An introduction to global modeling

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2nd WCRP Summer School on Climate Model Development: Scale aware parameterization for representing sub-grid scale processes
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São Paulo, Brazil.

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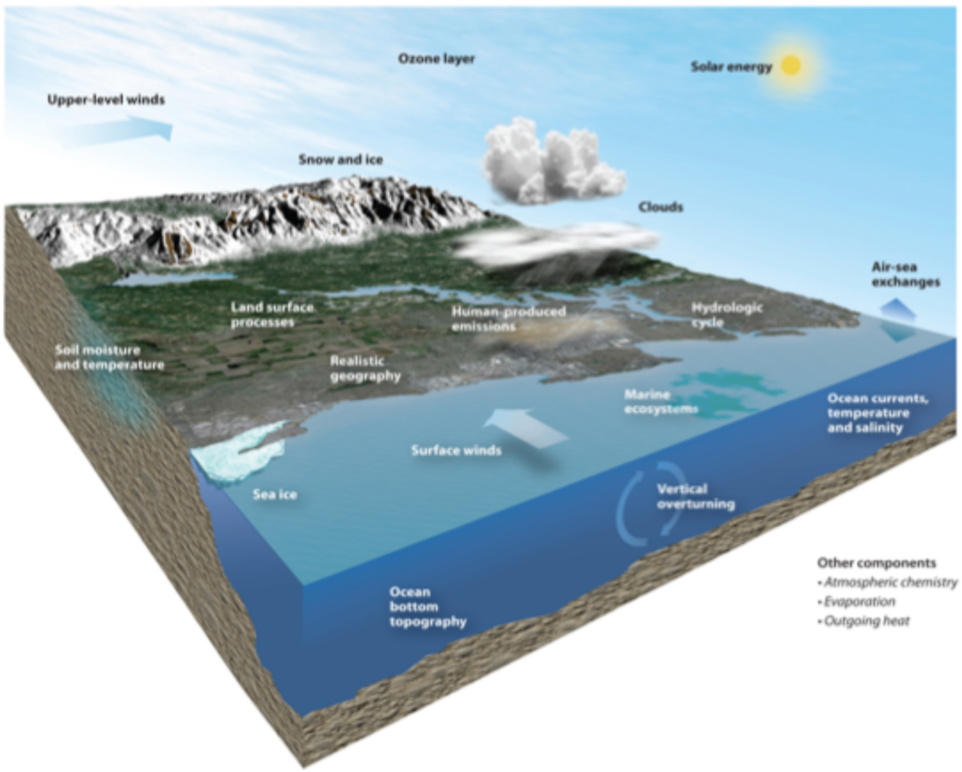
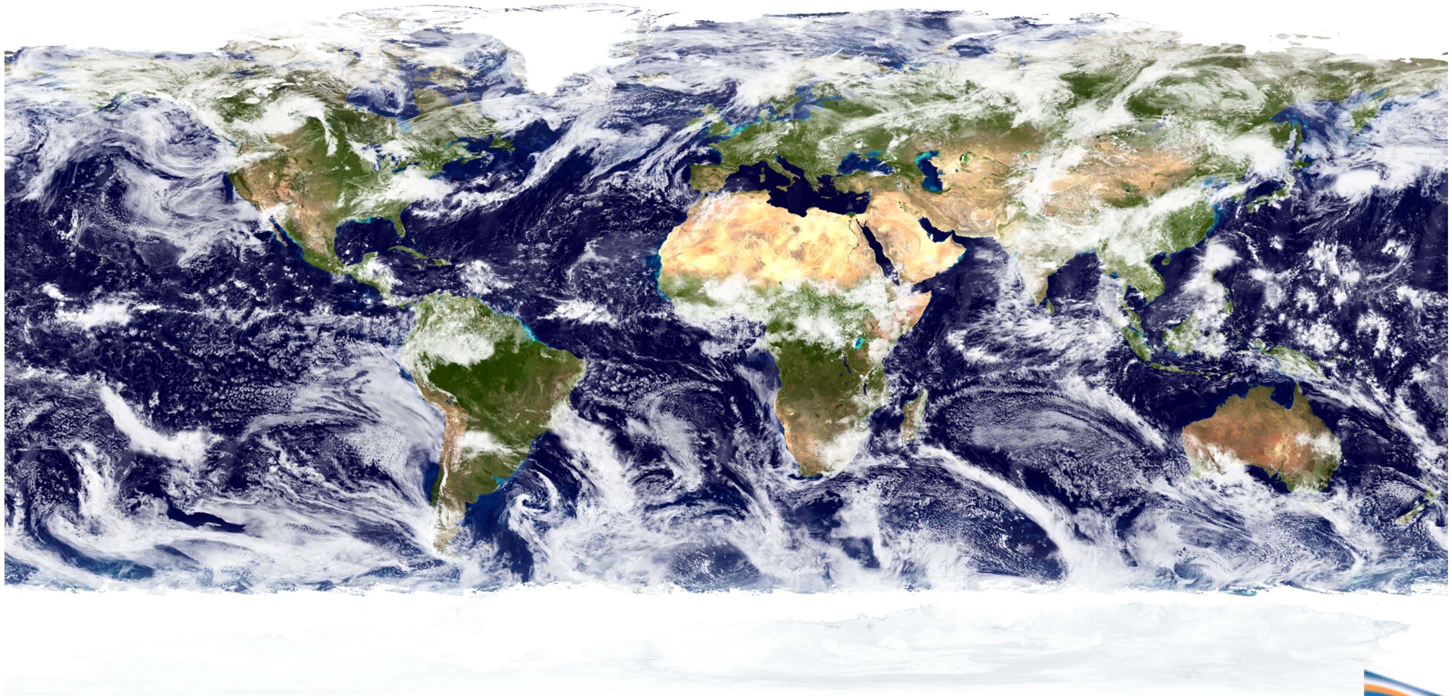
NCAR's CESM
(Community Earth System Model)



Community Atmosphere Model (CAM)

Domain

This talk: Some Basic Dynamics Relevant to the Design of Global Atmospheric Models



Source: NASA Earth Observatory

Multi-scale nature of atmospheric dynamics

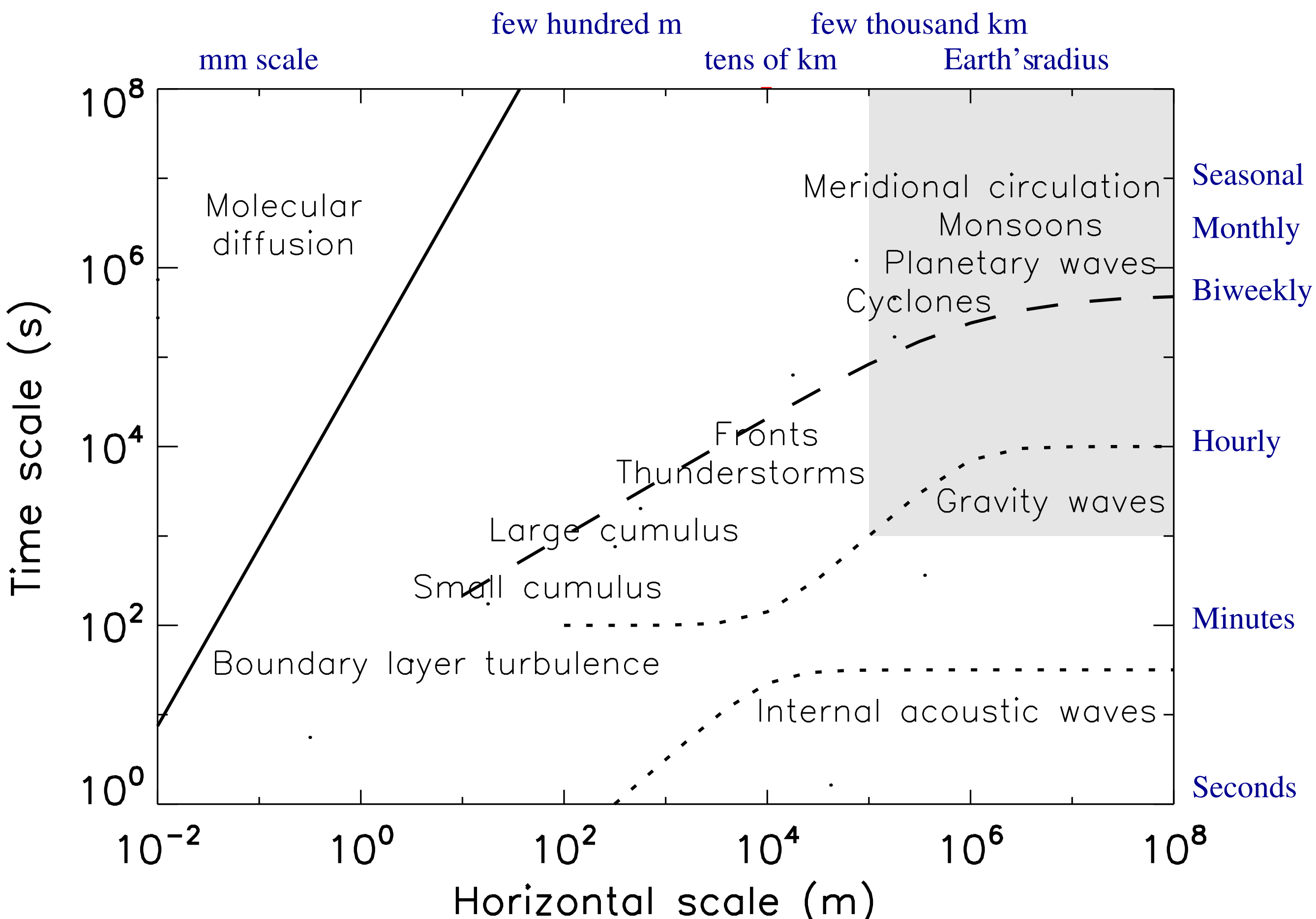
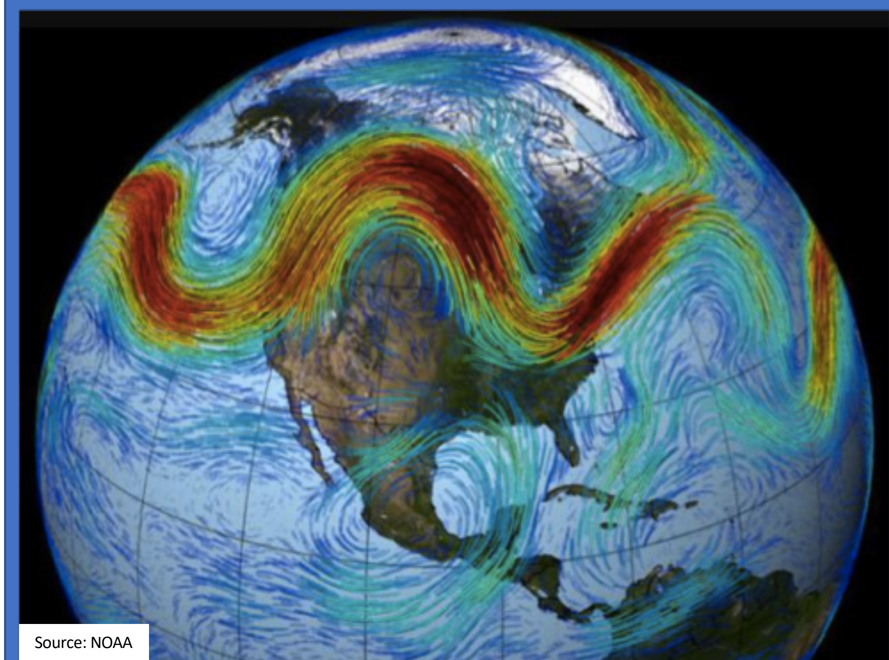
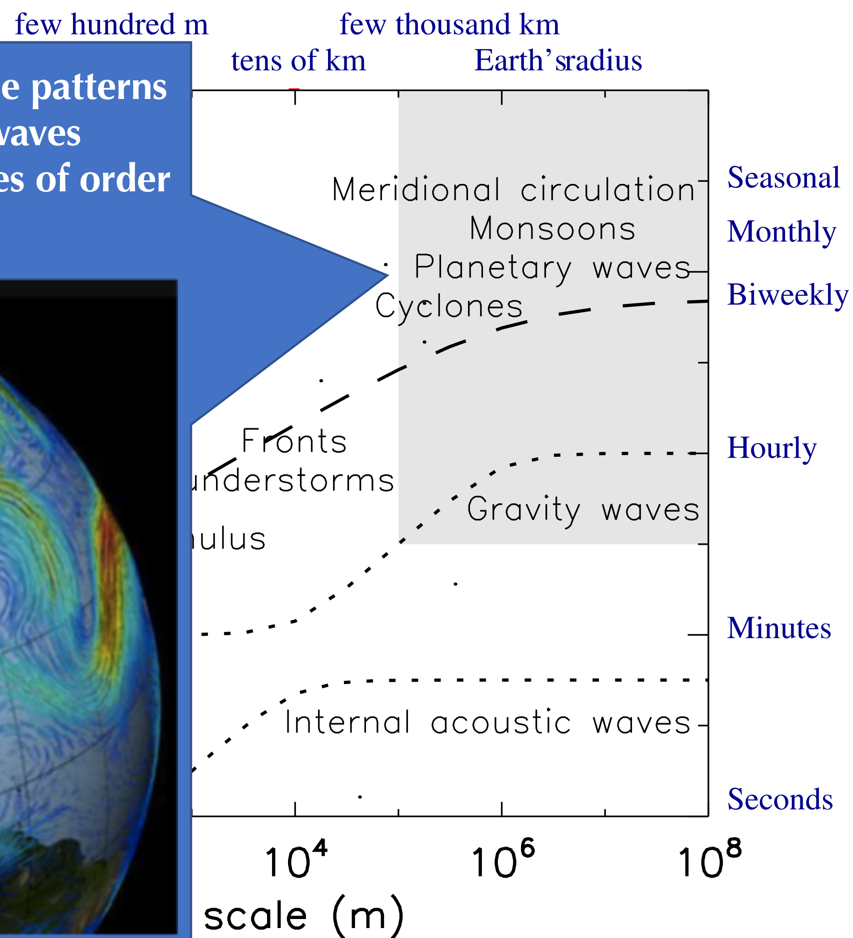


Figure from Thuburn (2011)

Multi-scale nature of atmospheric dynamics

Undulations in the jet stream and pressure patterns associated with the largest scale Rossby waves (called planetary waves) have length scales of order 10^4 km and seasonal time-scale.





Figure

Multi-scale nature of atmospheric dynamics

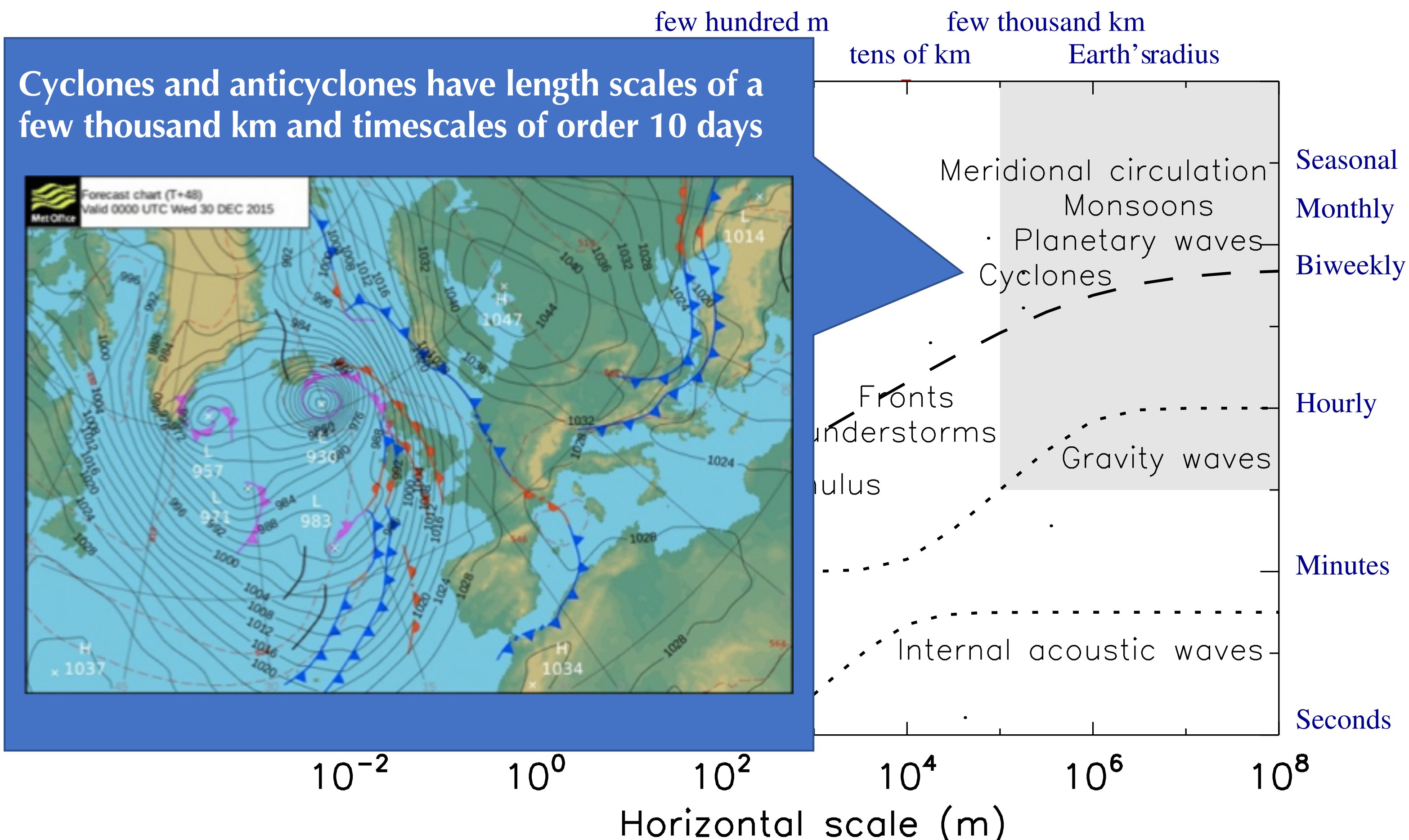
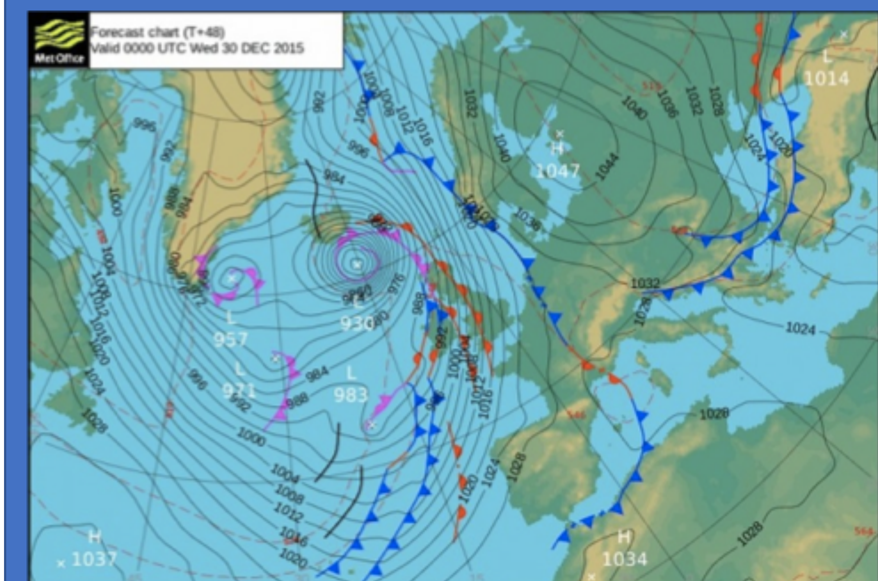


Figure from Thuburn (2011)

Multi-scale nature of atmospheric dynamics

The transition zones between relatively warm and cool air masses can collapse in scale to form fronts with widths a few tens of km.



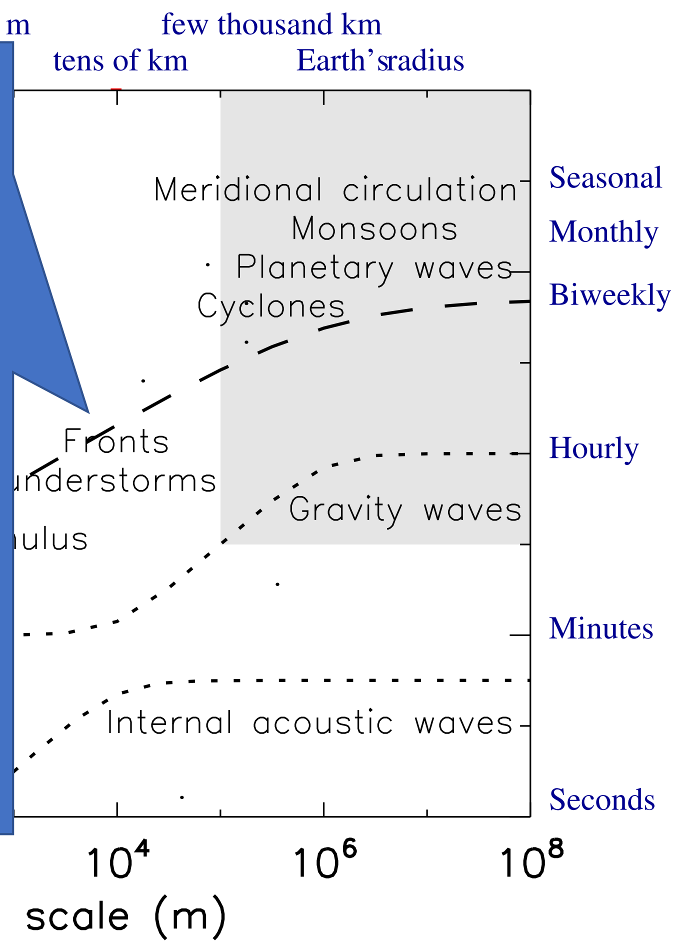


Figure from Thuburn (2011)

Convection can be organized on a huge range of different scales, from the tropical intraseasonal oscillation on scales of thousands of km and a timescale of months, through supercell complexes and squall lines of order 10 km across with lifetimes of several hours, down to individual small cumulus clouds on scales of a few hundred meters and a few minutes.


https://popperfont.files.wordpress.com/2014/09/clouds-5.jpg

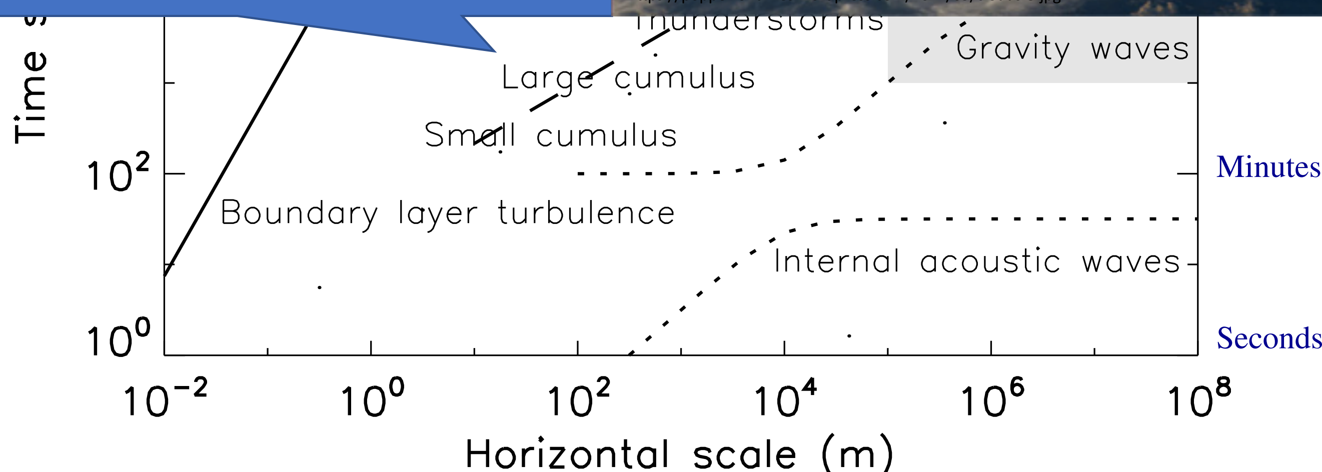


Figure from Thuburn (2011)

Multi-scale nature of atmospheric dynamics

Small cumulus clouds are formed when the turbulent eddies in the boundary layer lift and cool air far enough for condensation to occur.

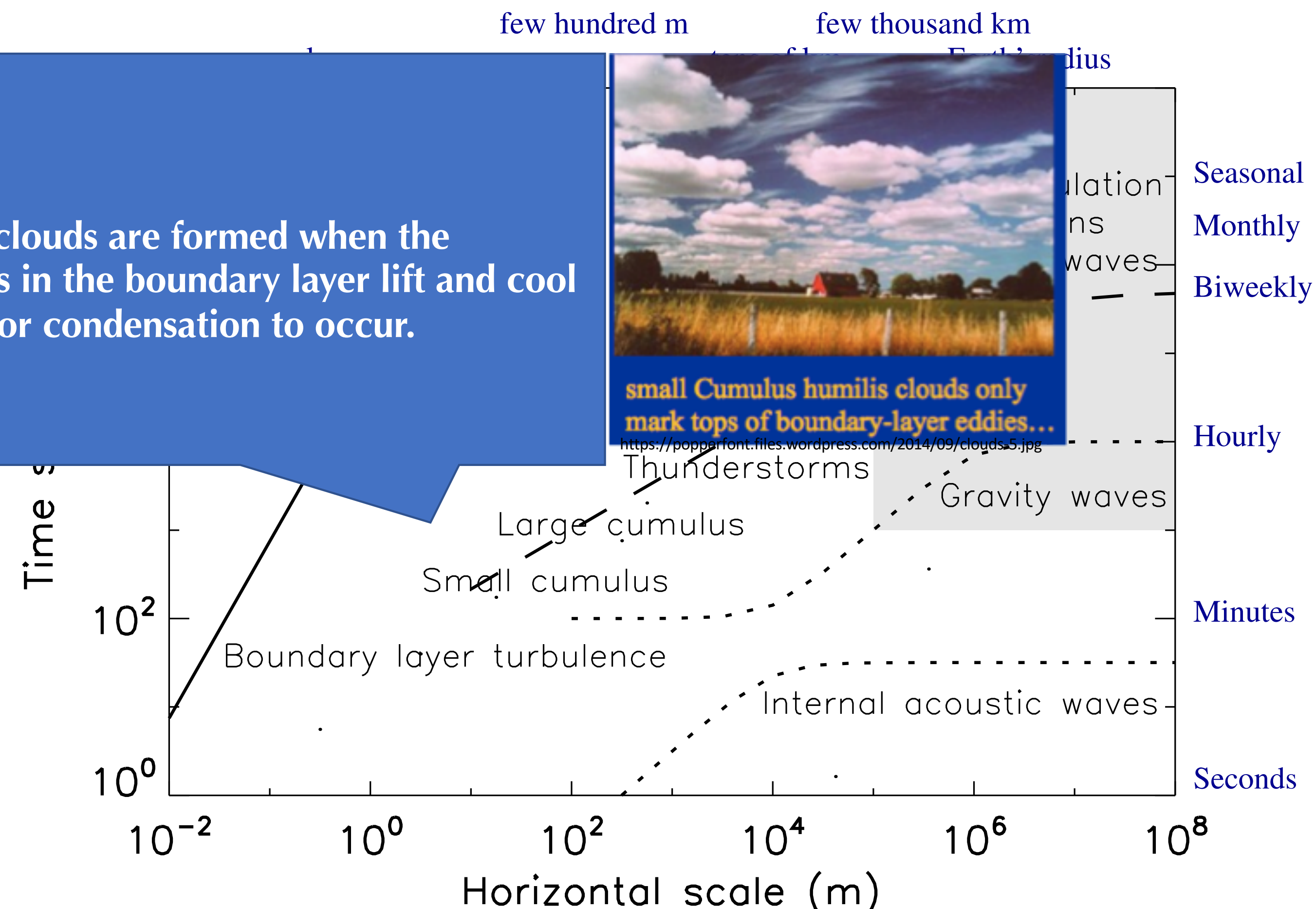


Figure from Thuburn (2011)

Multi-scale nature of atmospheric dynamics

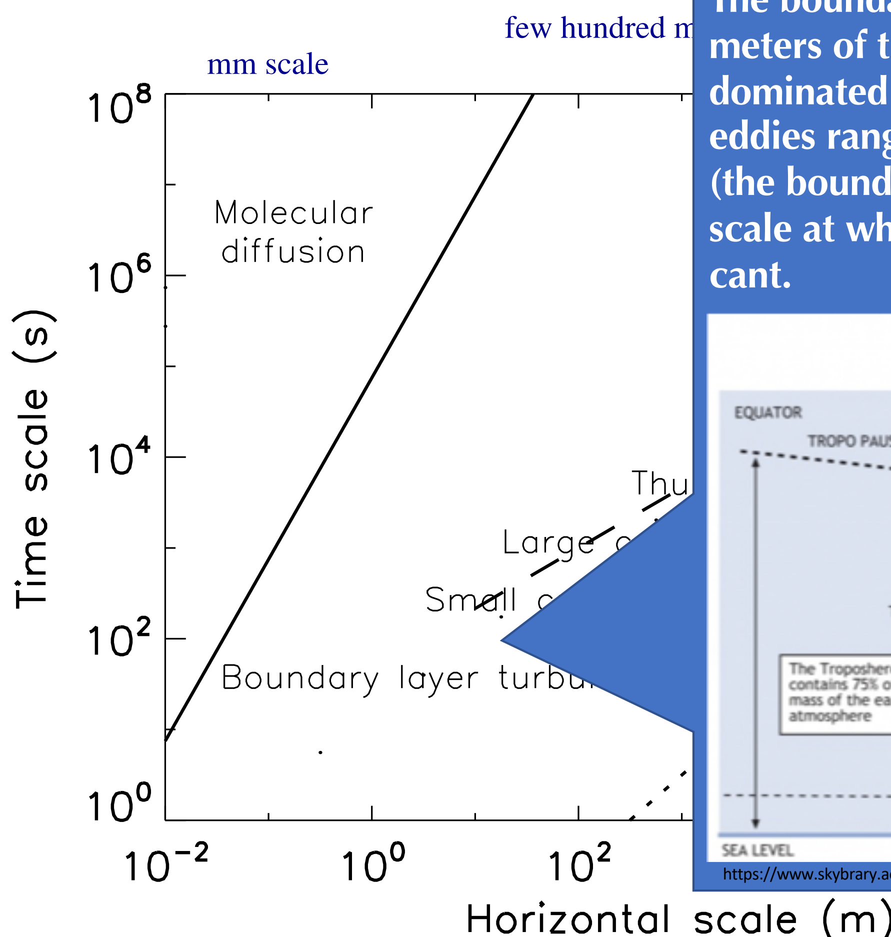
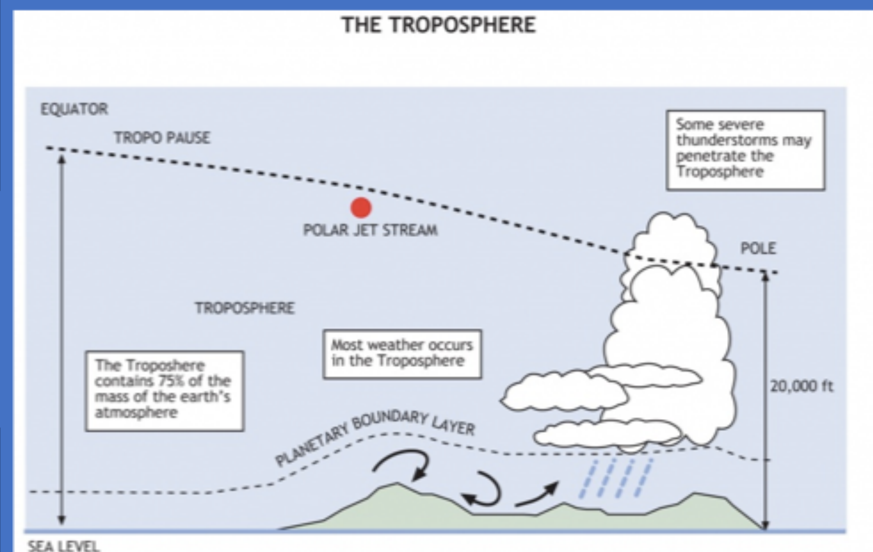


Figure from Thuburn (2011)

The boundary layer is the lowest few hundred meters of the atmosphere, where the dynamics is dominated by turbulent transports. The turbulent eddies range in scale from a few hundred meters (the boundary layer depth) down to the millimeter scale at which molecular diffusion becomes significant.



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Multi-scale nature of atmospheric dynamics

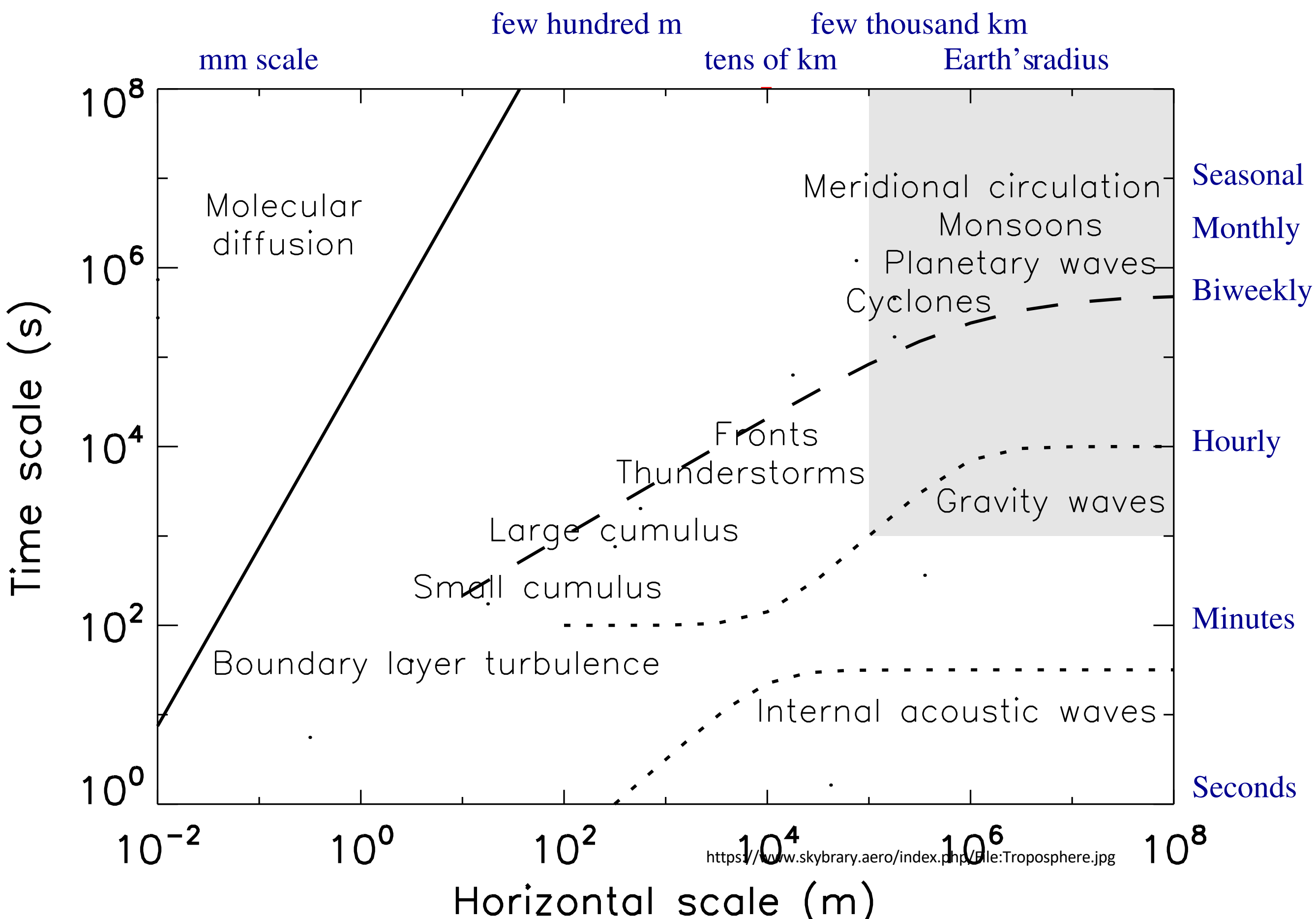
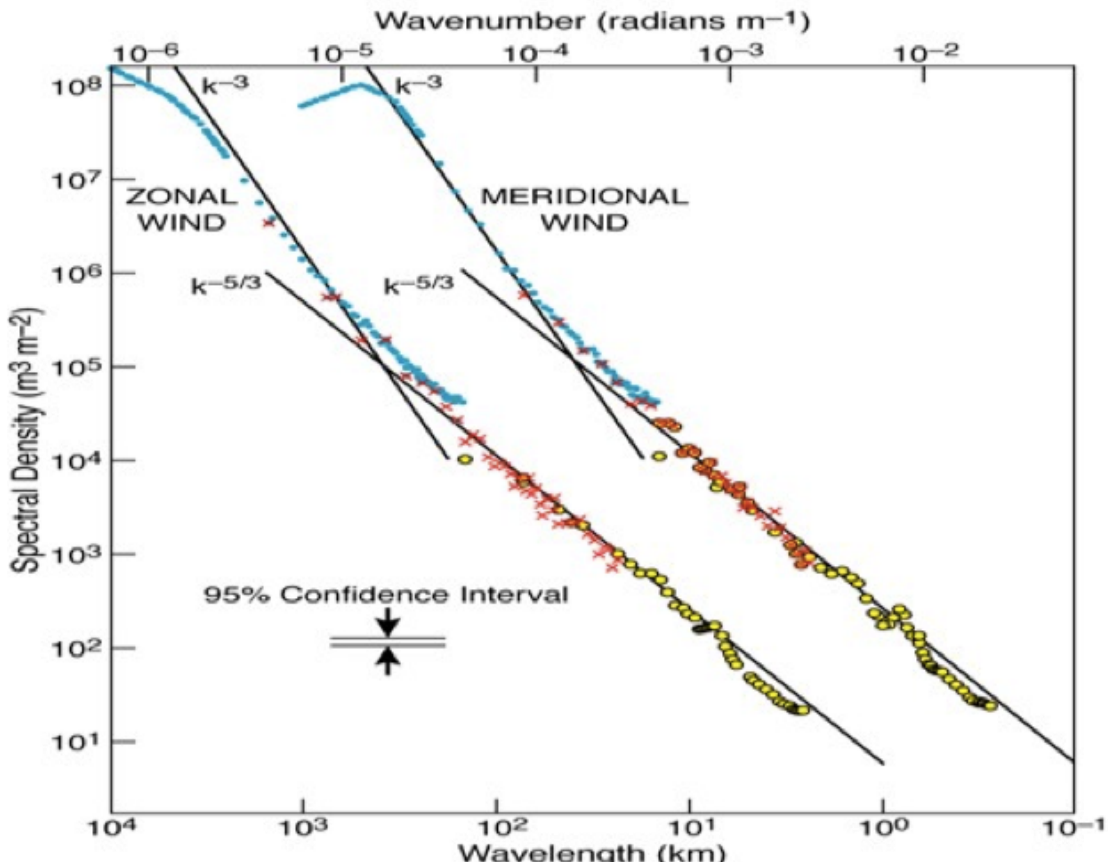


Figure from Thuburn (2011)

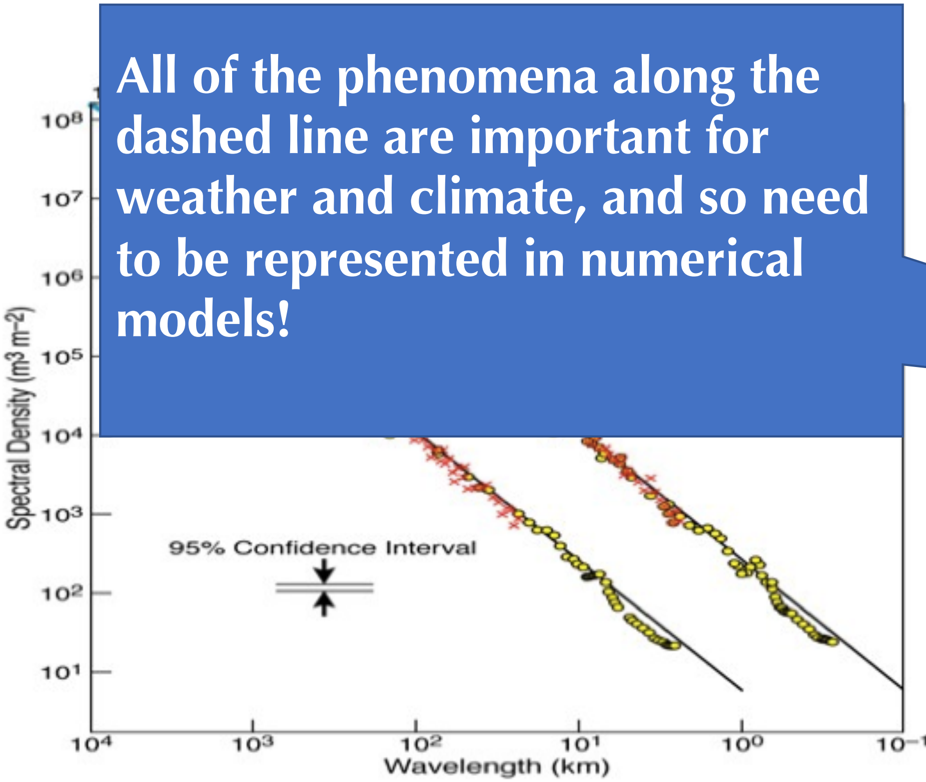
The atmospheric spectrum of horizontal kinetic energy is observed to have a slope very close to k^{-3} on large scales and $k^{-5/3}$ on small scales, where k is the horizontal wavenumber, with a gradual transition between the two at scales of a few 100 km

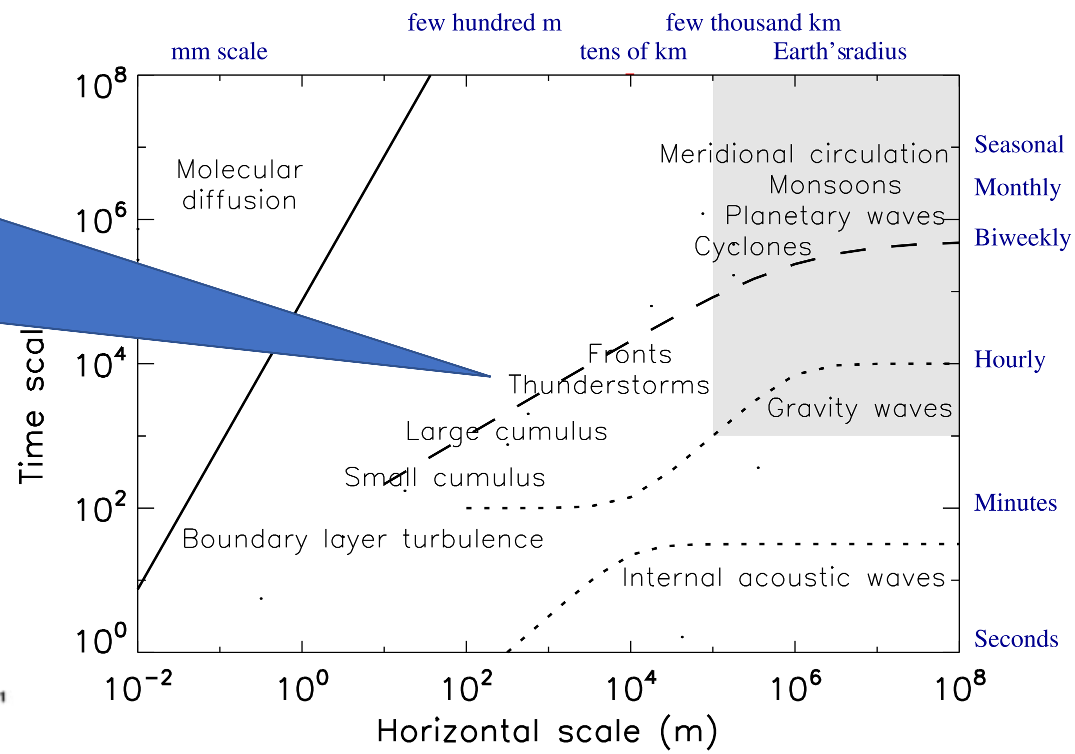


Nastrom & Gage (1985) Spectrum

Dashed line in right Fig. is consistent with the observed spectrum, re-expressed in terms of length and time scales. The dynamically important phenomena (mentioned before) are those that dominate the atmospheric energy spectrum, and all lie close to this dashed line.

All of the phenomena along the dashed line are important for weather and climate, and so need to be represented in numerical models!





Nastrom & Gage (1985) Spectrum

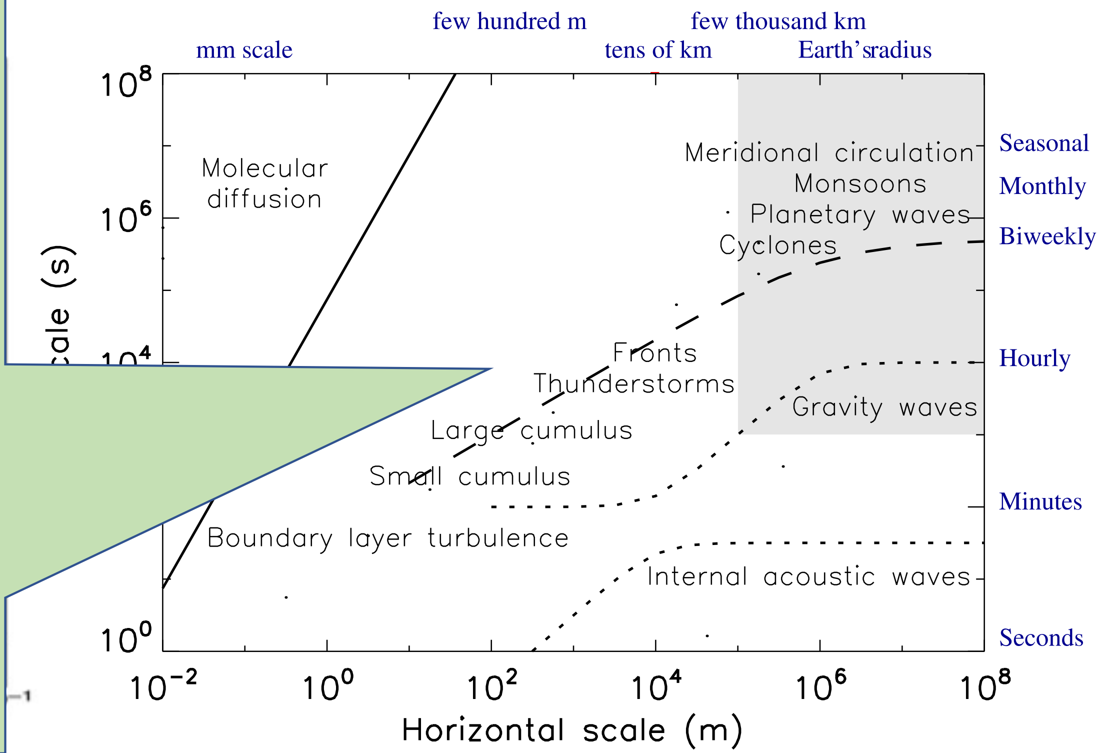
Dashed line in right Fig. is consistent with the observed spectrum, re-expressed in terms of length and time scales.
Th ... re) are those that dominate the atmospheric energy spectrum,
an

Note: Important phenomena occur at all scales – there is no significant spectral gap.

Moreover, there are strong interactions between the phenomena at different scales, and these interactions need to be represented.

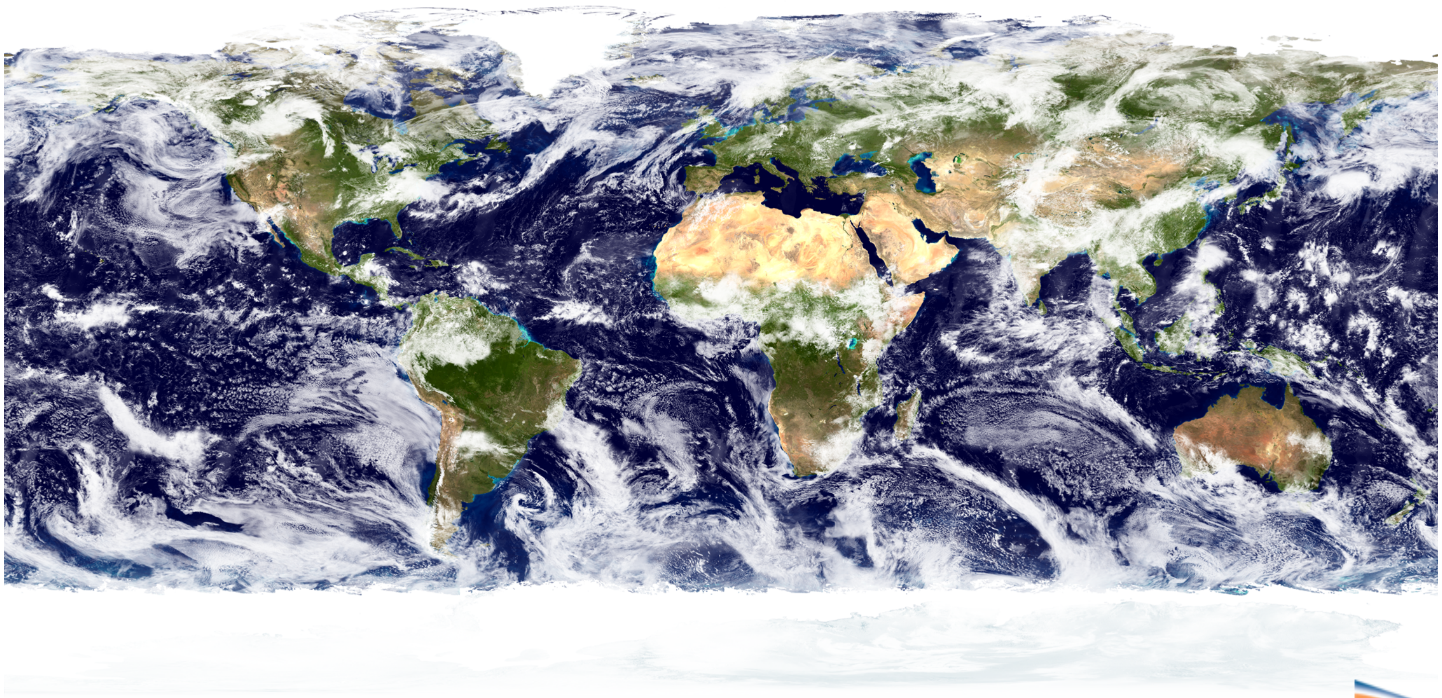
THIS MAKES NUMERICAL MODELING OF THE ATMOSPHERE VERY CHALLENG!

Let me elaborate …



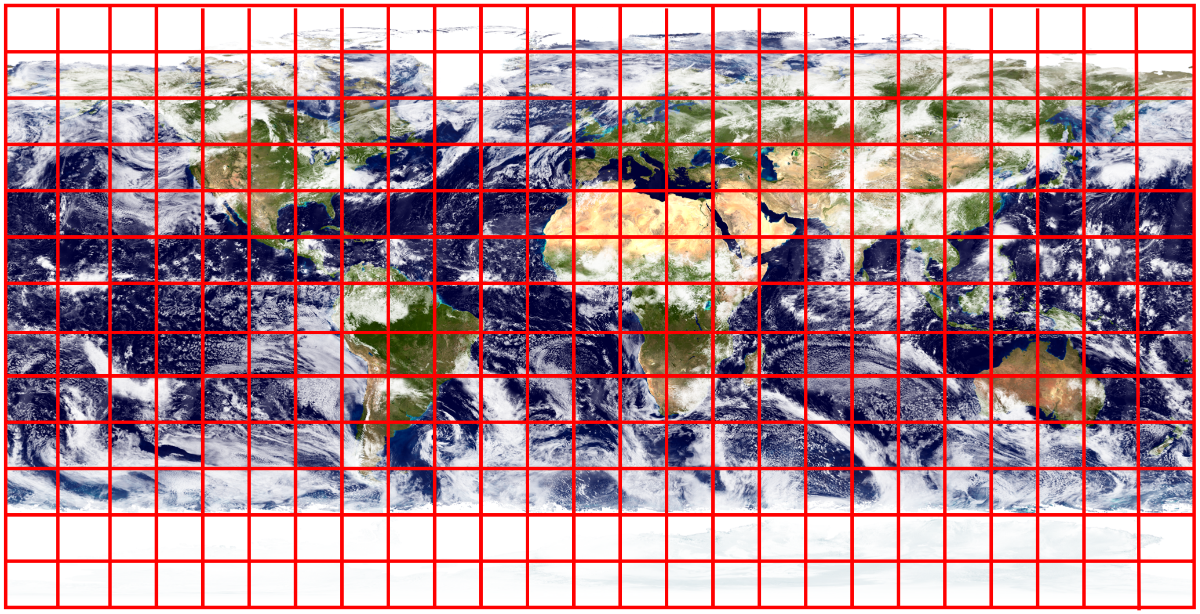
Nastrom & Gage (1985) Spectrum

Domain



Source: NASA Earth Observatory

Horizontal computational space



- Red lines: regular latitude-longitude grid
- Grid-cell size defines the smallest scale that can be resolved ($\neq$ **effective resolution!**)
- Many important processes taking place sub-grid-scale that must be parameterized
- Loosely speaking, the parameterizations compute grid-cell average tendencies due to sub-grid-scale processes in terms of the (resolved scale) atmospheric state
- In modeling jargon parameterizations are also referred to as *physics* (what is unphysical about resolved scale dynamics?)

Model code

Parameterization suite

- Moist processes: deep convection, shallow convection, large-scale condensation
- Radiation and Clouds: cloud microphysics, precipitation processes, radiation
- Turbulent mixing: planetary boundary layer parameterization, vertical diffusion, gravity wave drag

2.5 Equations of motion

The $\eta^{(d)}$-coordinate adiabatic and frictionless atmospheric primitive equations assuming floating Lagrangian vertical coordinates [*Starr*, 1945; *Lin*, 2004] can be written as

$$\frac{\partial \vec{v}}{\partial t} + (\zeta + f)\,\hat{\vec{k}} \times \vec{v} + \nabla_{\eta^{(d)}}\left(\frac{1}{2}\vec{v}^2 + \Phi\right) + \frac{1}{\rho}\nabla_{\eta^{(d)}} p = 0,$$

$$\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla_{\eta^{(d)}} T - \frac{1}{c_p \rho}\omega = 0,$$

$$\frac{\partial}{\partial t}\left(\frac{\partial \mathcal{P}^{(d)}}{\partial \eta^{(d)}} m^{(\ell)}\right) + \nabla_{\eta^{(d)}} \cdot \left(\frac{\partial \mathcal{P}^{(d)}}{\partial \eta^{(d)}} m^{(\ell)} \vec{v}\right) = 0, \quad \ell = \text{‘}d\text{‘}, \text{‘}v\text{‘}, \text{‘}cl\text{‘}, \text{‘}ci\text{‘},$$

‘Resolved’ dynamics

‘Roughly speaking, the **dynamical core** solves the governing fluid and thermodynamic equations on resolved scales, while the parameterizations represent sub-grid-scale processes and other processes not included in the dynamical core such as radiative transfer.’ - Thuburn (2008)

Model code

Parameterization suite

- Moist processes: deep convection, shallow convection, large-scale condensation
- Radiation and Clouds: cloud microphysics, precipitation processes, radiation
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But the transition from resolved to unresolved dynamics-processes is a gradual transition due to numerical diffusion near the grid scale …

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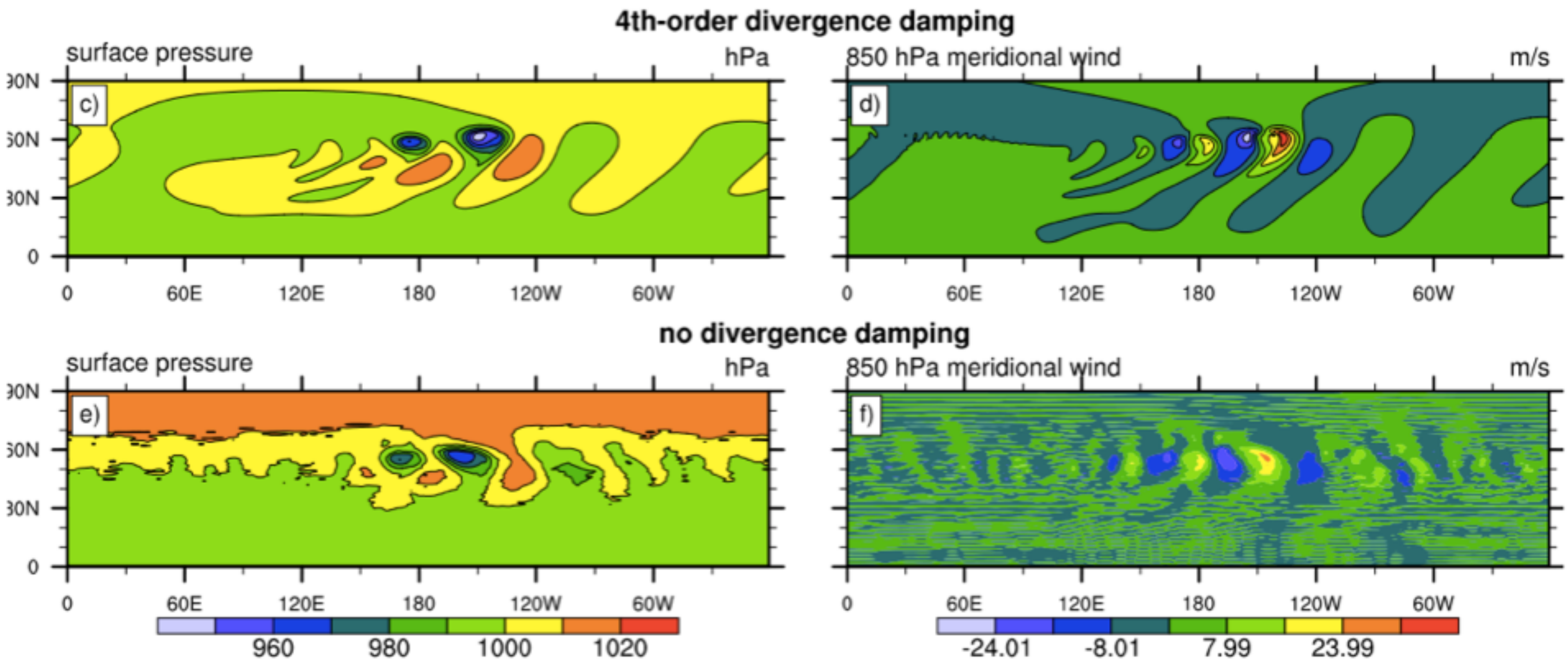
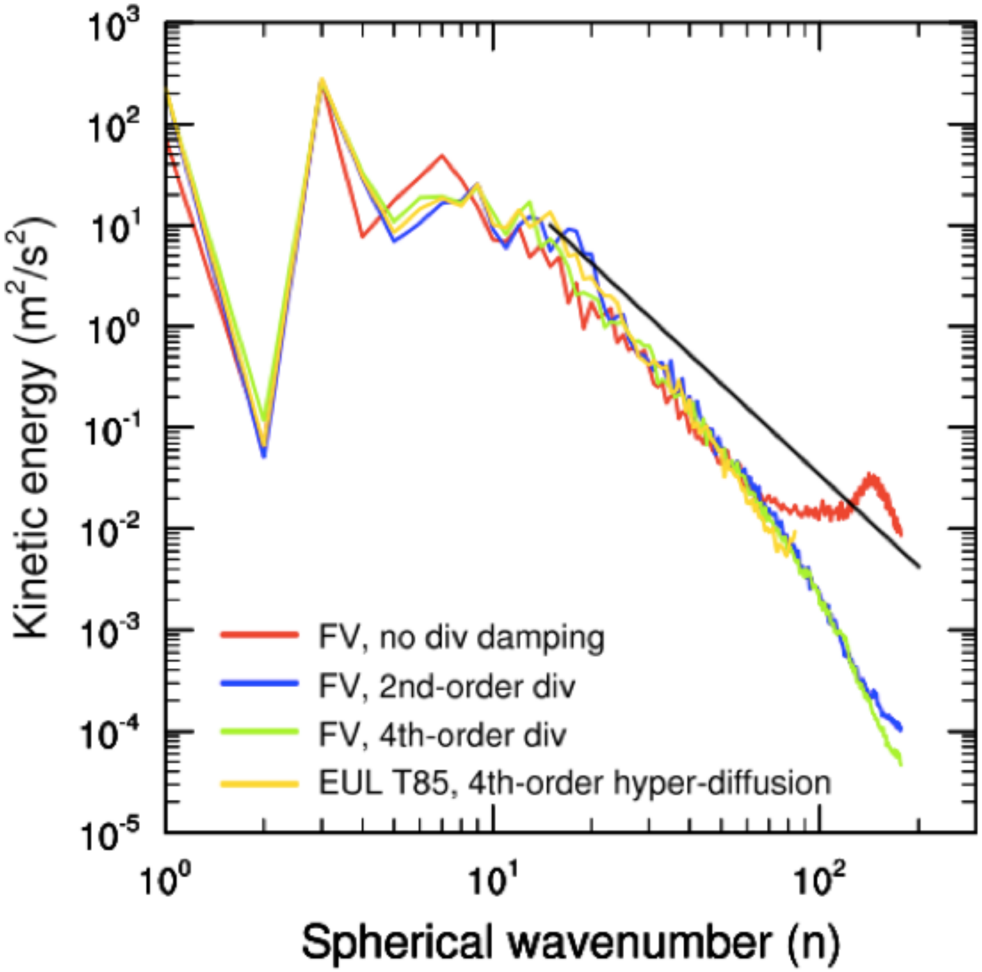


Figure from Jablonowski and Williamson (2011)



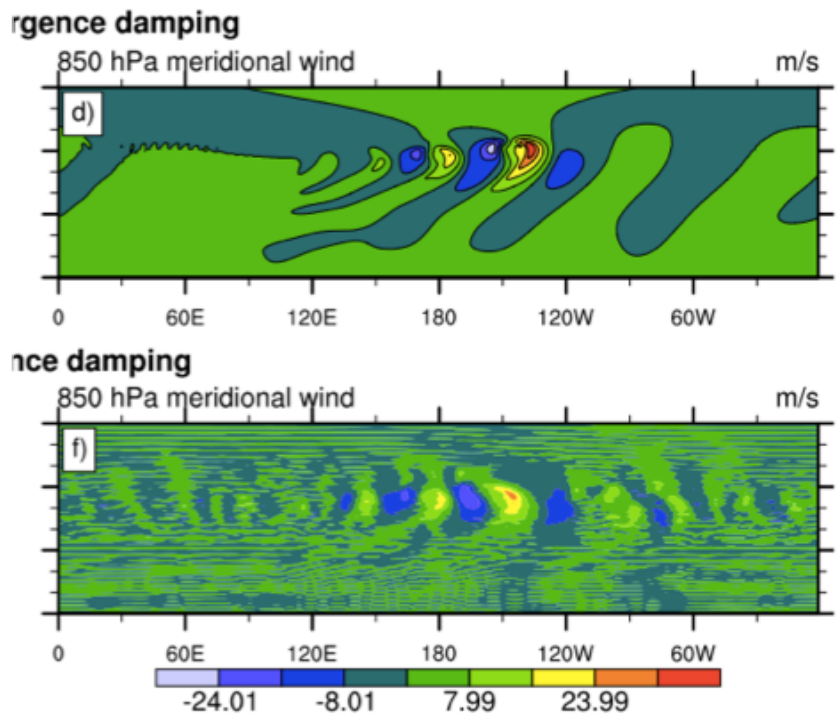
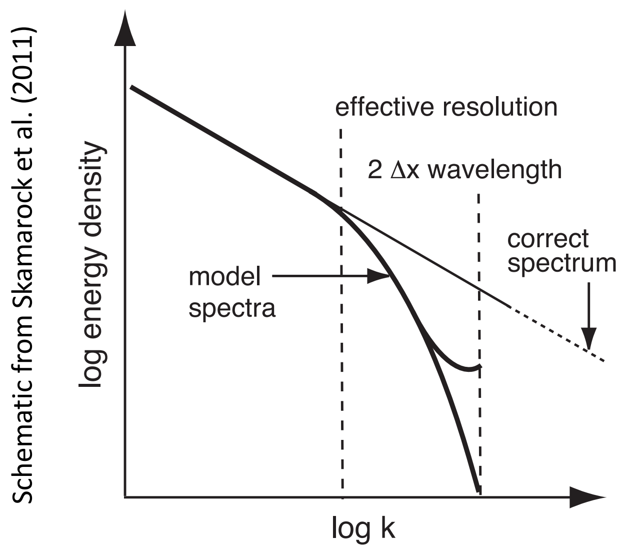


Figure from Jablonowski and Williamson (2011)

Effective resolution: smallest scale (highest wave-number $k = k_{eff}$) that model can accurately represent

- k_{eff} can be assessed analytically for linearized equations (Von Neumann analysis)
- In a full model one can assess k_{eff} using total kinetic energy spectra (TKE) of, e.g., horizontal wind $\vec{v}$ (see Figure below)

Effective resolution is typically 4-10 grid-lengths depending on numerical method!



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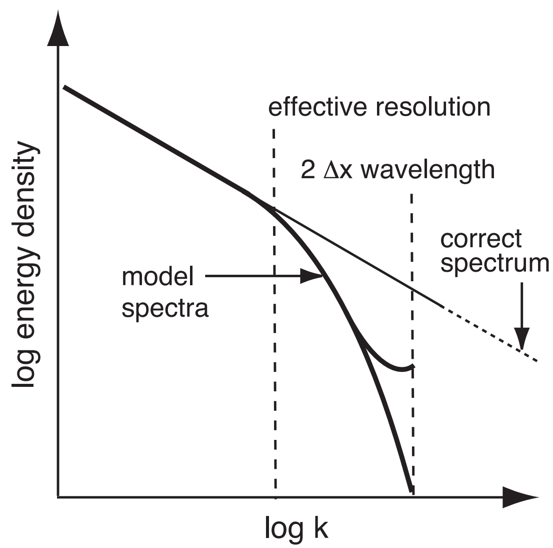


Schematic from Skamarock et al. (2011)

Be careful if you analyze grid-scale quantities; for example, precipitation at the grid scale

Divergence damping and extreme precip

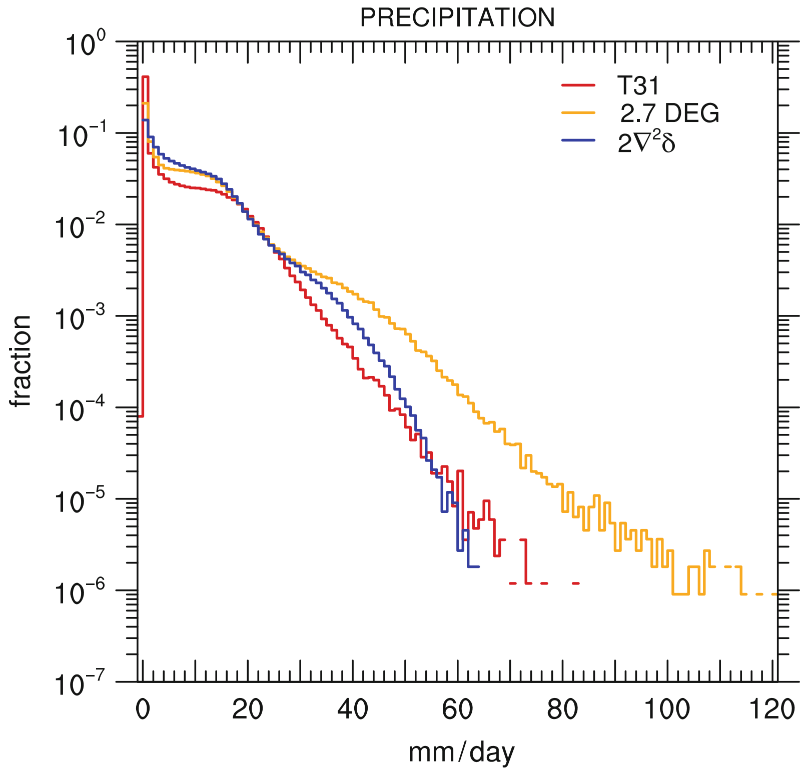


Fig. 13.8 Fraction of the time the tropical precipitation is in 1 mm day^{-1} bins ranging from 0 to 120 mm day^{-1}, calculated from 6-h averages for all grid points between $\pm 10°$. This frequency distribution is an annual average. The aqua-planet simulations are (*blue*, *yellow*) CAM FV at the coarse *lat* $\times$ *lon* resolution 2.7° $\times$ 3.3° L26 and (*red*) CAM EUL at the resolution T31L26 (with time step $\Delta t = 1{,}800$ s). *Yellow FV curve*: standard second-order divergence damping (13.70). *Blue curve*: FV simulation with a doubled coefficient. The figure is courtesy of Peter H. Lauritzen,

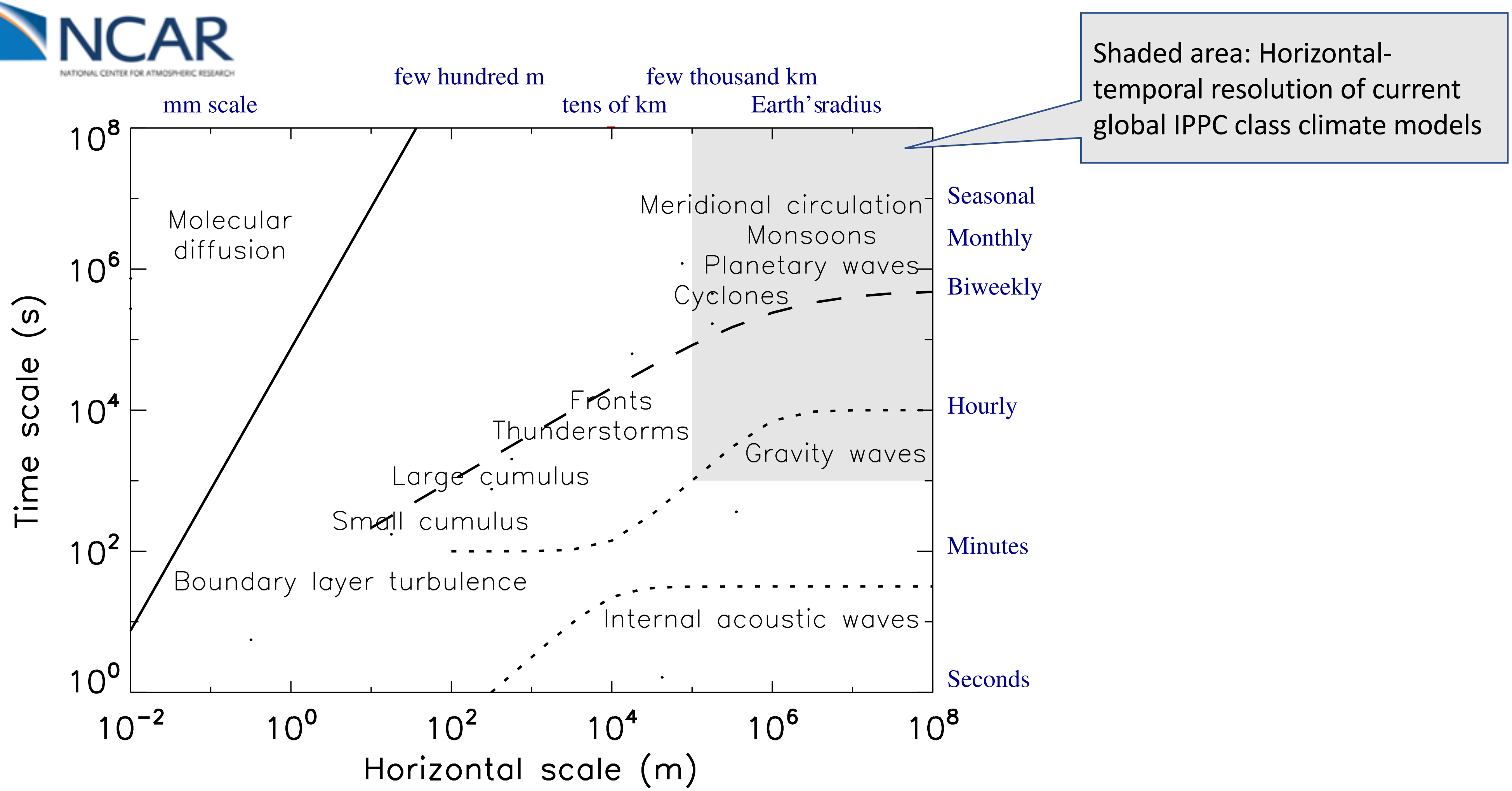
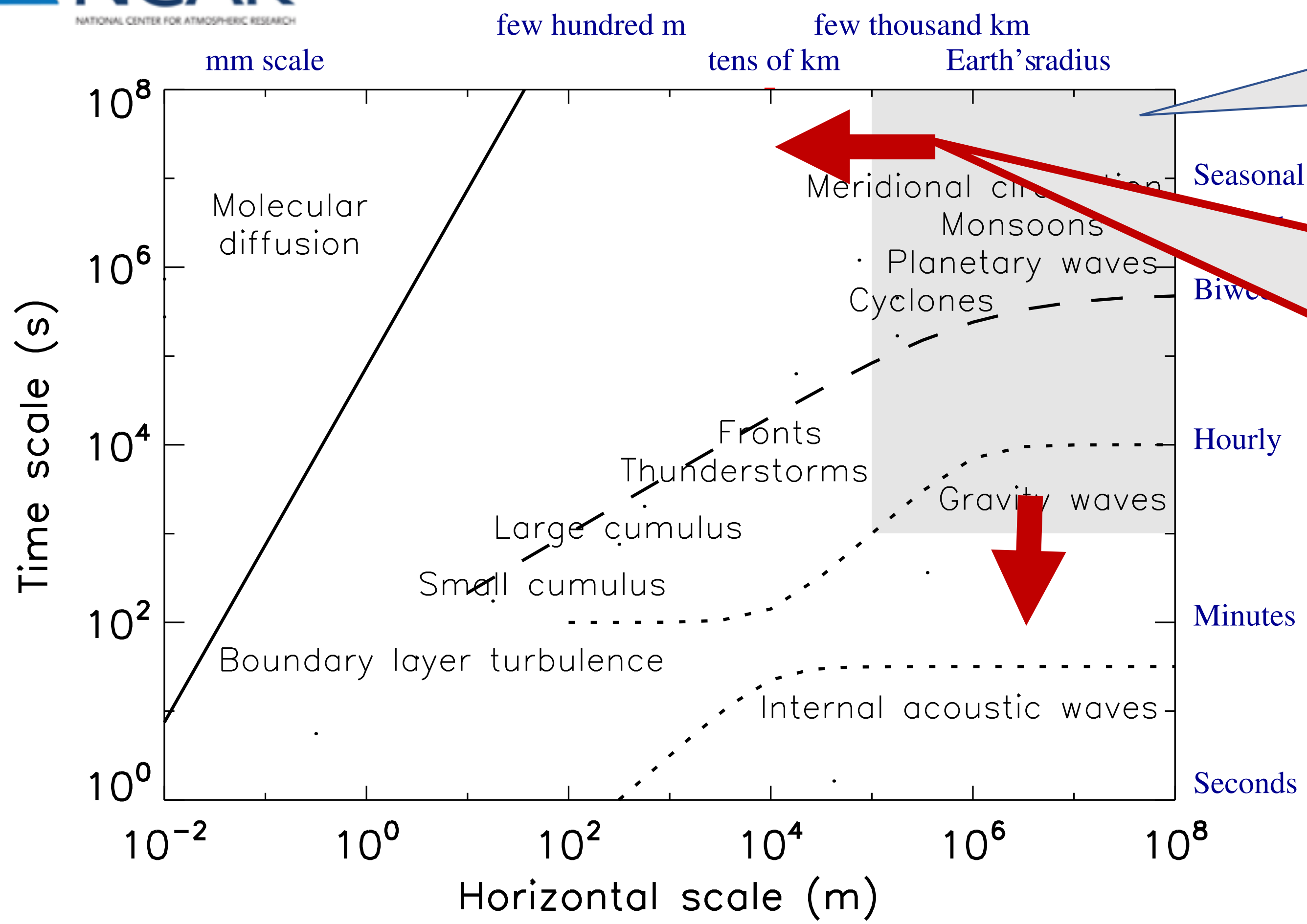


Figure from Thuburn (2011)



Shaded area: Horizontal-temporal resolution of current global IPPC class climate models

With increases in horizontal and vertical resolution we start explicitly resolving more phenomena.

For example, high resolution climate modeling at NCAR is done at approximately 25km

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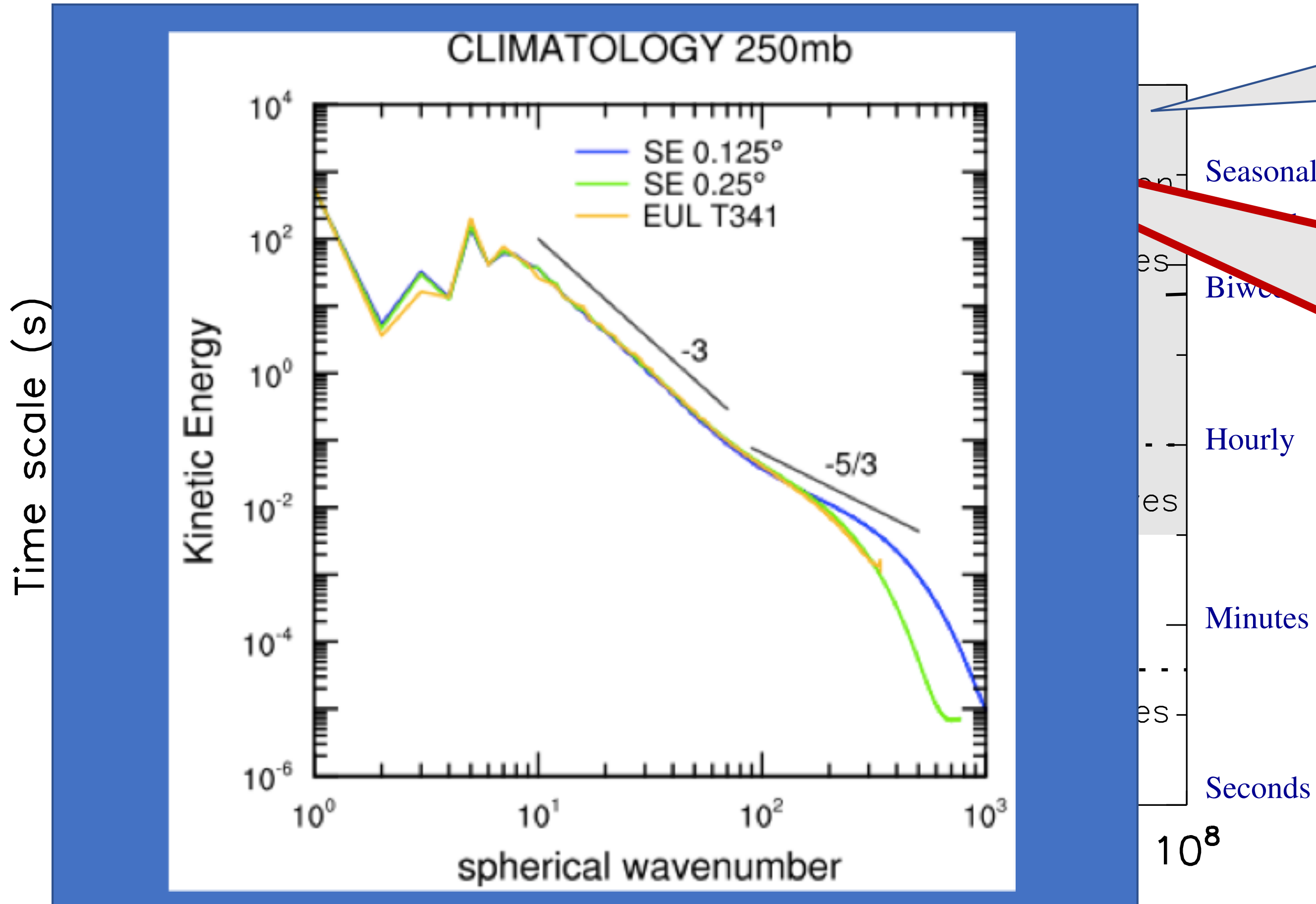


Figure courtesy of Mark Taylor

o/index.php/File:Troposphere.jpg

Figure from Thuburn (2011)

One aspect that improves drastically with resolution is representation of topography in models

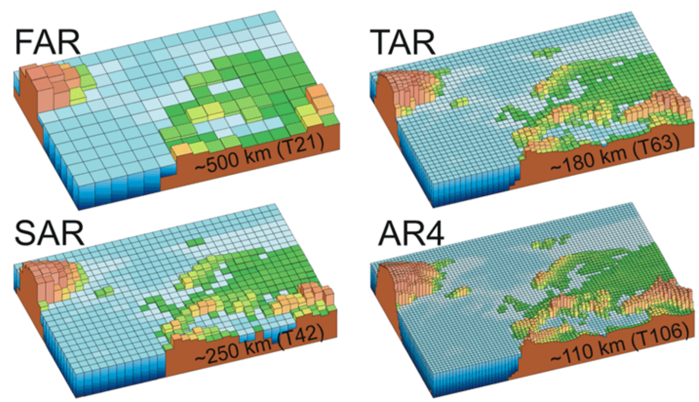
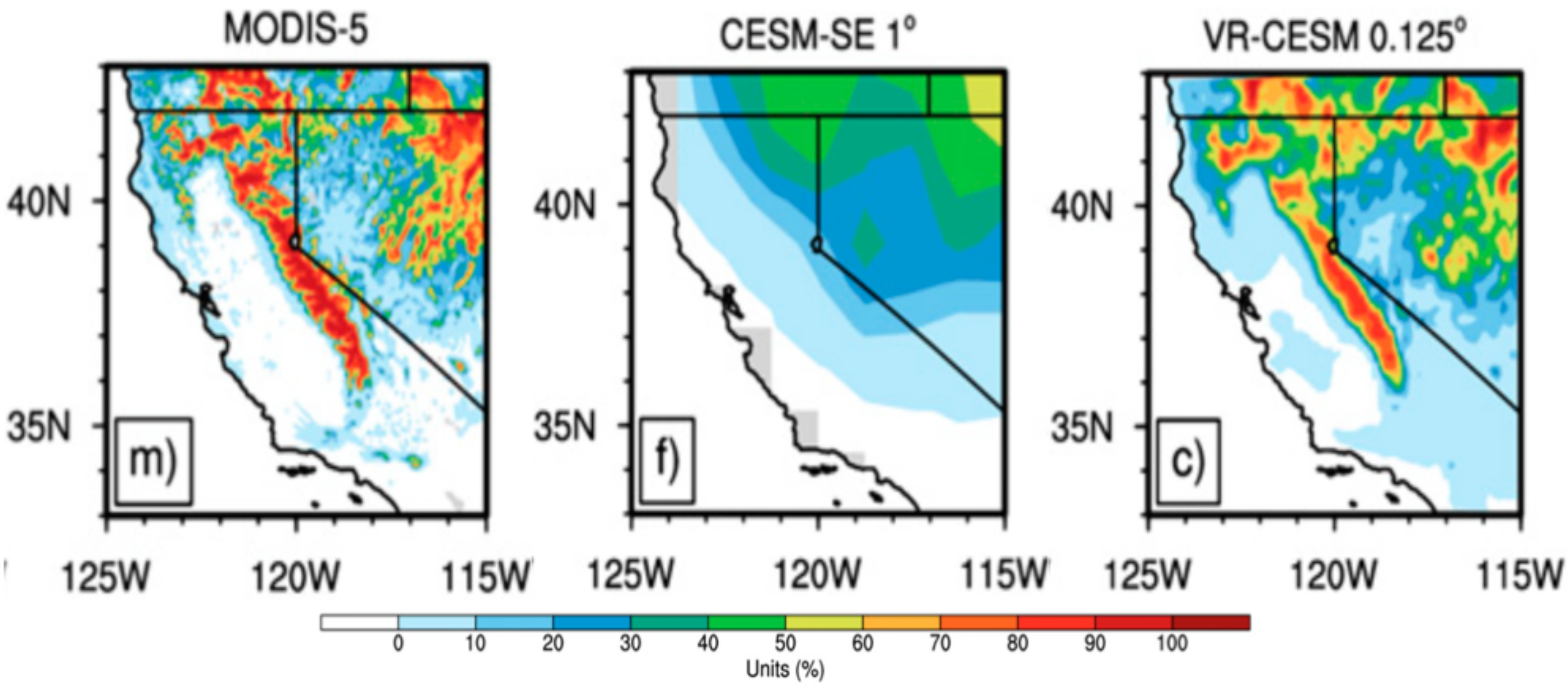
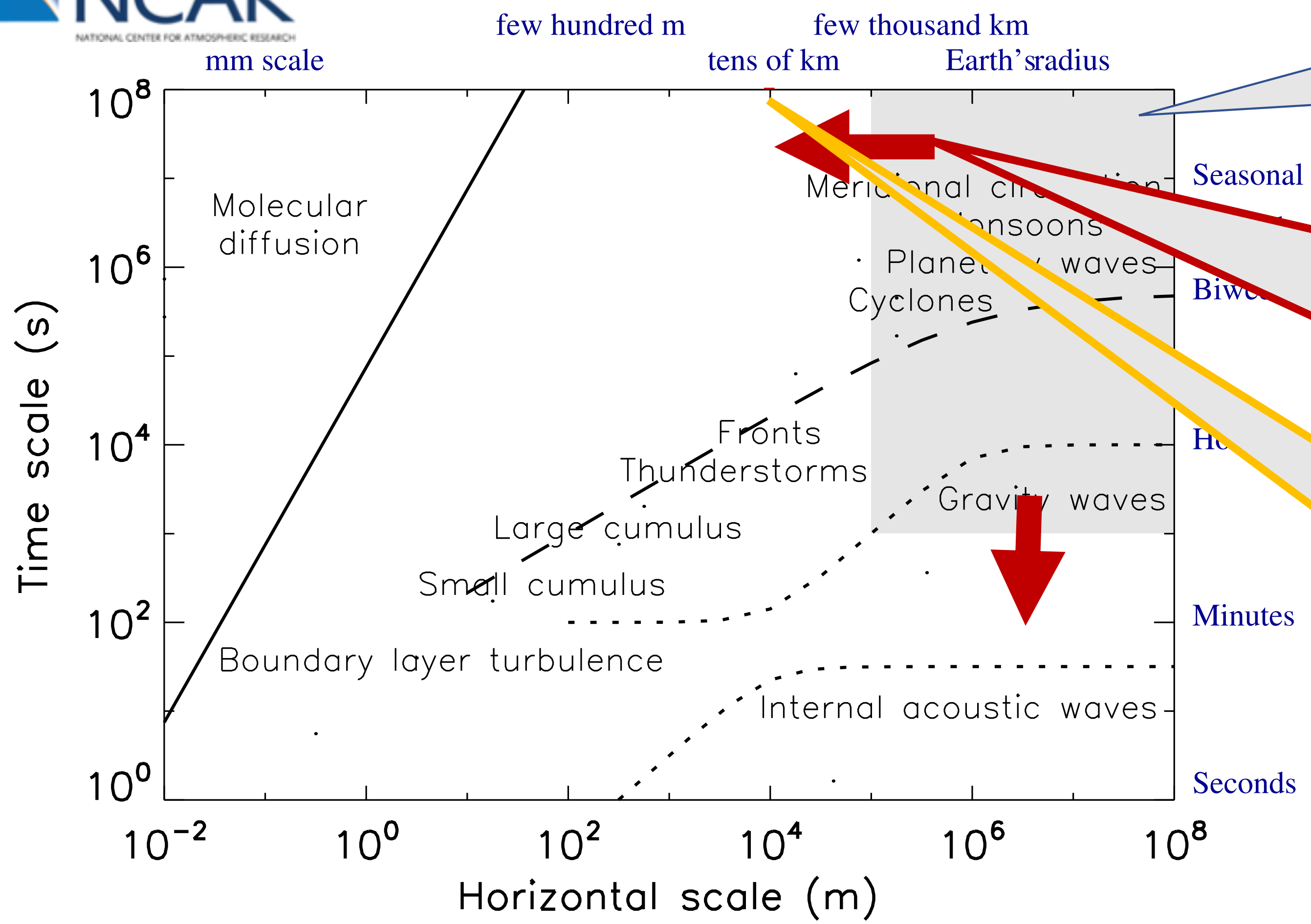


Figure courtesy of IPCC, AR4 WG Chapter 1

Simulated snow cover fraction



Rhoades et al, in prep



Shaded area: Horizontal-temporal resolution of current global IPPC class climate models

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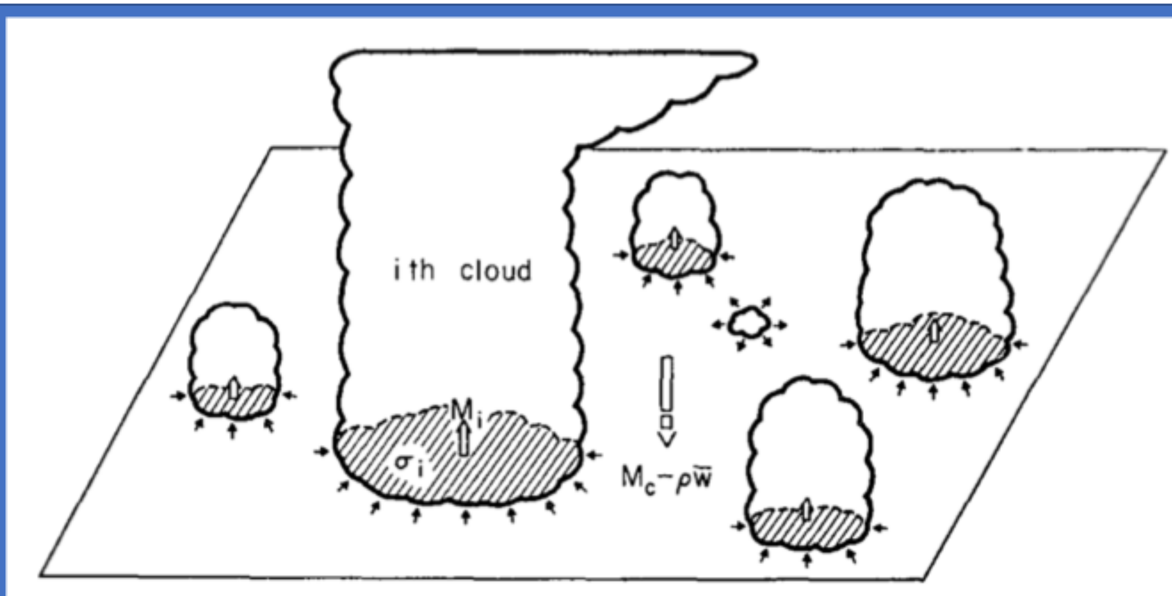
Some parameterizations are based on assumptions that break down at higher horizontal resolution; .e.g. deep convection

Figure from Thuburn (2011)



"Consider a horizontal area ... large enough to contain an ensemble of cumulus clouds, but small enough to cover only a fraction of a large-scale disturbance. The existence of such an area is one of the basic assumptions of this paper."
-- Arakawa and Schubert (1974)

Horizontal resolutions at which assumptions made in the parameterizations start to break down and until the processes are explicitly resolved (e.g., individual updrafts) is called the grey zone…

Figure from Thuburn (2011)

re.jpg

Shaded area: Horizontal-temporal resolution of current global IPPC class climate models

With increases in horizontal and vertical resolution we start explicitly resolving more phenomena.

For example, high resolution climate modeling at NCAR is [illegible] at approximately 25km

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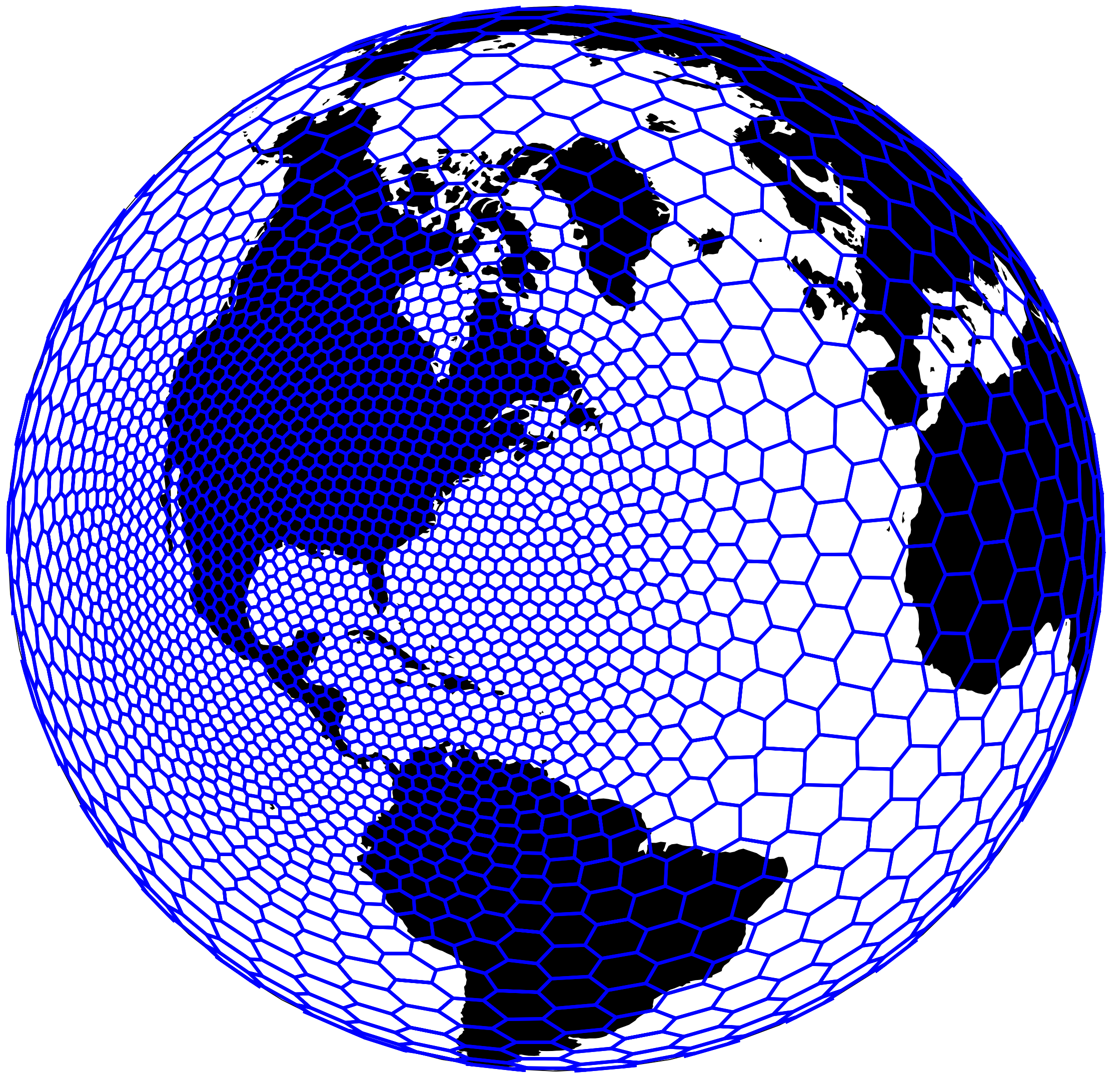
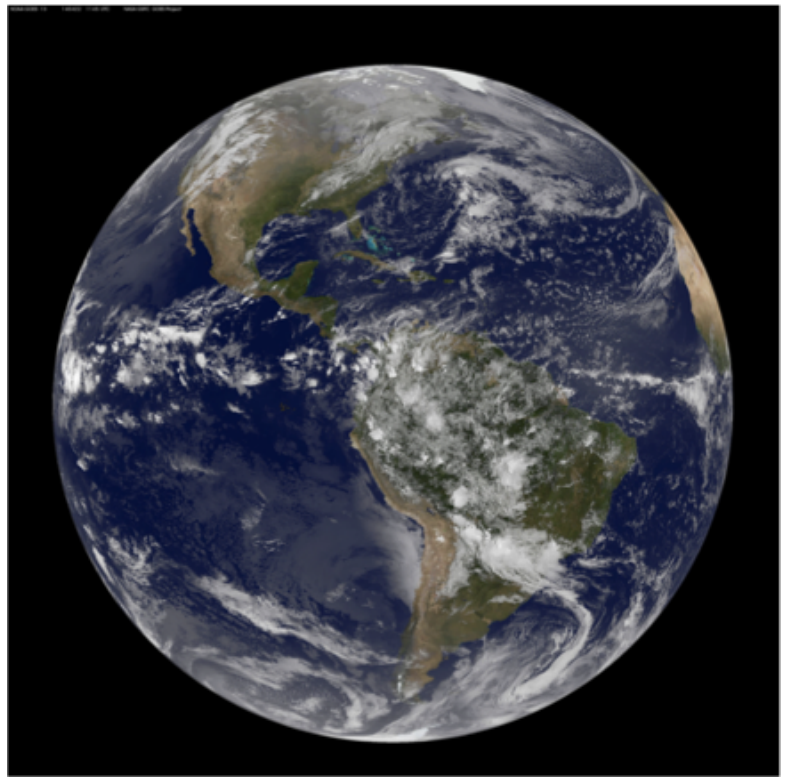


Done with dynamics introduction

Next:

“Ingredients” of a global atmosphere model

Building a global model – choices specific to the dynamical core?



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A. Choose equation set and prognostic variables

A. Choose equation set and prog. vars.

"Exact" Euler equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$

$$\frac{D\theta}{Dt} = Q,$$

$$\frac{D\mathbf{u}}{Dt} + 2\boldsymbol{\Omega} \times \mathbf{u} = -\frac{1}{\rho}\nabla p - \nabla \Phi + \mathbf{F}.$$

"However, it is often desirable to work with approximate versions of the governing equations. These may be conceptually simpler, for example by filtering out certain kinds of motion; they may be analytically more tractable; or they may be easier to solve numerically, for example by removing certain terms or types of motion that are difficult to handle numerically." –Thuburn (2011)

In large-scale global modeling the following approximations are usually made:

- **spherical geoid**: geopotential Φ is only a function of radial distance from the center of the Earth r: $\Phi = \Phi(r)$ (for planet Earth the true gravitational acceleration is much stronger than the centrifugal force).
  $\Rightarrow$ Effective gravity acts only in radial direction
- **quasi-hydrostatic approximation** (also simply referred to as *hydrostatic approximation*): Involves ignoring the acceleration term in the vertical component of the momentum equations so that it reads:
  $$\rho\, g = -\frac{\partial p}{\partial z}, \tag{1}$$
  where g gravity, ρ density and p pressure. Good approximation down to horizontal scales greater than approximately $10km$.
- **shallow atmosphere**: a collection of approximations. Coriolis terms involving the horizontal components of Ω are neglected (Ω is angular velocity), factors $1/r$ are replaced with $1/a$ where a is the mean radius of the Earth and certain other metric terms are neglected so that the system retains conservation laws for energy and angular momentum.

We are slowly removing some of these approximates:

- **Global shallow-atmosphere non-hydrostatic models are now more common (NICAM, MPAS, FV3, ICON, …)**
- **Some global models have gotten rid of shallow atmosphere approximation (NUMA, UK Met Office)**

- **quasi-hydrostatic approximation** (also simply referred to as *hydrostatic approximation*): Involves ignoring the acceleration term in the vertical component of the momentum equations so that it reads:

$$\rho\, g = -\frac{\partial p}{\partial z}, \quad (1)$$

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A. Choose equation set and prognostic variables

B. Choose a horizontal global grid

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(not a comprehensive list)

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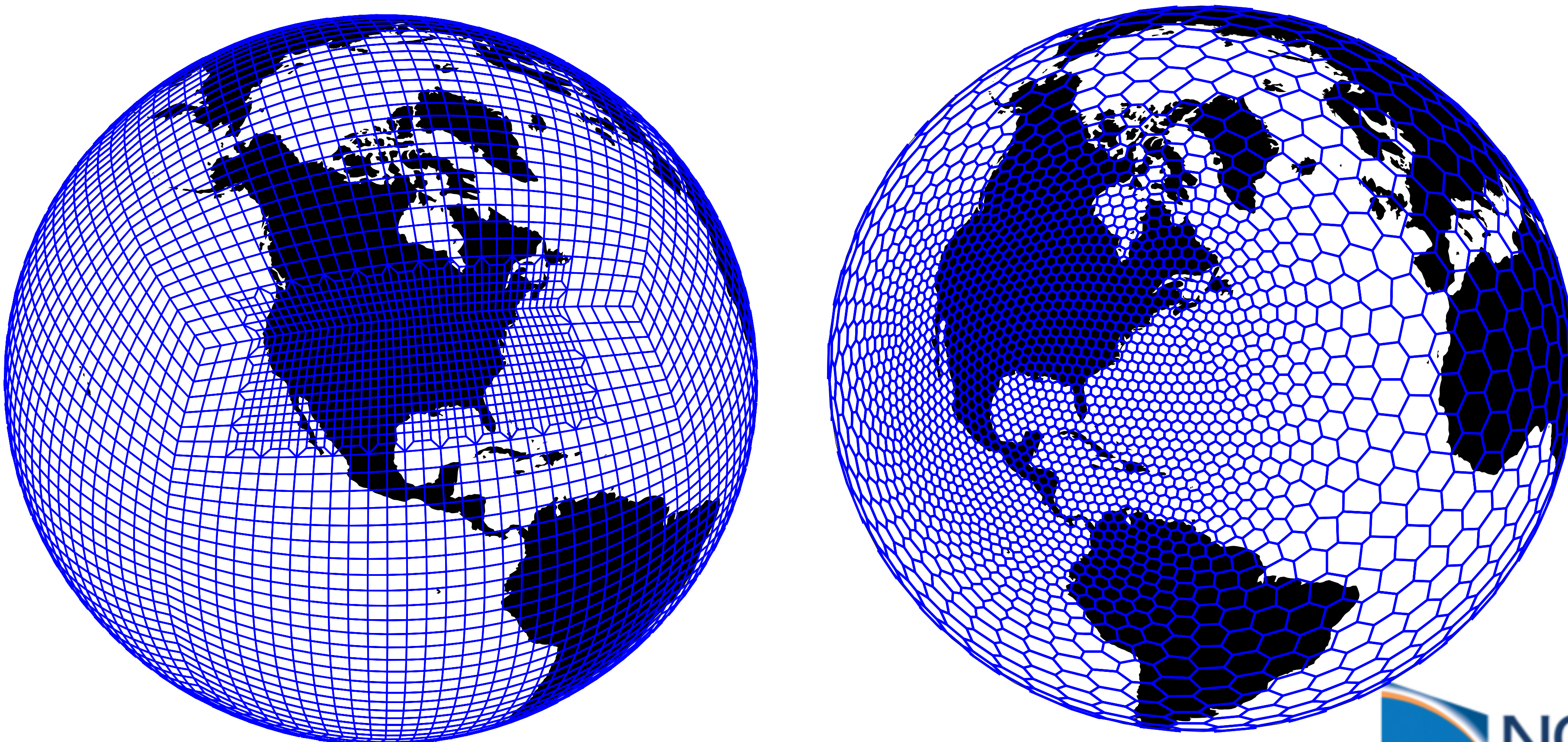
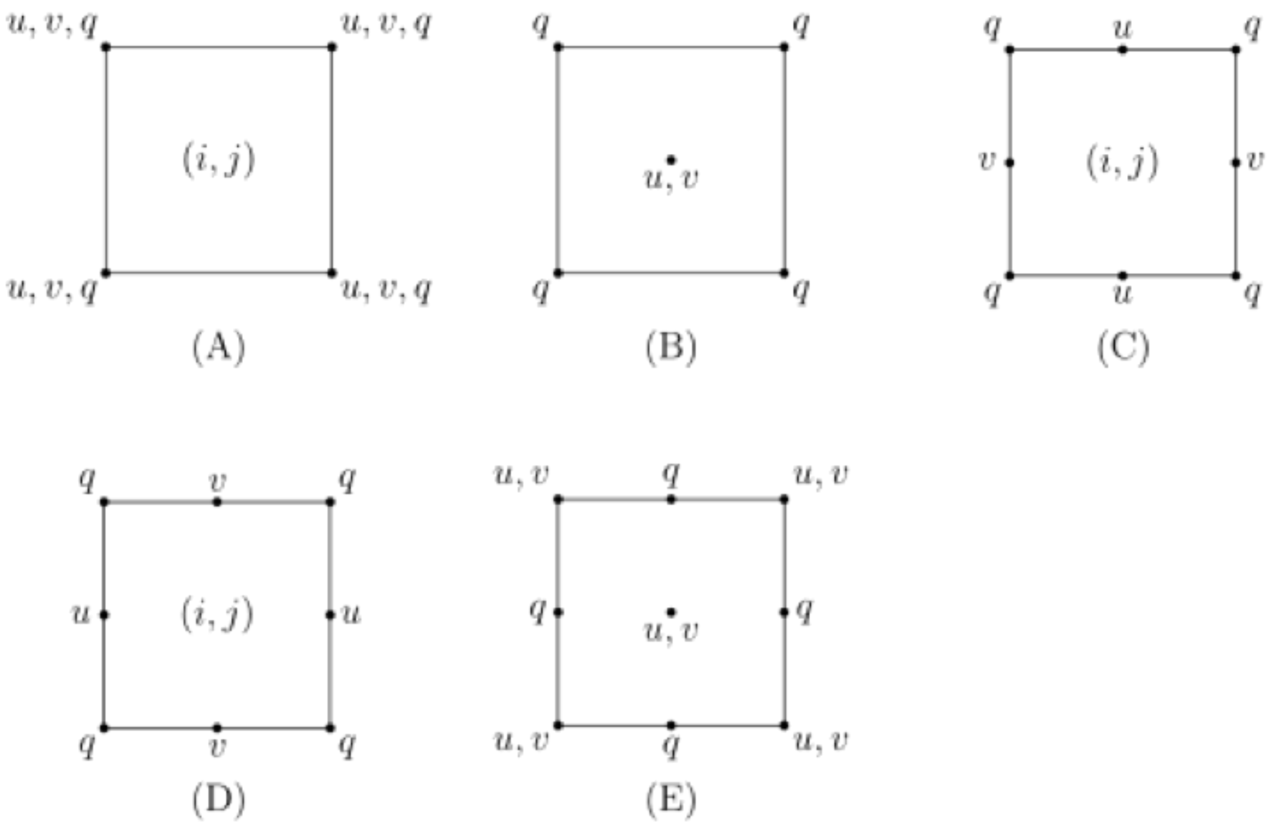


B. Choose a horizontal global grid

Part of the horizontal grid is staggering of the prognostic variables which affect damping/dispersion properties near the grid scale



Arakawa grids

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A. Choose equation set and prognostic variables

B. Choose a horizontal global grid

C. Choose a vertical coordinate

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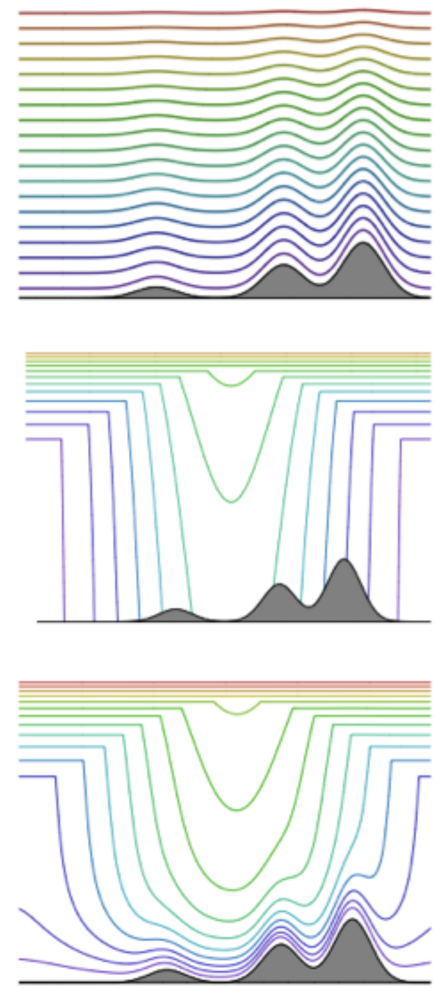
C. Choose a vertical grid/coordinate



- Height based - z/z_s or z
- Sigma based - P/P_S
- Theta (potential temperature)
- Various hybrids:
  - Sigma-pressure
  - Sigma-theta

Vertical coordinate: hybrid sigma ($\sigma = p/p_s$)-pressure (p) coordinate

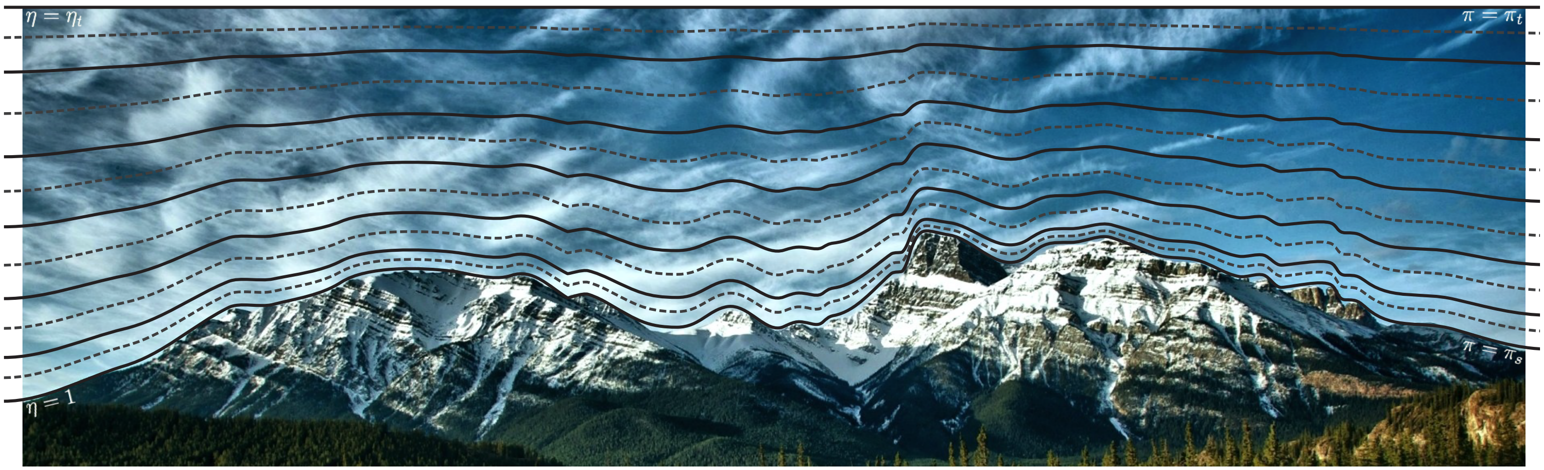


Figure courtesy of David Hall (CU Boulder).

Sigma layers at the bottom (following terrain) with isobaric (pressure) layers aloft.

Pressure at model level interfaces

$$p_{k+1/2} = A_{k+1/2}\, p_0 + B_{k+1/2}\, p_s,$$

where p_s is surface pressure, p_0 is the model top pressure, and $A_{k+1/2}(\in [0:1])$ and $B_{k+1/2}(\in [1:0])$ hybrid coefficients (in model code: *hyai* and *hybi*). Similarly for model level mid-points.

Note: vertical index is 1 at model top and *klev* at surface.

Why do we use terrain-following coordinates?

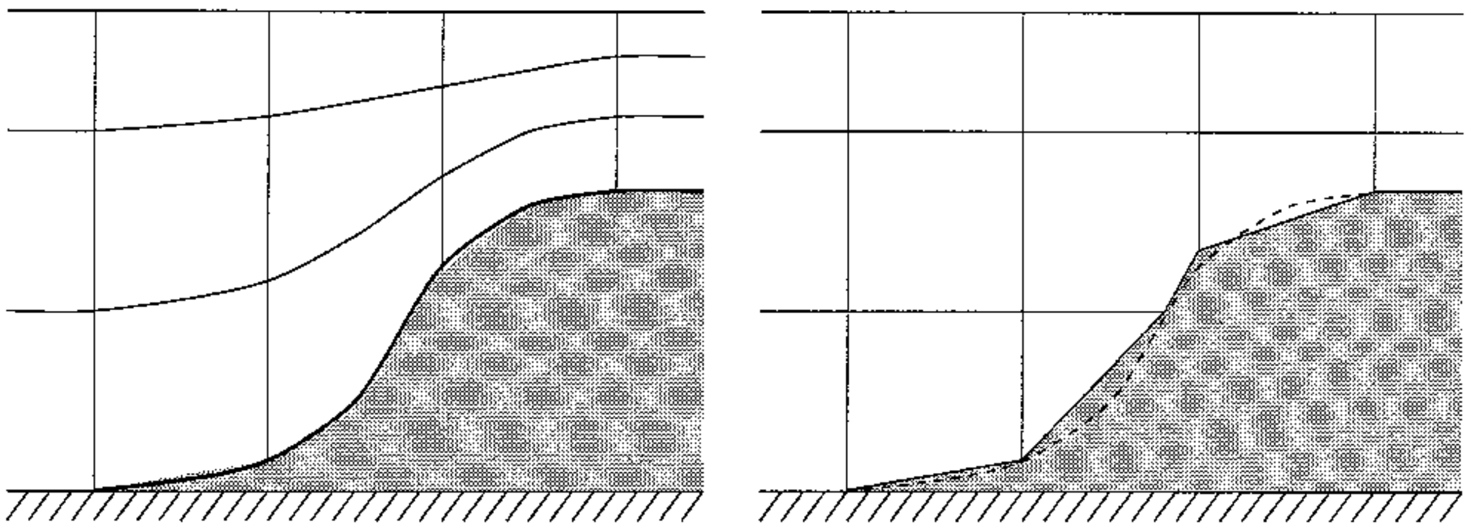


Figure: Representation of a smoothly varying bottom (dashed line) in (left) a terrain-following coordinate model, and (right) a height coordinate model with piecewise constant slopes (cut-cells, shaved-cells)

Figure is from Adcroft et al. (1997).

→ The main reason is that the lower boundary condition is very simple when using terrain-following coordinates!

While terrain-following coordinates simplify the bottom boundary condition, they may introduce errors:

- Pressure gradient force (PDF) errors: $\frac{1}{\rho}\nabla p_z = \frac{1}{\rho}\nabla_\eta p + \frac{1}{\rho}\frac{dp}{dz}\nabla_\eta z$, (Kasahara, 1974) where ρ is density, p pressure and z height.
- Errors in modeling flow along constant z-surfaces near the surface

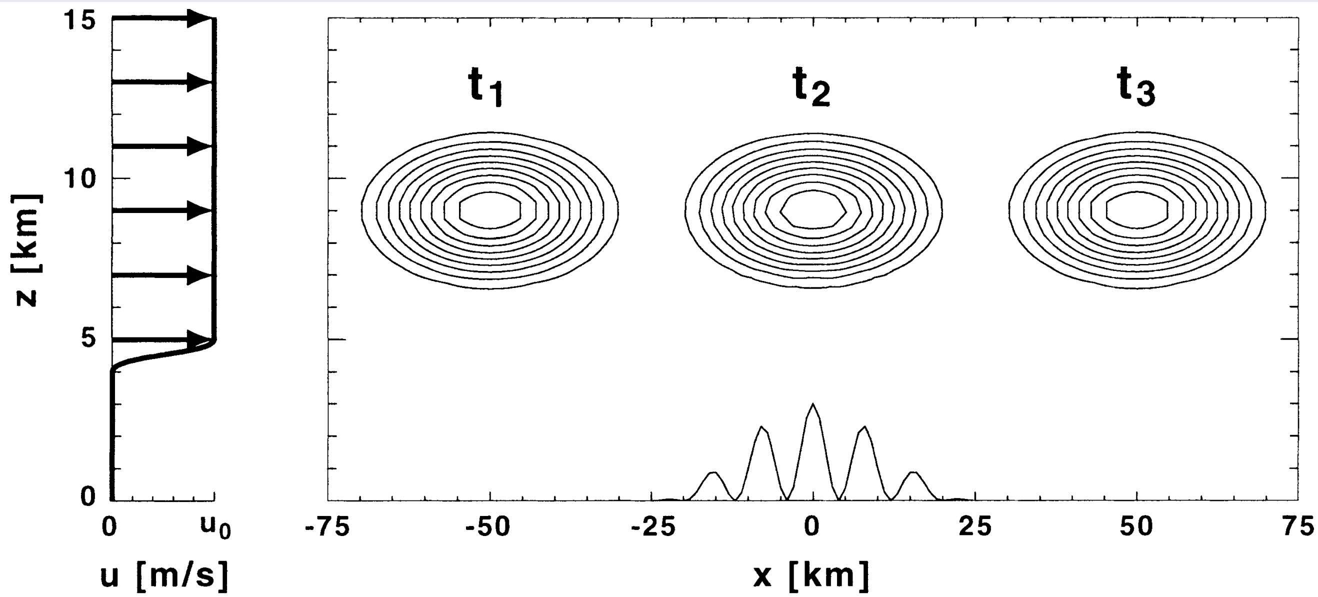
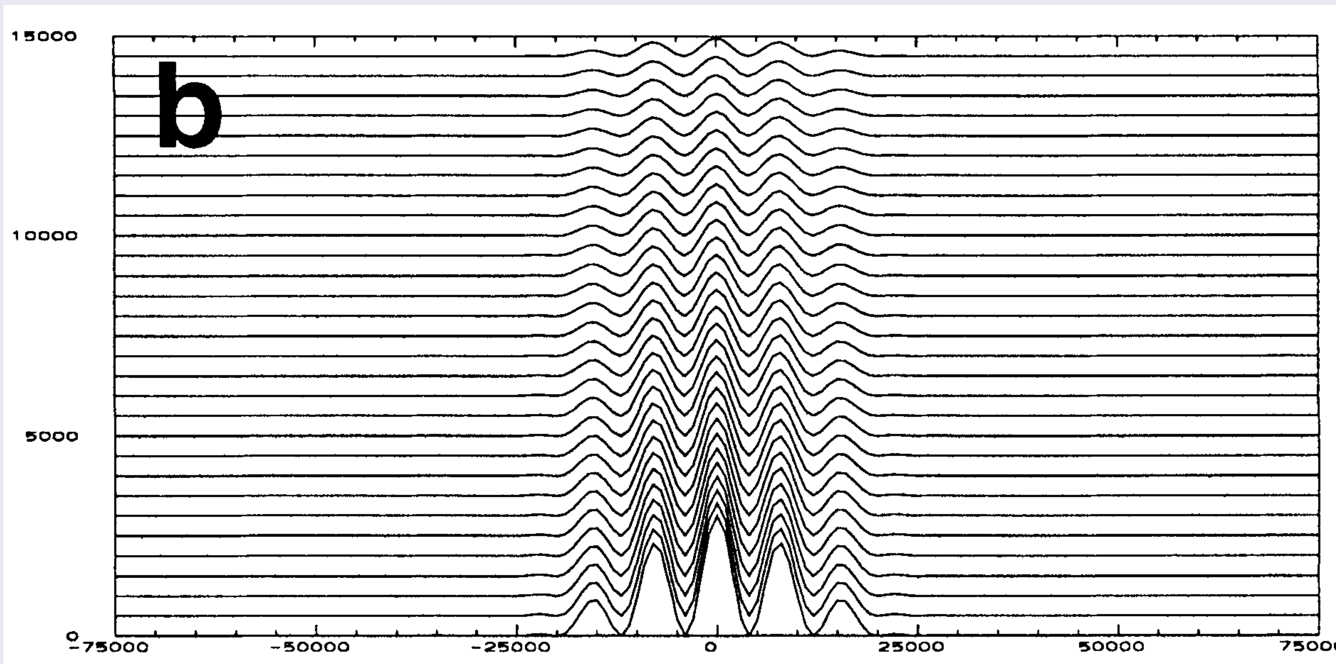


FIG. 4. Vertical cross section of the idealized two-dimensional advection test. The topography is located entirely within a stagnant pool of air, while there is a uniform horizontal velocity aloft. The analytical solution of the advected anomaly is shown at three instances.

Schär et al. (2002)

While terrain-following coordinates simplify the bottom boundary condition, they may introduce errors:

- Pressure gradient force (PDF) errors: $\frac{1}{\rho}\nabla p_z = \frac{1}{\rho}\nabla_\eta p + \frac{1}{\rho}\frac{dp}{dz}\nabla_\eta z$, (Kasahara, 1974) where ρ is density, p pressure and z height.
- Errors in modeling flow along constant z-surfaces near the surface



Schär et al. (2002)

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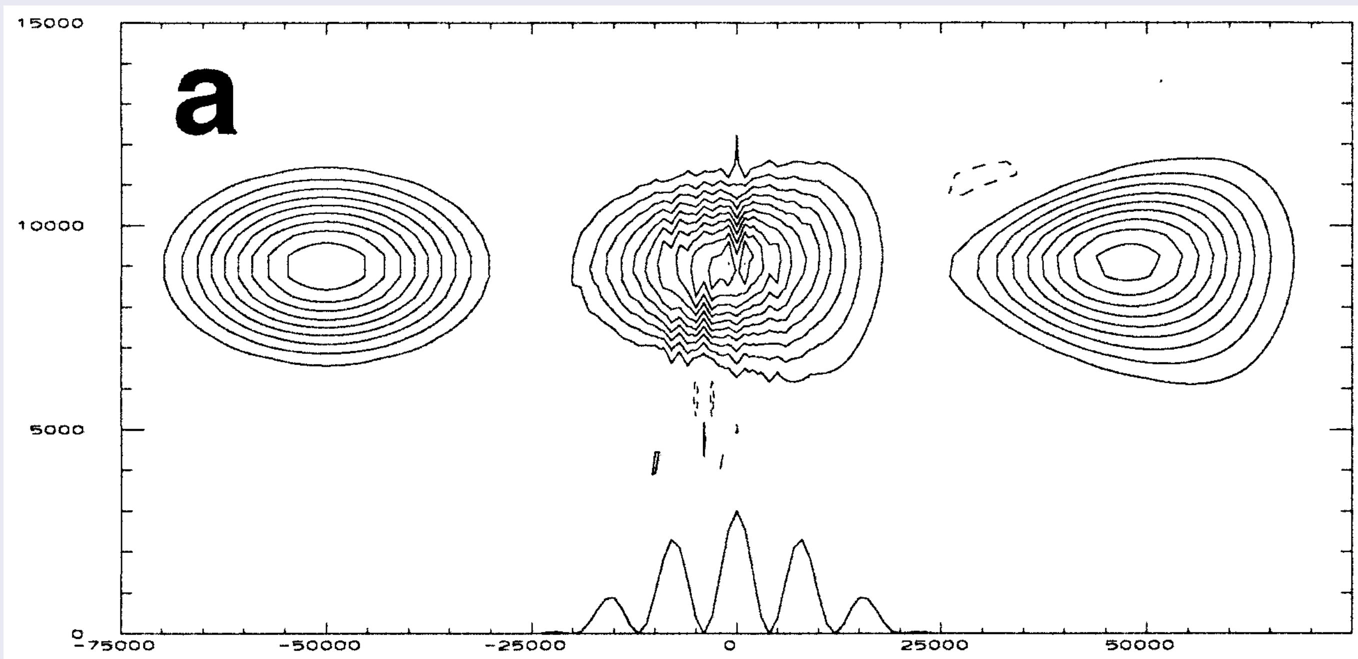


Schär et al. (2002)

A. Choose equation set and prognostic variables

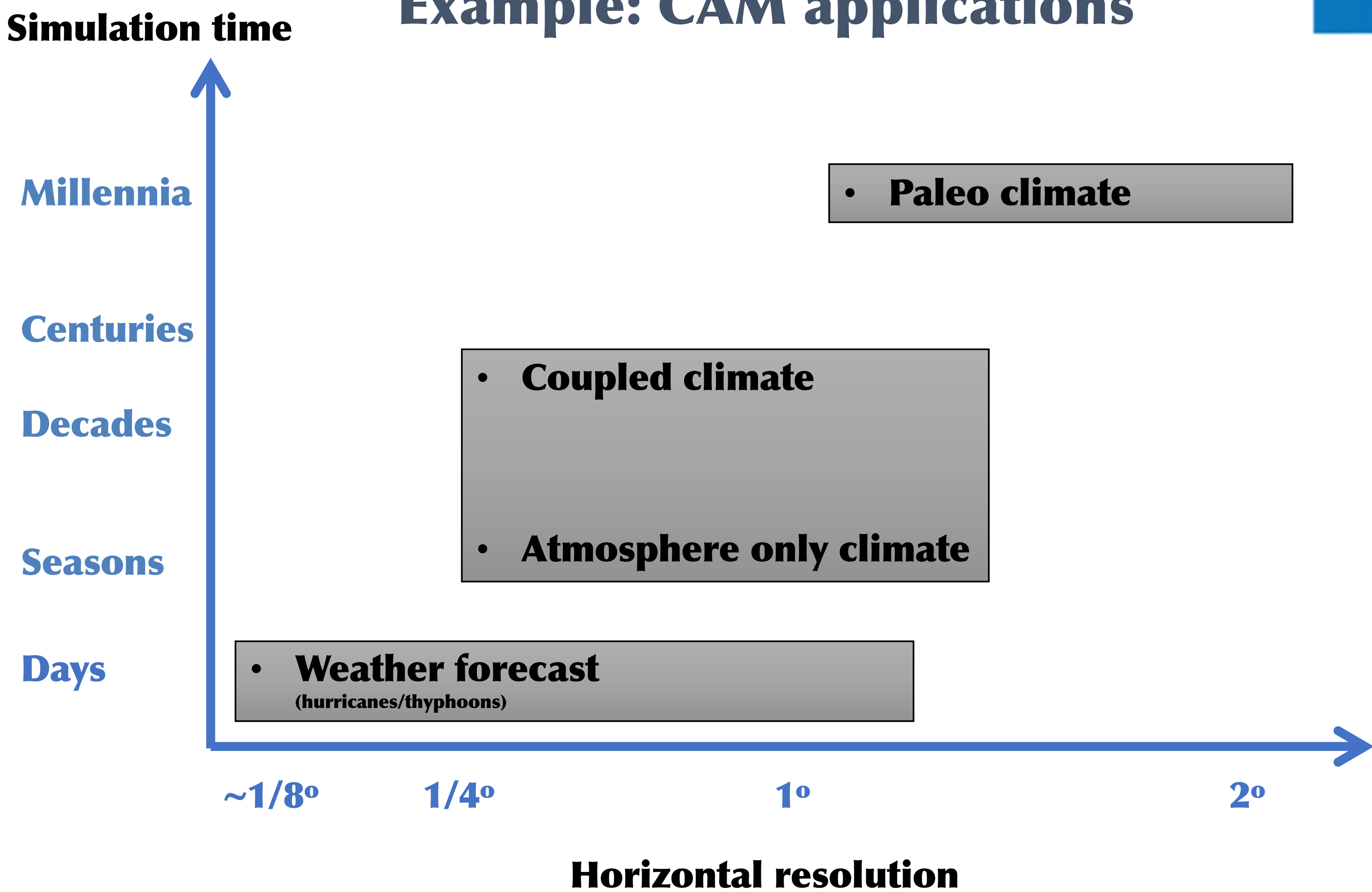
B. Choose a horizontal global grid

C. Choose a vertical grid/coordinate

D. Choose numerical method

(Pedro Peixoto talk)

Example: CAM applications



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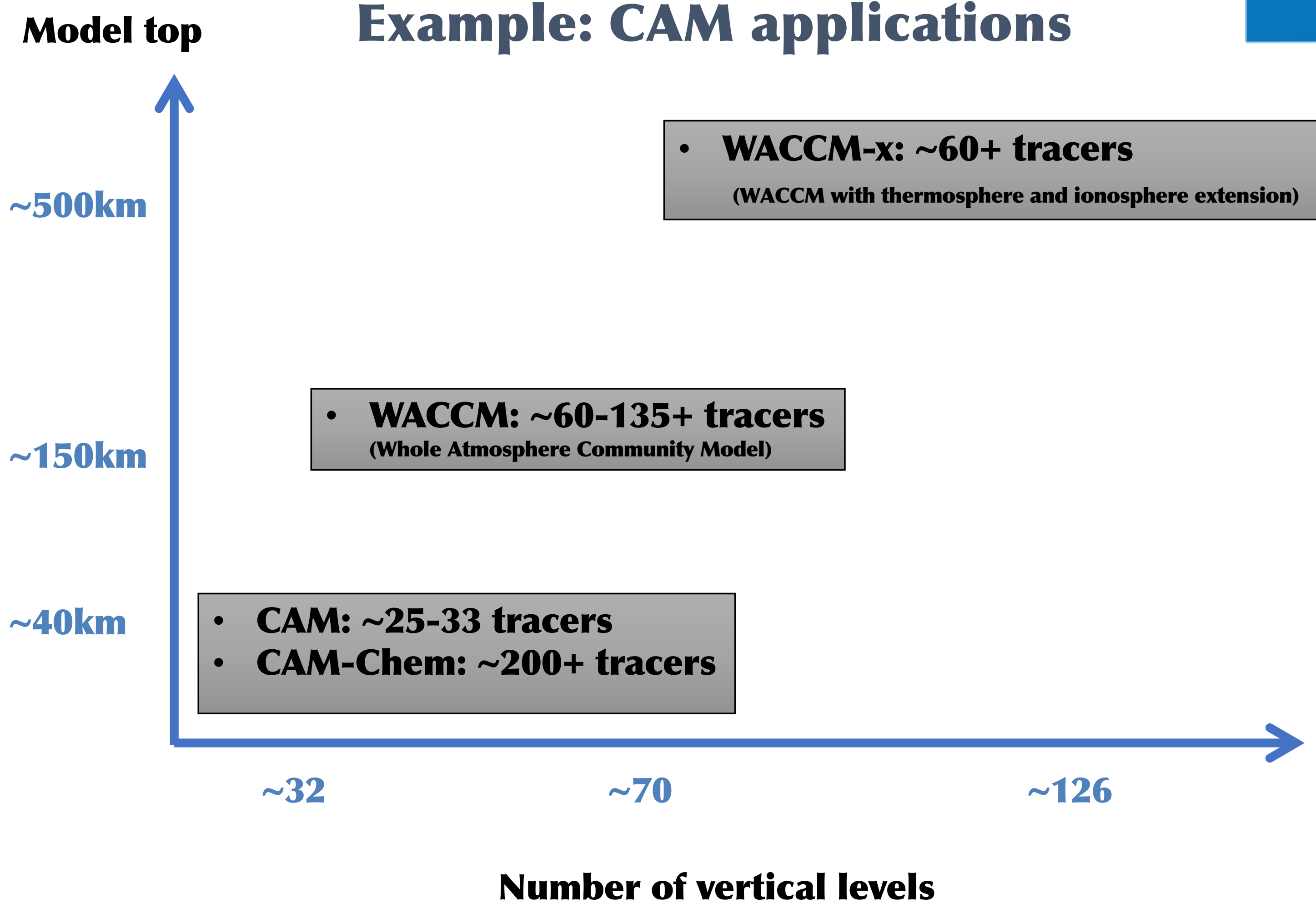
Example: CAM applications



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Compute platforms on which CAM is run

A dynamical core must be computationally efficient (climate applications require ~10 SYPD)
- for lower resolution applications – strong scaling
- for high resolution – weak scaling
- efficient on new compute architectures (multi-core nodes)

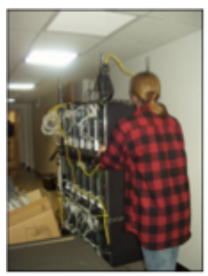
"Gigantic" cluster
~1000000 cores

e.g., DOE facilities

Large cluster
~100000 cores

e.g., NCAR's Yellowstone (soon Cheyenne)

Small cluster
~100-1000 cores



e.g., CGD's Hobart cluster

Laptop
~4 cores

e.g., NCAR scientist

LECTURE NOTES IN COMPUTATIONAL SCIENCE AND ENGINEERING

This book surveys recent developments in numerical techniques for global atmospheric models. It is based upon a collection of lectures prepared by leading experts in the field. The chapters reveal the multitude of steps that determine the global atmospheric model design. They encompass the choice of the equation set, computational grids on the sphere, horizontal and vertical discretizations, time integration methods, filtering and diffusion mechanisms, conservation properties, tracer transport, and considerations for designing models for massively parallel computers. A reader interested in applied numerical methods but also the many facets of atmospheric modeling should find this book of particular relevance.

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Numerical Techniques for Global Atmospheric Models

LECTURE NOTES IN COMPUTATIONAL SCIENCE AND ENGINEERING

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