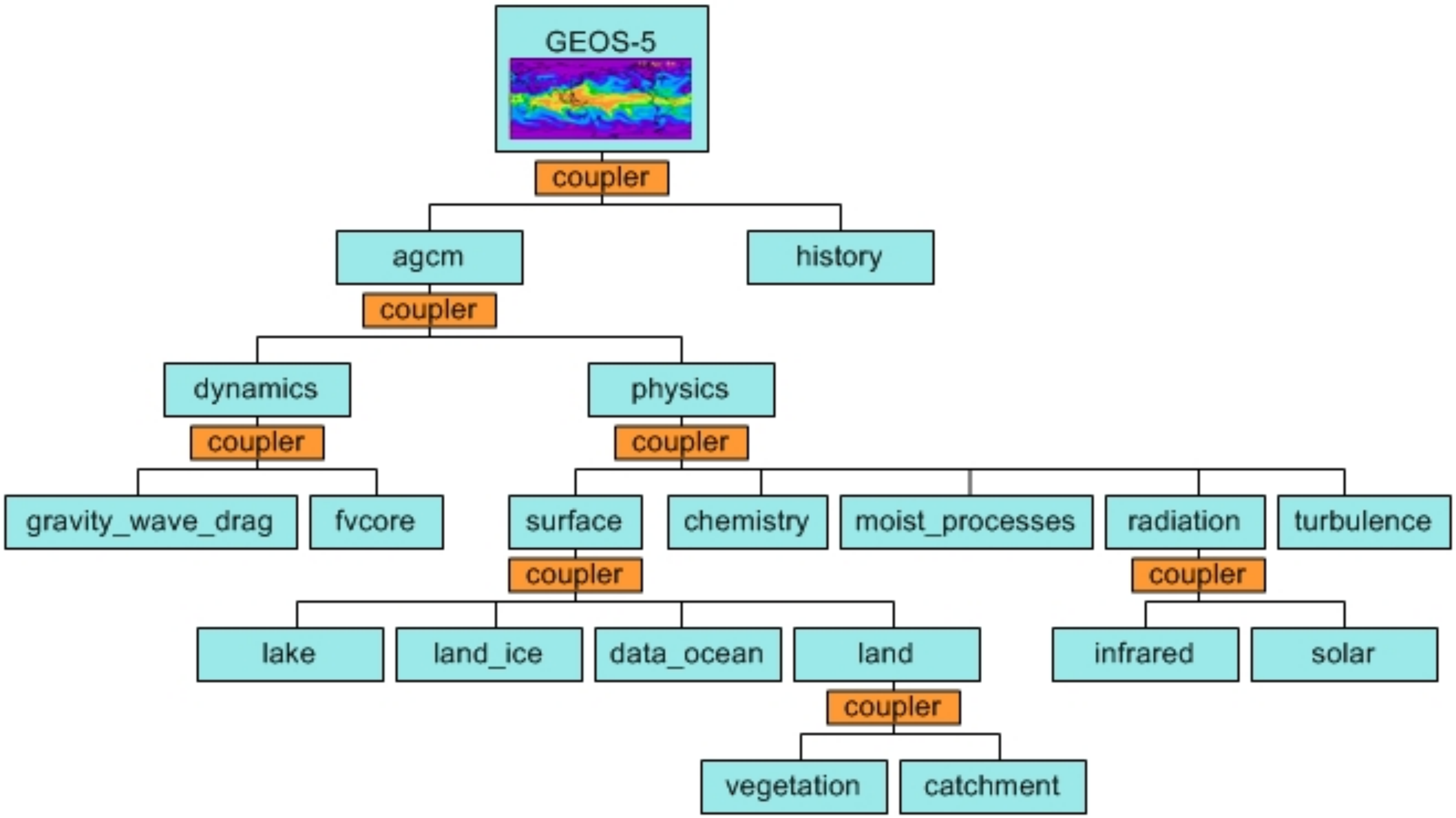
# Coupling in Atmospheric Models



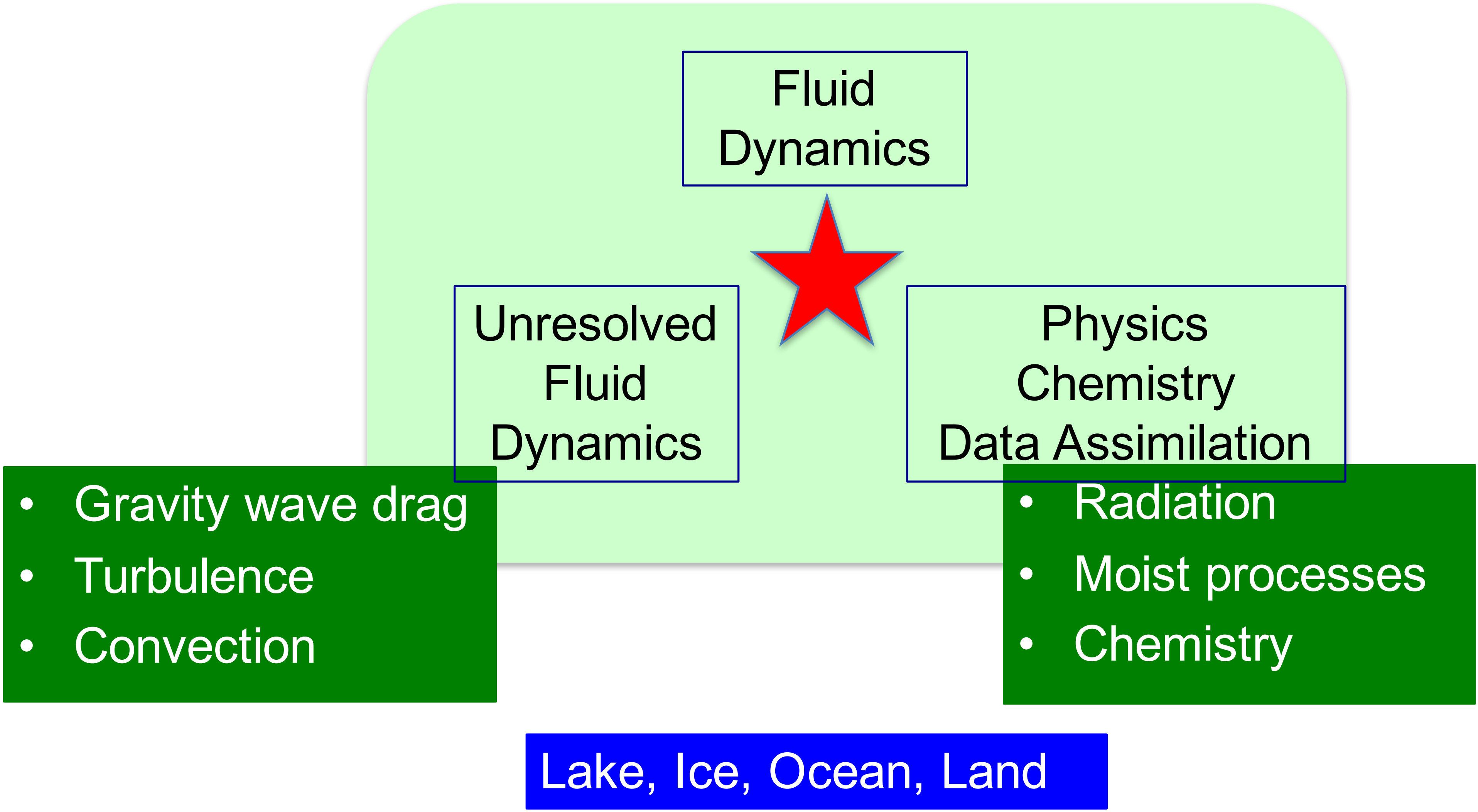

- Focus on this, especially scientific considerations.
- Is there any reason that this is different from coupling to Ocean, Ice, Wave, Land, …?

# GEOS-5 Atmospheric Model

(Might be factually outdated, but the point remains the same.)



# Mapping GEOS-5 to Categories

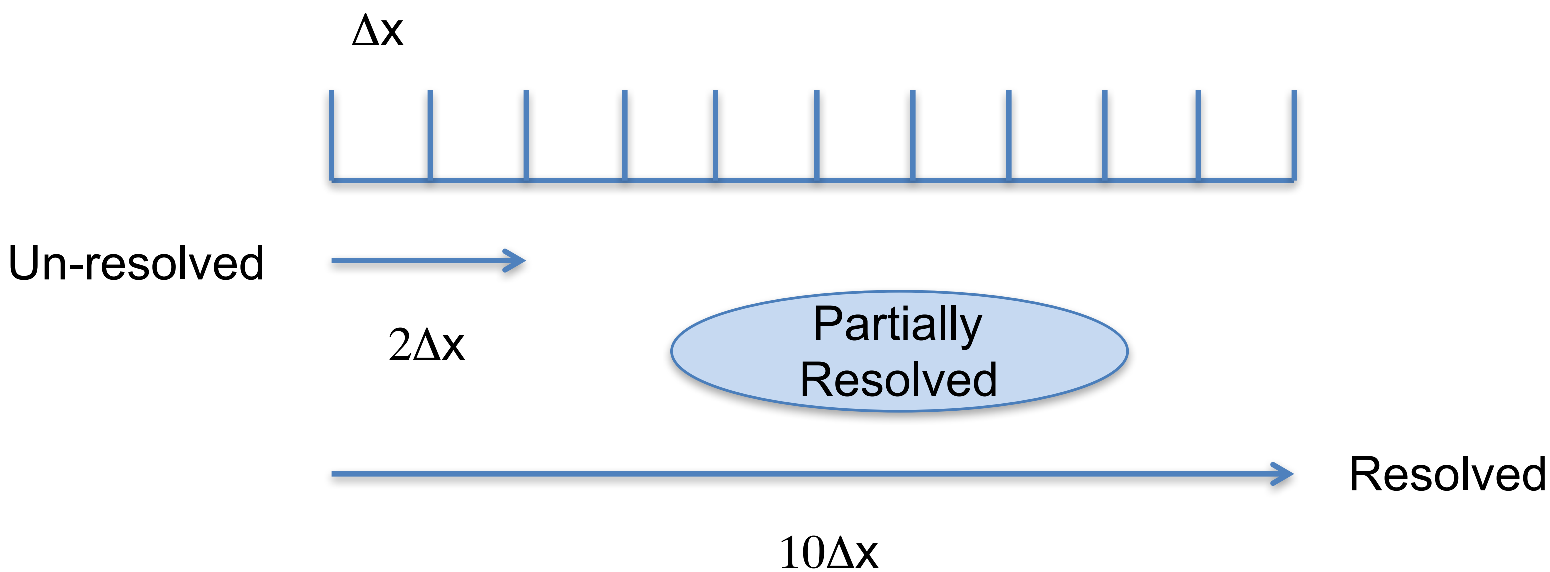


# What is in a dycore?

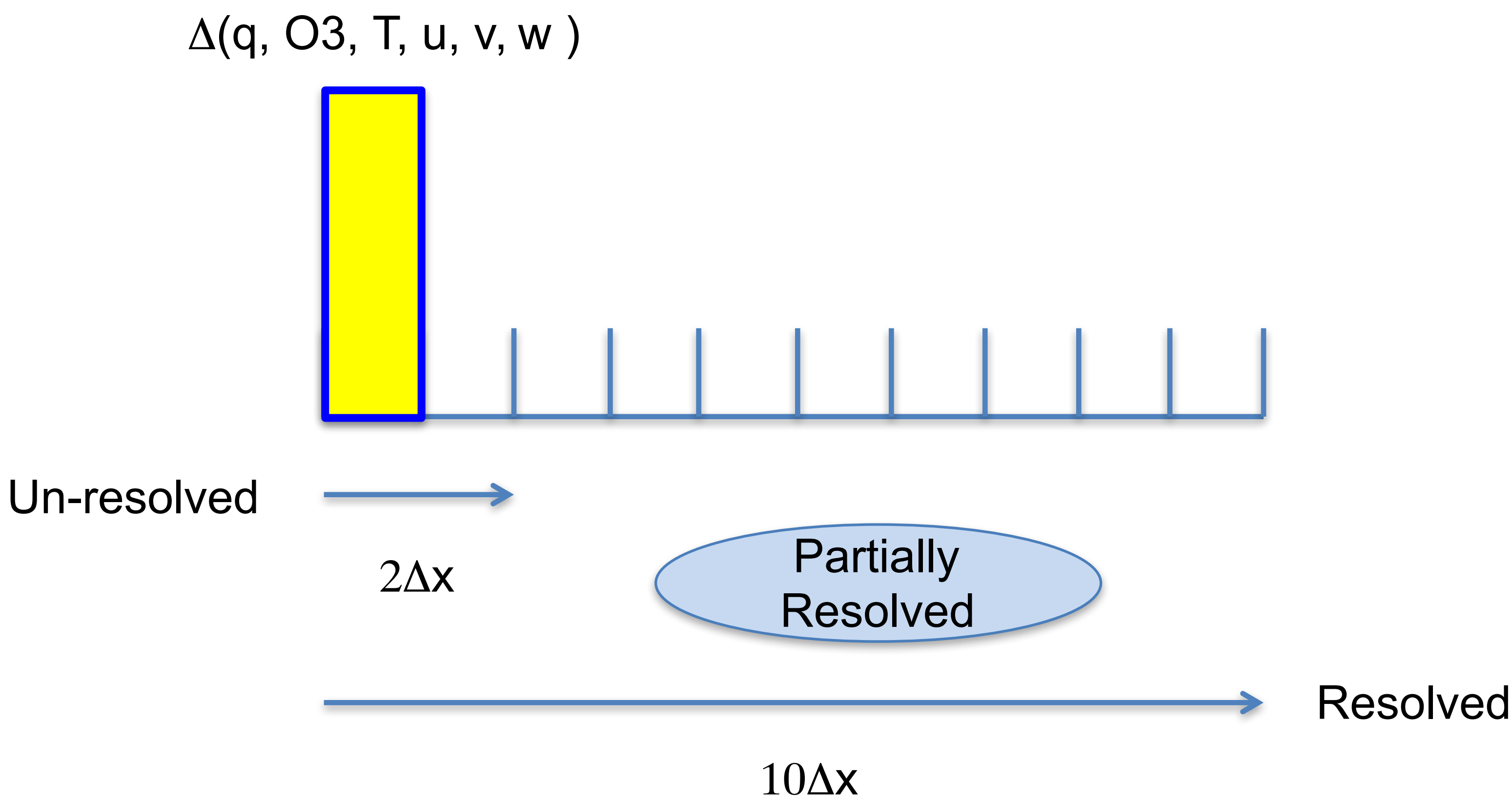
(Rood (2011), Perspective)

- A specification of the grid.
- A specification of topography.
- A specification of the pressure gradient force.
- A specification of the Coriolis force.
- The resolved advection of momentum in the horizontal plane.
- The resolved vertical advection of momentum.
- Unresolved sub-scale transport of momentum.
- The resolved advection of scalars in the horizontal plane.
- The resolved vertical advection of scalars.
- Unresolved sub-scale transport of scalars.
- A portfolio of filters and fixers that accommodate errors related to both the numerical technique and the characteristics of the underlying grid.

# Thinking about Fluid Dynamical Resolution

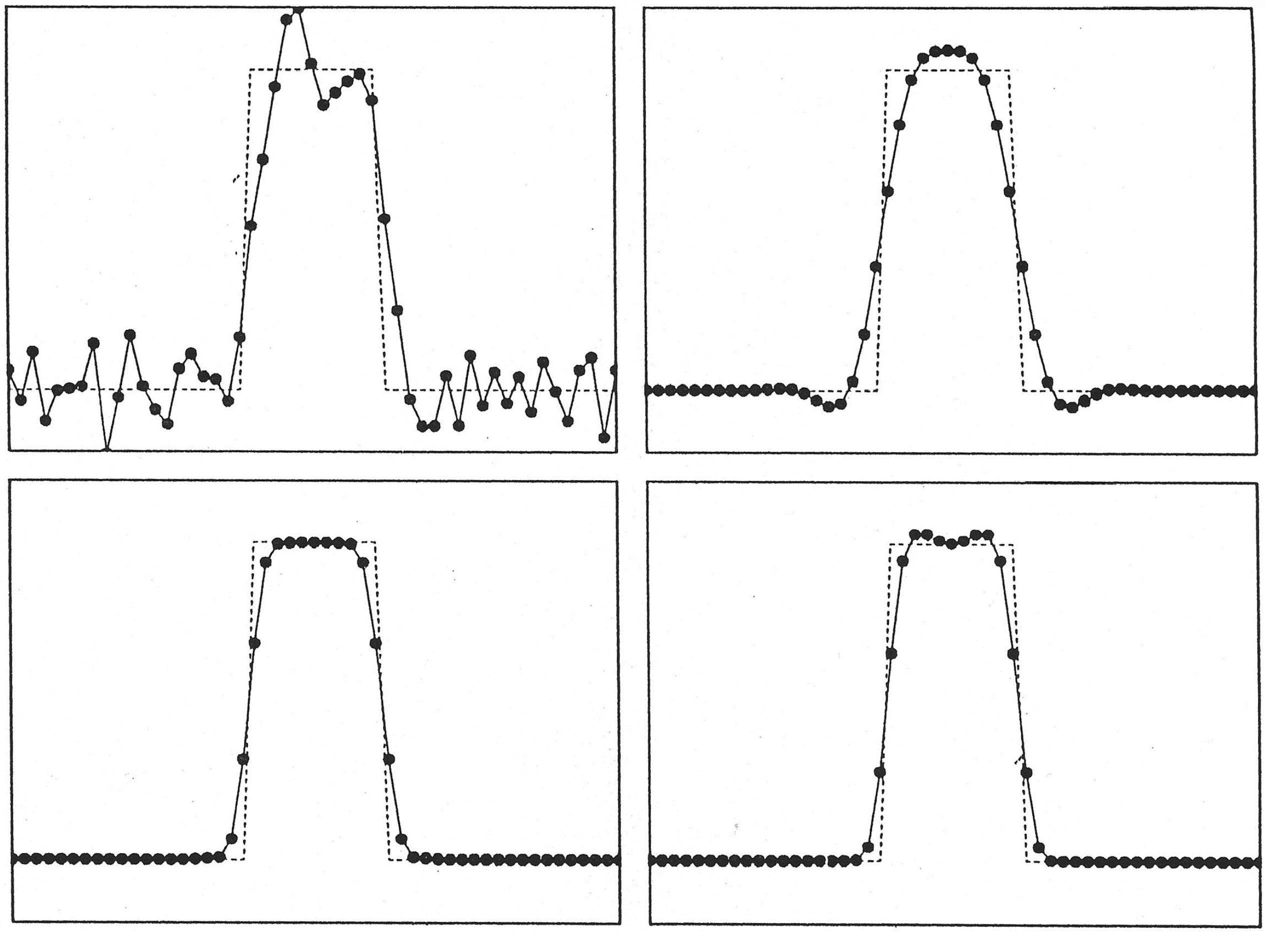


# Thinking about "Physics"




- Physics, Chemistry, Data Assimilation make an impulse change at some time.
- We expect the fluid dynamics to ***organize*** these impulse changes into Resolved features.
- Has to somehow propagate information through the desolate land of the Partially Resolved

# Take the earlier picture, and rather than advection of a pulse (square wave), think of pulses that occur at the grid size. How is this information managed?



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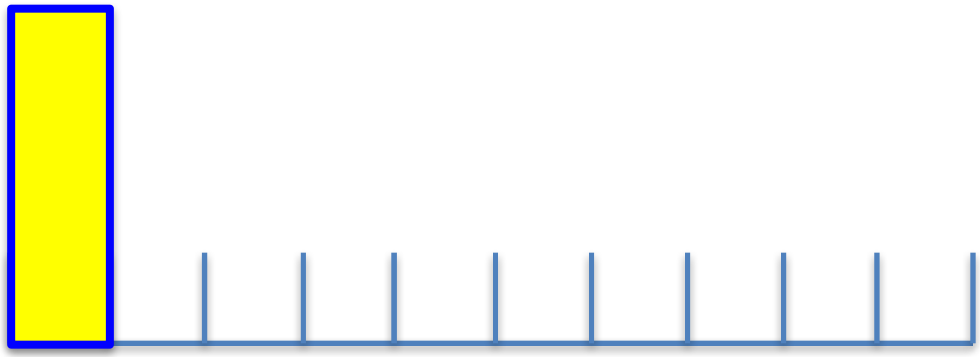
# Thinking about Managing Information

$\Delta$(q, O3, T, u, v, w )



- We often try two approaches
  - **Global:** High order numerical approximations that are formally accurate, but require a large stencil, number of points. (pseudo-spectral schemes at one extreme)
  - **Local:** Managing not only the parameter of interest, but its moments (some information on the sub-grid, Prather, 1986 at an extreme).
  - We often settle someplace in between.
  - We are still left with need to manage information.

# Attributions of the “physics”

- Representation of processes that
  - Occur at the size of the grid.
  - Are characterized by many time scales.

- So we have to deal not only with the spatial challenges, but with temporal challenges.

- Require a two-way exchange of information.

# Some references

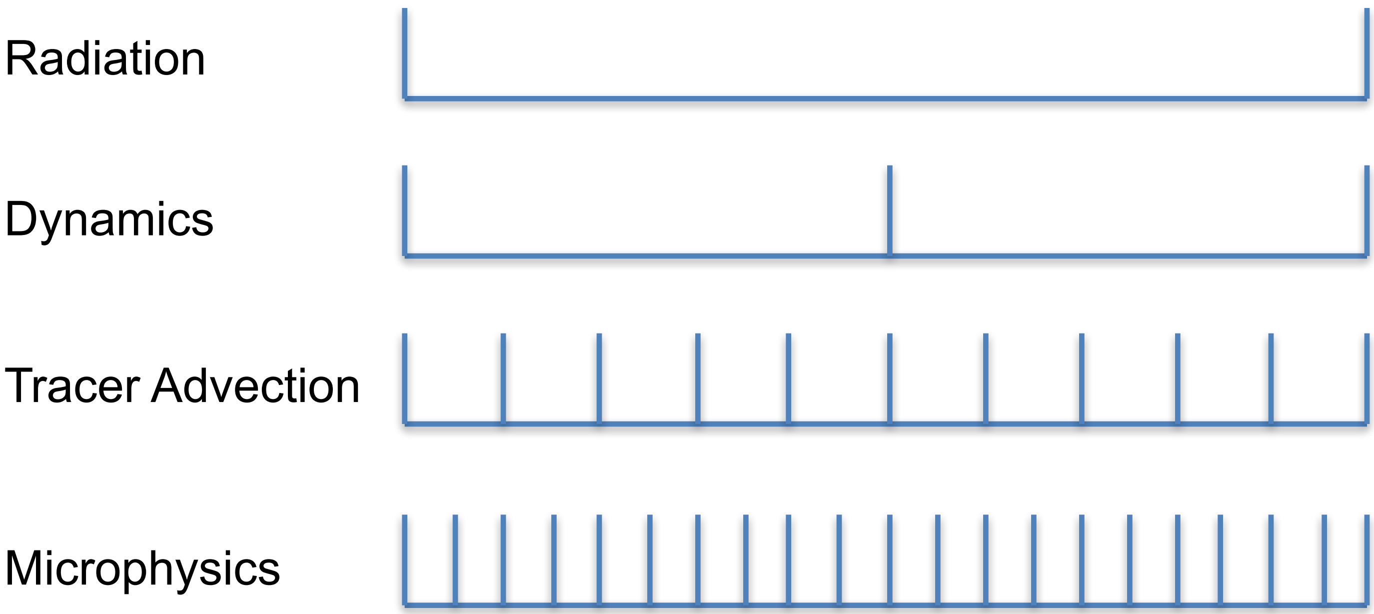
- Staniforth et al. (2007):Aspects of unified dynamical core.
- Williamson (2002): Process split and time split comparison.

- Much of the discussion in the literature is about managing the fast and slow time scales in a computationally viable and scientifically justifiable manner.

# Basic idea is to split things:

- Perhaps a dynamical time step.
- Perhaps a tracer advection time step.
- Perhaps a microphysics time step.
- Perhaps a radiation time step.

# Thinking about Managing Time Scales



# Borrowing Dave Randall's Metaphor

http://www.gingerrogers.com/

Impulse (Lead) and Response (Follow): We are trying to represent a process with a series of discrete steps.

# What is in a dycore? (Topography)

(Rood, Perspective)

- A specification of the grid.
- A specification of topography.
- A specification of the pressure gradient force.
- A specification of the Coriolis force.
- The resolved advection of momentum in the horizontal plane.
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- A portfolio of filters and fixers that accommodate errors related to both the numerical technique and the characteristics of the underlying grid.

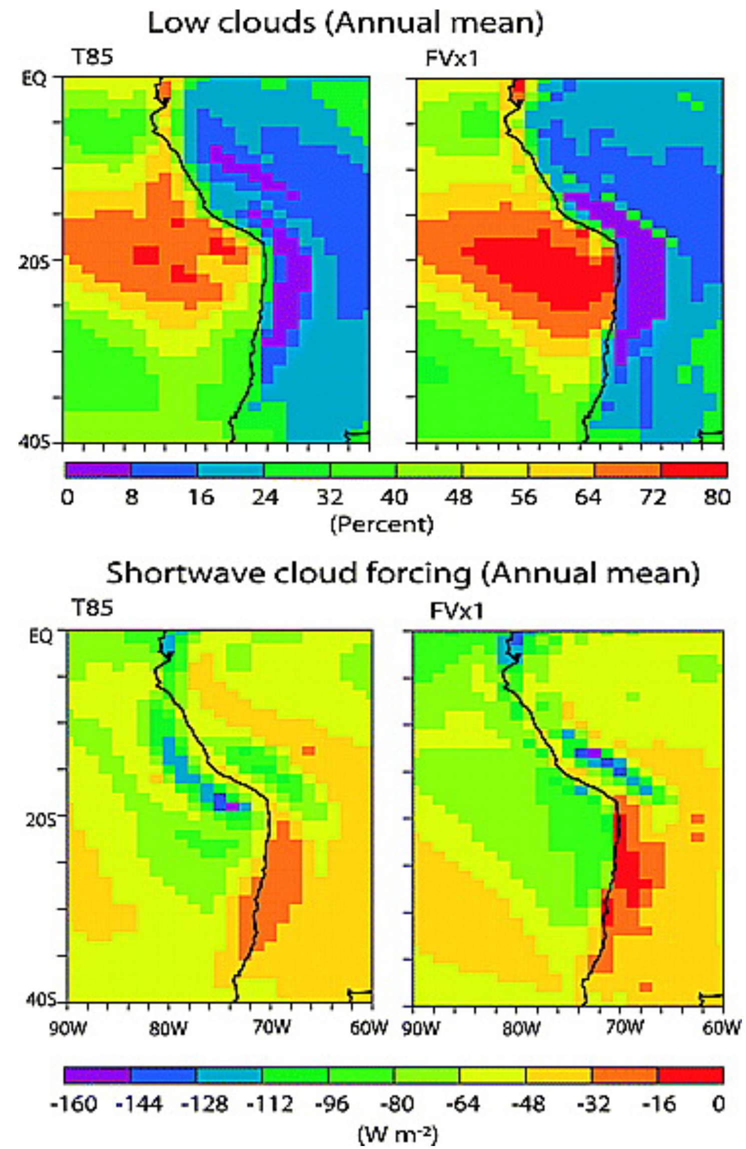
## Simulated climate near steep topography: Sensitivity to numerical methods for atmospheric transport (Bala et al., 2008)

Community Climate System Model v 3:

Spectral dynamical core (left)
Finite-volume dynamical core (right)

Low clouds (top)
Shortwave cloud forcing (bottom)

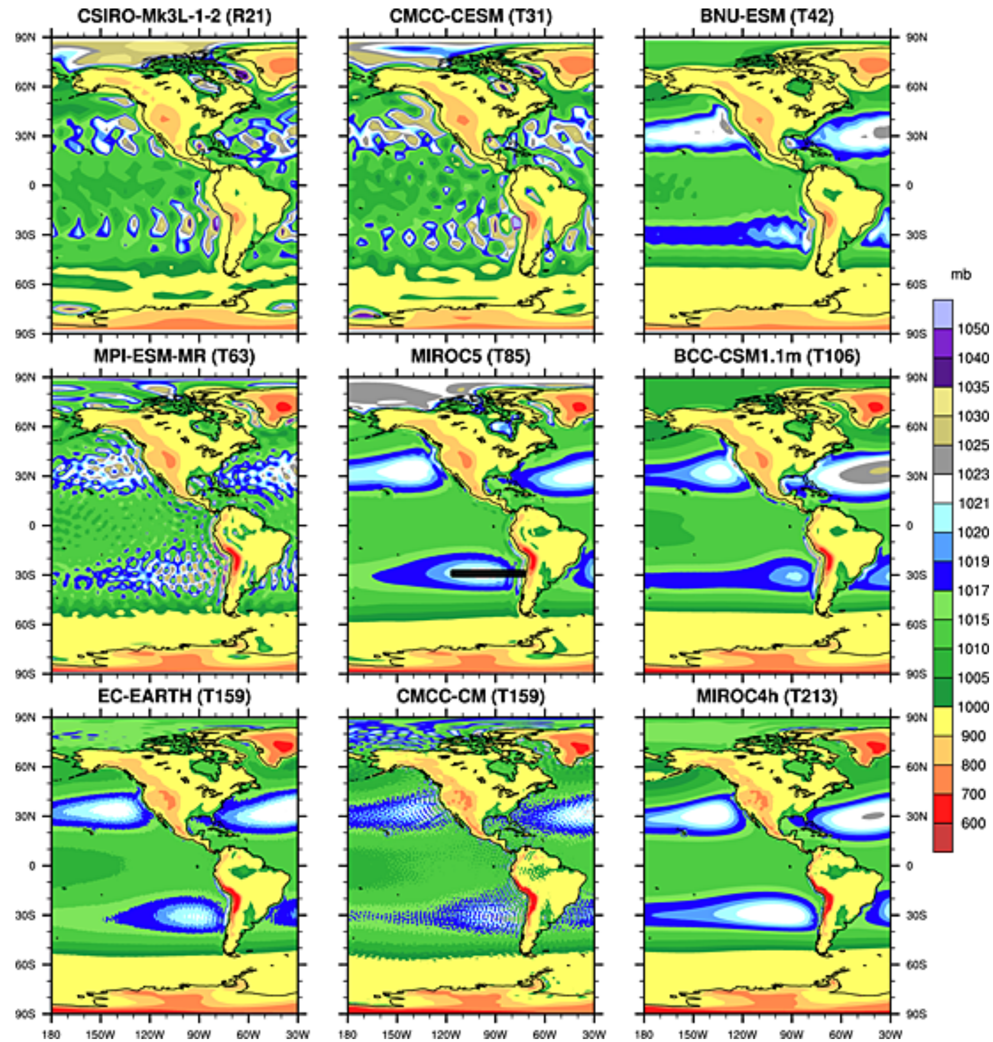
Looking at western boundary of South America





**Geophysical Research Letters**
Volume 35, Issue 14, L14807, 22 JUL 2008 DOI: 10.1029/2008GL033204
http://onlinelibrary.wiley.com/doi/10.1029/2008GL033204/full#grl24350-fig-0001

# Quantitative characterization of spurious numerical oscillations in 48 CMIP5 models




**<u>Geil and Zeng (2015)</u>**
**<u>From the Abstract</u>:**

Spurious numerical oscillations (SNOs) (e.g., Gibbs oscillations) can appear as unrealistic spatial waves near discontinuities or sharp gradients in global model fields (e.g., orography) and have been a known problem in global models for decades.
…

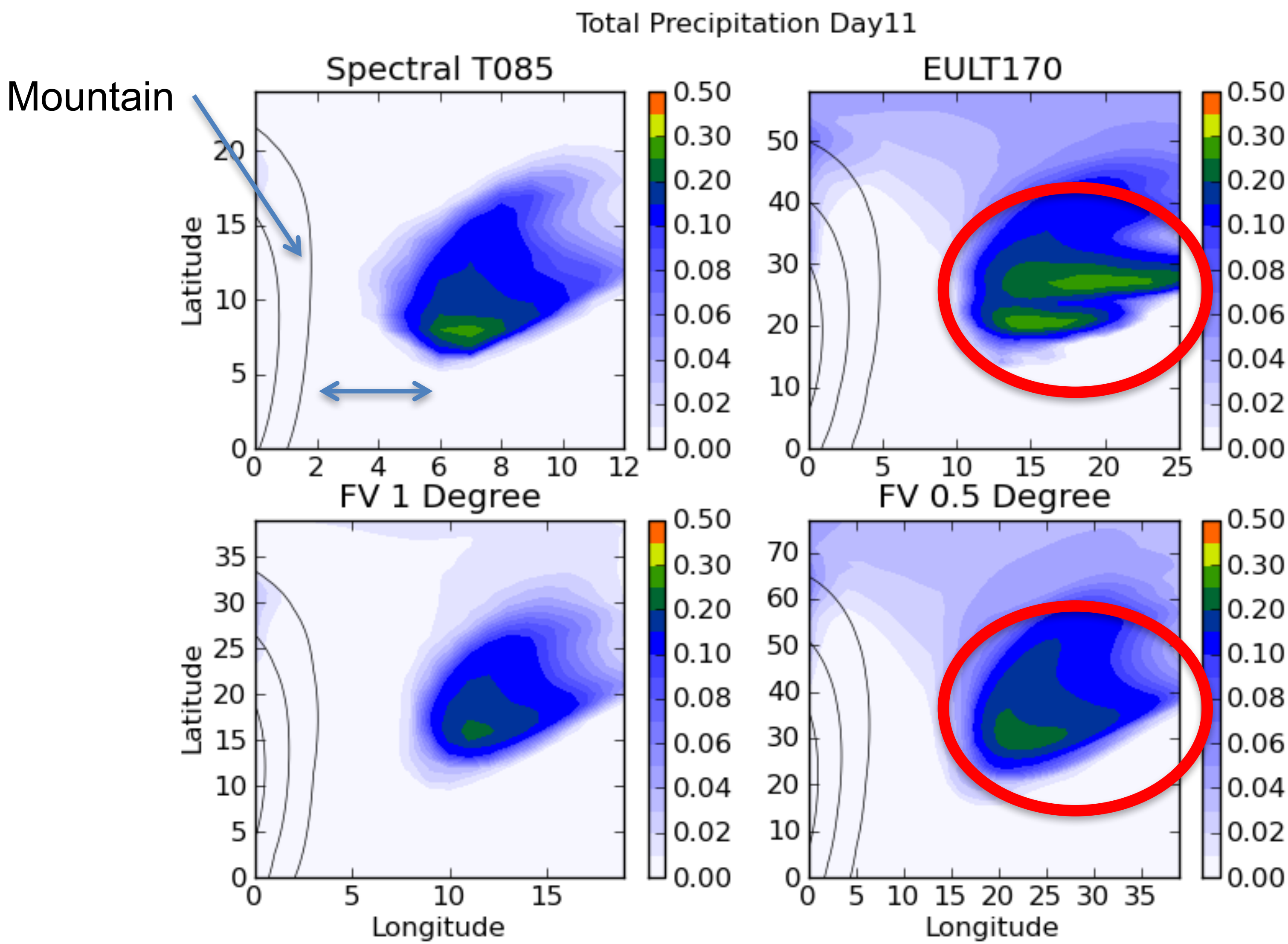
Results show that 48% of nonspectral models and 95% of spectral models have at least one variable with SNO amplitude as large as, or greater than, atmospheric interannual variability.

**Geophysical Research Letters**
Volume 42, Issue 12, pages 5066-5073, 29 JUN 2015 DOI: 10.1002/2015GL063931
http://onlinelibrary.wiley.com/doi/10.1002/2015GL063931/full#grl52998-fig-0001

# Some more references

- Yorgun and Rood (2014) Dynamical cores, precipitation, and simple topography 1 (J Climate)
- Yorgun and Rood (2014) Dynamical cores, precipitation, and simple topography 2 (J Climate)
- Use the Rossby mountain wave test case with simple physics

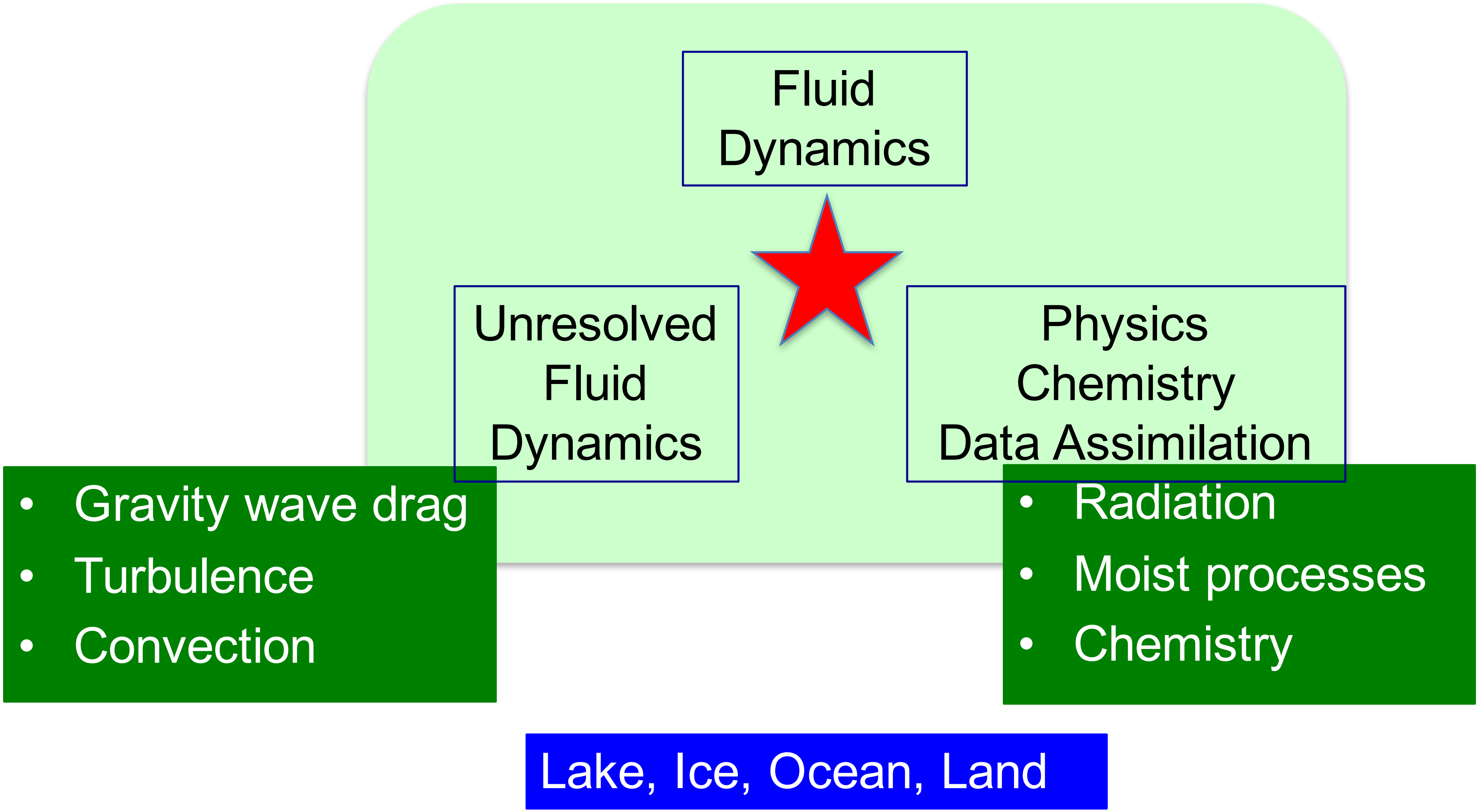
# Precipitation of wave in lee of the mountain (No topography at the surface of the wave.)



# Dynamical Core and Physics

- Dynamical core has impacts on physical variables in models.
- Interface of dynamical core to physics is, *de facto*, a coupling problem to manage information.
- Hence, it requires scientific consideration.

# Importance of Coupling



# Looking forward: Scientific benefits

- We work, for the most part, with models whose dynamics and physics are bundled in packages that reflect the history of their development.
- Deconstruction of these packages into components expose the important spatial and temporal scales and provides scientific and computational advantage.
- Allows formalization of coupling strategies.
- Allows experimentation on how coupling influences system performance.

# Looking forward: Community

- Important developments come from many places.
  - The intellectual contributions for comprehensive systems are spread across institutions and individuals.
- Formalized approaches to coupling facilitate the exchange of ideas and algorithms.

# Looking forward: Unified modeling

- We are looking to build unified weather and climate models, that serve applications from storm forecasts to space-weather forecasts.
  - Configurable physics and configurable components based on applications.
  - Scientific and computational quality is required in coupling.
  - Develop strategies for evaluation coupling and coupled

# Coupling is important

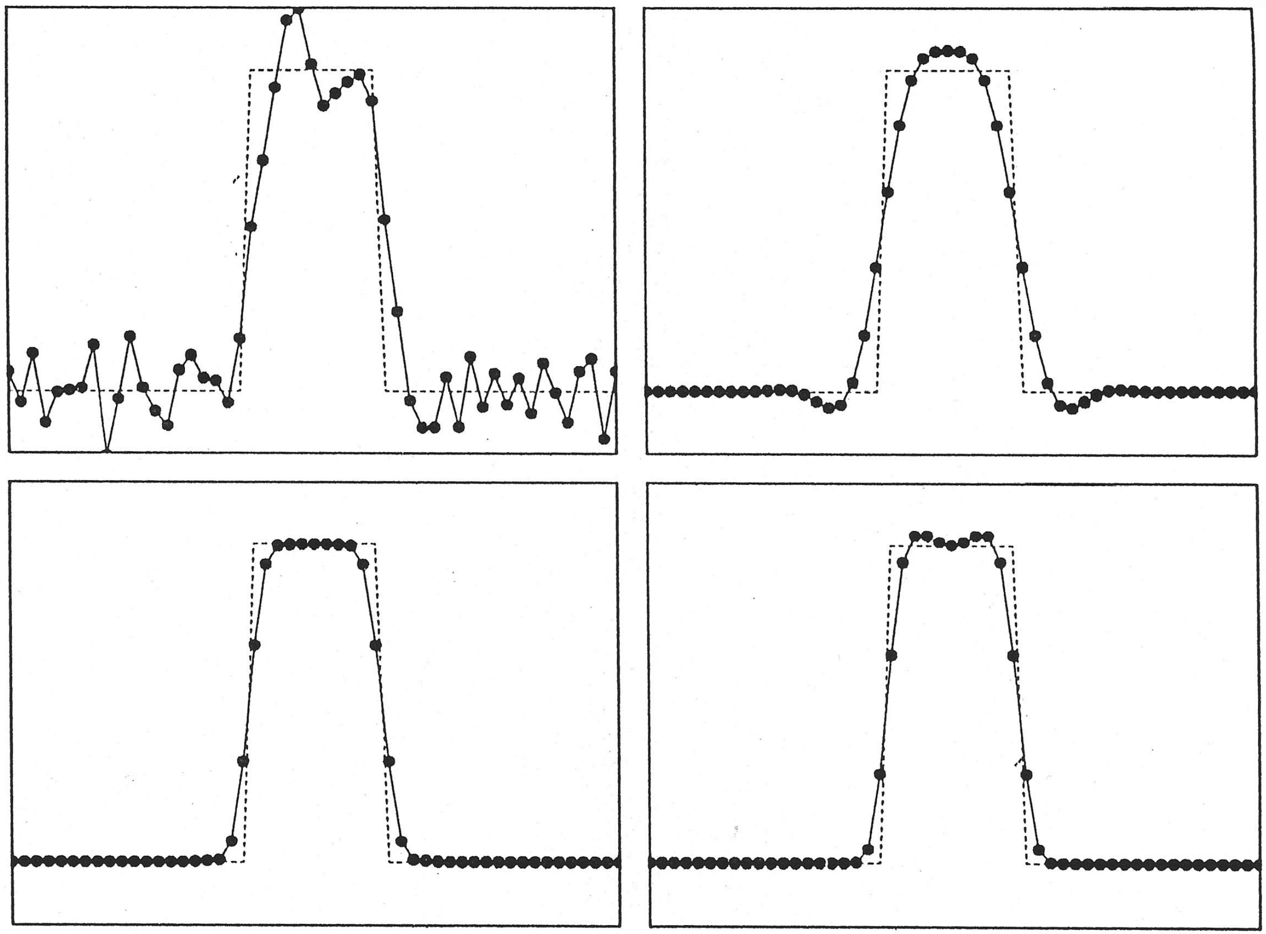
- Scientific
- Computational
- Collaboration
- Unification of applications and systems
- Cost

# Some stuff

- Sharp gradients
  - Fronts – dynamical barriers
  - Pauses --- tropopause, chemical source and sinks, day and night
  - Mountains
  - Coasts

# Background

- Implementation of dycores
  - Stability
  - Conservation
  - Diffusion and Dispersion
  - Computational viability
  - Consistency ---
    - for example, geostrophy
    - Vertical velocity
    - Conservation of moments
    - Correlative information



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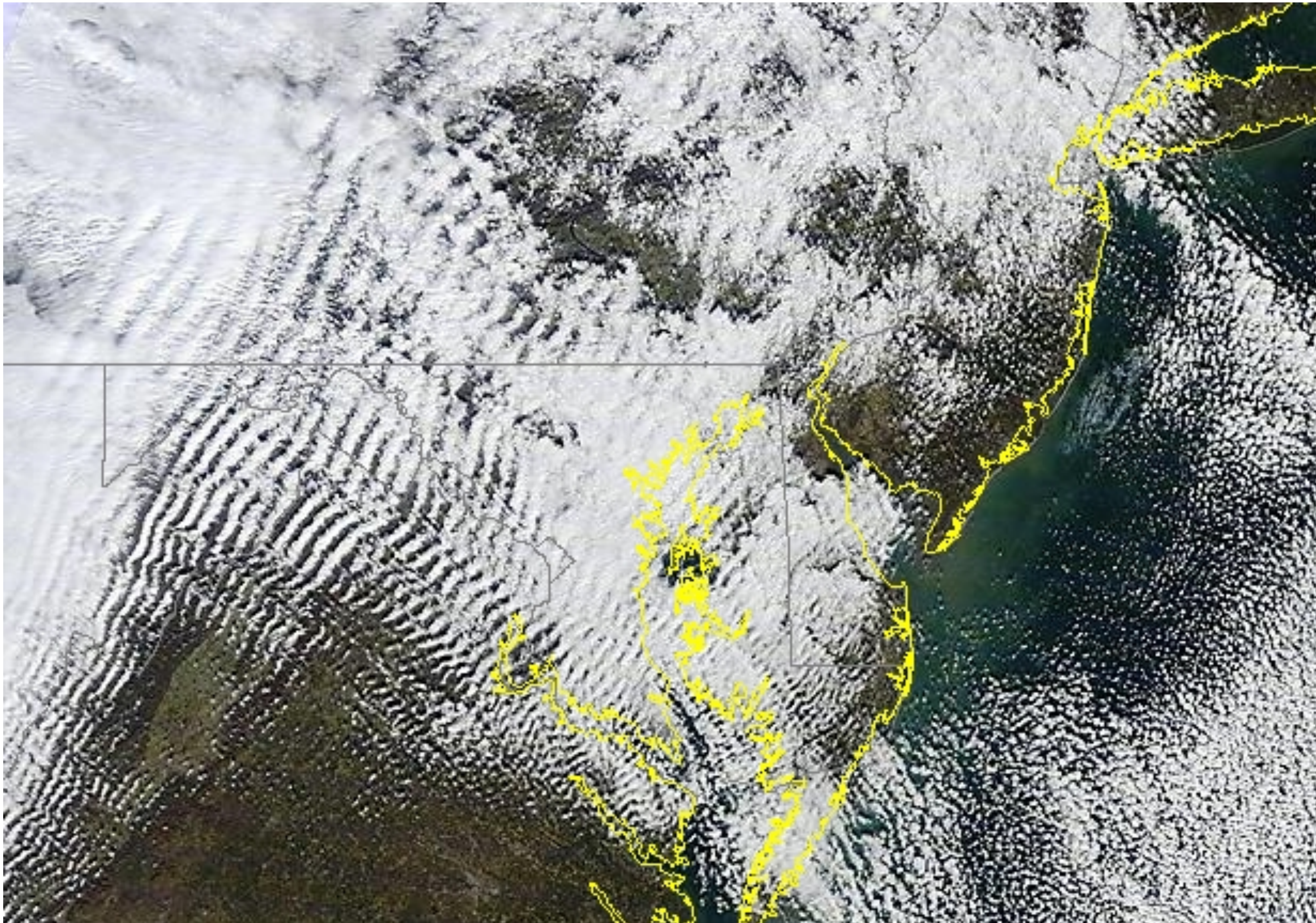
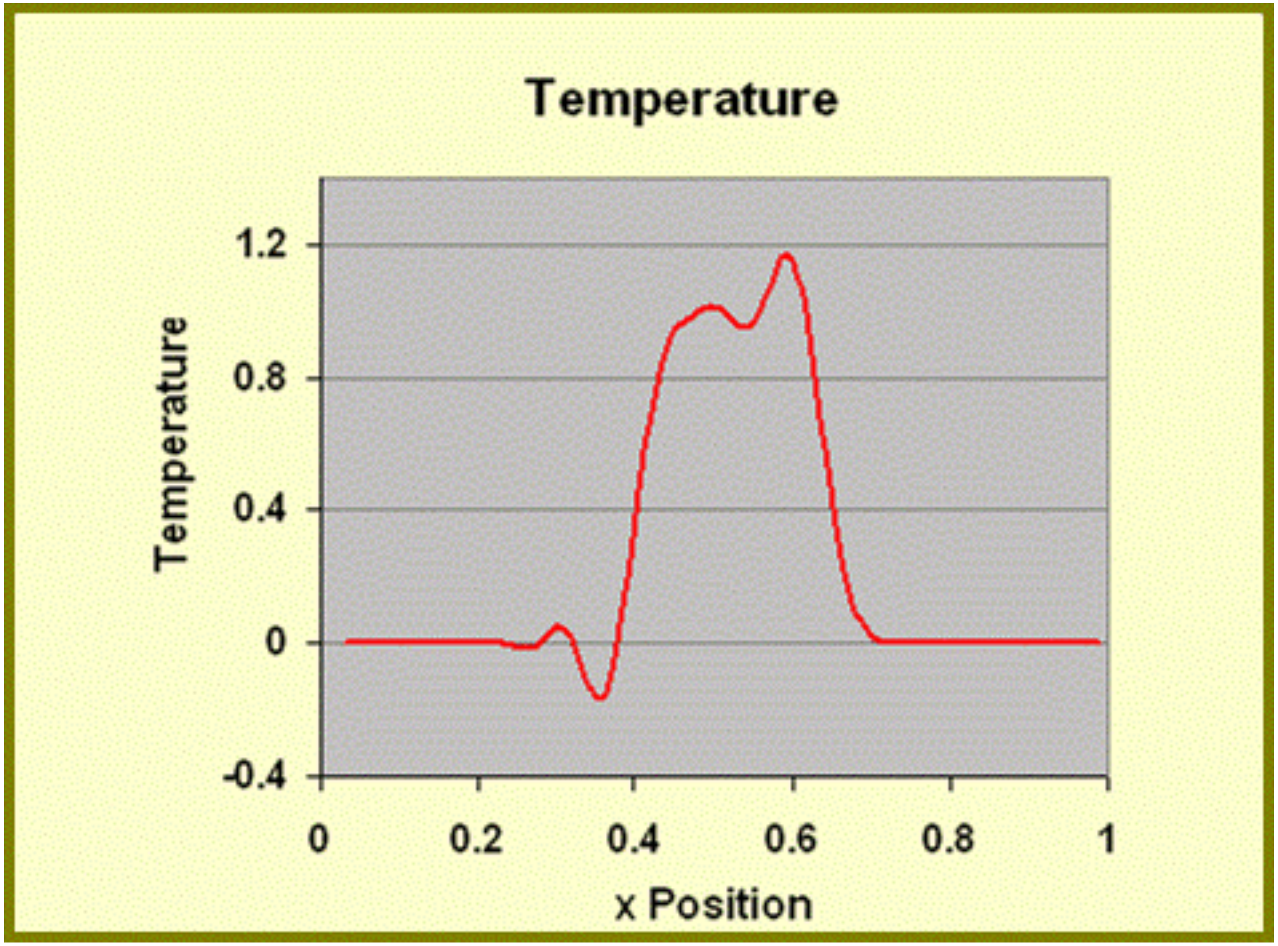


# Let’s take this nice figure

Advection of a Passive Scalar in One and Two Dimensions




From University of Virginia: Spreadsheets for Heat Transfer