

# Exploring a lower resolution physics grid in CAM-SE-CSLAM

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## **Key Points:**

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## Abstract

## 1 Introduction

Global atmospheric models fundamentally consist of two components. The dynamical core (*dynamics*), which numerically integrate the adiabatic equations of motion and tracer advection, and the physical parameterizations (*physics*), which compute the effects of diabatic and subgrid-scale processes (e.g., radiative transfer and moist convection) on the grid-scale. More out of convenience than anything else, the physics are evaluated on the dynamics grid, i.e., the physics grid and dynamics grid coincide. From linear stability and accuracy analysis of numerical methods, it is a common result that the shortest simulated wavelengths are not accurately represented by the dynamical core. Additionally, simulated downscale cascades result in an unrealistic collection of energy and/or enstrophy near the truncation scale, which may be observed from kinetic energy spectra in model simulations [Skamarock, 2011]. Some form of dissipation must be incorporated into models to mitigate these numerical artifacts near the grid scale [Jablonowski and Williamson, 2011]. This numerical dissipation has no physical analogy [although see Grinstein *et al.*, 2007], and the grid-scale is therefore contaminated by numerous un-physical processes. The under-resolved nature of the grid-scale led Lander and Hoskins [1997] to speculate whether the physics should be evaluated on a grid that is more reflective of the scales actually resolved by the dynamical core.

Experimentation with different physics grid resolutions have so far been limited to models employing the spectral transform method [Lander and Hoskins, 1997; Williamson, 1999; Wedi, 2014]. Lander and Hoskins [1997] argue that passing under-resolved states to the physics may be especially problematic in spectral transform models, since the physics are evaluated on a latitude-longitude transform grid, and contains more degrees of freedom than the spectral representation to prevent aliasing of quadratic quantities. However, Lander and Hoskins [1997] find that the spectral truncation of the physics tendencies damps errors that may result from passing an under-resolved state to the physics, although the extent to which these errors may still be present in the model was not addressed.

Another class of spectral-transform models evaluate the quadratic terms using semi-Lagrangian methods, which are implicitly diffusive, relaxing constraints on the resolution of the transform grid. Wedi [2014] experimented with different transform grid resolutions and concluded that the standard high resolution quadratic grid actually improves forecast skill over the use of a lower-resolution transform grid. They suggest that increasing the resolution of the transform grid simulates a kind of sub-grid variability on the spectral state, which is thought to be under-represented in global atmospheric models [Shutts, 2005]. This is in principle the purpose of “super-parameterization,” in which a cloud resolving model is embedded in each grid cell to simulate the requisite subgrid variability, and improves both diurnal and sub-seasonal variability in the model [Randall *et al.*, 2003].

After the physics tendencies are transformed into spectral space, the tendencies may be truncated at any particular wave number. Williamson [1999] conducted a pair of convergence tests using a global spectral transform model; a conventional convergence test and one in which the spectral truncation of the physics tendencies is held fixed and the resolution of the dynamical core increased. In contrast to the realistic weather forecasts of Wedi [2014], Williamson [1999] run their model to equilibrium in an idealized climate configuration. When the physics and dynamics resolutions increase together, as in more typical convergence studies, the strength of the Hadley Cell increases monotonically with resolution. This sensitivity of Hadley Cell strength to horizontal resolution is a common result of global models at hydrostatic resolutions [see Herrington and Reed, 2017, and references therein]. But with the truncation wave number of physics tendencies held fixed, the Hadley Cell showed very little sensitivity to dynamical core resolution, resembling the

solution for which the dynamics truncation wave number is equal to that of the lower resolution physics.

*Herrington and Reed* [2017] speculate that the results of *Williamson* [1999] indicate that the scales of motion resolved by the dynamical core are aliased to the lower resolution physics. It may be worth considering that if the resolution of the dynamics is reduced in response to a coarser physics grid, then the dynamics may be no better resolved on the coarser physics grid, compared with the conventional method of evaluating the physics and dynamics at the same resolution. The results of *Williamson* [1999] and *Wedi* [2014] do not provide evidence that a lower resolution physics grid reduces computational errors in spectral transform models, but this was seldom discussed in either study.

Global spectral transform models, while remarkably efficient at small processor counts, do not scale well on massively parallel systems. High-order Galerkin methods are becoming increasingly popular in climate and weather applications due to their high-parallel efficiency, high-processor efficiency, high-order accuracy (for smooth problems), and geometric flexibility facilitating mesh-refinement applications. High resolution climate simulations with NCAR’s Community Atmosphere Model [CAM; *Neale et al.*, 2012] are typically performed using a continuous Galerkin dynamical core referred to as CAM-SE [CAM Spectral Elements; *Taylor et al.*, 2008; *Dennis et al.*, 2012; *Lauritzen et al.*, 2018]. CAM-SE may be optionally coupled to a conservative, semi-Lagrangian tracer advection scheme for accelerated multi-tracer transport [CAM-SE-CSLAM; *Lauritzen et al.*, 2017]. Tracer advection then evolves on an entirely separate, finite-volume grid which contains the same degrees of freedom as CAM-SE’s quadrature node grid.

Element-based Galerkin methods are susceptible to grid-imprinting, and may need be considered when contemplating a particular physics grid [*Herrington et al.*, 2018, hereafter referred to as H18]. Grid imprinting manifests at the element boundaries, since the global basis is least smooth ( $C^0$ ; all derivatives are discontinuous) for quadrature nodes lying on the element boundaries, and the gradients (e.g., the pressure gradient) are systematically tighter producing local extremes. Through computing the physics tendencies at the nodal points, element boundary extrema is also observed in the physics tendencies.

H18 has shown that through evaluating the physics on the finite-volume tracer advection grid in CAM-SE-CSLAM, element boundary noise is substantially reduced, although still problematic in regions of steep terrain, at low latitudes. Through integrating CAM-SE’s basis functions over the control volumes of the finite-volume grid, element boundary extrema is additionally weighted by the  $C^\infty$  solutions (i.e., the basis representation is infinitely smooth and all derivatives are continuous) of the element interior, and the state is smoother. Additionally, in defining an area averaged state, the finite-volume physics grid is made consistent with assumptions inherent to the physics, and is more appropriate for coupling to other model components (e.g., the land model), which is typically performed using finite-volume based mapping algorithms.

The finite-volume grid of H18 is found through dividing the elements of CAM-SE’s gnomonic cubed-sphere grid with equally spaced, equi-angular coordinate lines parallel to the equi-angular element boundaries, such that there are  $3 \times 3$  control volumes per element (hereafter referred to as *pg3*). While a  $3 \times 3$  physics grid was chosen in order to have the same degrees of freedom as the dynamical core, the control volumes encompass a region of the element in which their proximity to the element boundaries are not equal. Therefore, not every control volume in an element has the same smoothness properties. This may be avoided through defining a physics grid in which the elements are instead divided into  $2 \times 2$  control volumes (hereafter referred to as *pg2*). The control volumes of the *pg2* grid all have the same proximity to the element boundaries, and should mitigate the element boundary noise that remains in the *pg3* grid, and shown in H18.

In this study, we test the hypothesis that the coarser, *pg2* physics grid is effective at reducing spurious noise at element boundaries, particularly over regions of rough topography. In addition, the recent trend towards running models at ever higher resolutions is an almost prohibitive computational burden. As the physics are responsible for over half of the computational cost in CAM-SE [Lauritzen *et al.*, 2018], the improvement in computational performance using a coarser resolution physics grid is potentially significant. However, any advantages of using a coarser physics grid need be weighed against any potential reduction in simulation quality, e.g., possible aliasing of the resolved scales of motion by the coarser grid, as suggested by the results of Williamson [1999]. Section 2 describes the implementation of the *pg2* grid into CAM-SE-CSLAM. Section 3 provides the results of a hierarchy of model configurations to identify any changes in grid imprinting, or in the overall solution, compared with the *pg3* configuration. Section 4 provides a discussion of the results and conclusions.

## 2 Methods

Separating dynamics, tracer and physics grids introduces the added complexity of having to map the state from dynamics and tracer grids to the physics grid; and mapping physics tracer tendencies back to the tracer grid and physics tendencies needed by the dynamical core to the dynamics grid. The dynamics grid refers to the Gauss-Lobatto-Legendre (GLL) quadrature nodes by the spectral-element method to solve the momentum equations for the momentum vector  $(u, v)$ , thermodynamics equation for temperature  $(T)$ , continuity equation for dry air  $(M)$ , and continuity equations for water vapor and condensates thermodynamically active [see, e.g., Lauritzen *et al.*, 2018, for details]. By tracer grid we refer to the *pg3* grid on which CSLAM performs tracer transport of water vapor, condensates and other tracers. The GLL value for water vapor and condensates is overwritten by the CSLAM values every physics time-step so that the spectral-element advection of water species does not become decoupled from the the CSLAM advection of the same water species. Mapping velocity components, dry air mass and temperature from the GLL grid to the *pg2* grid is done by using the internal degree 3 Lagrange basis functions in CAM-SE [as described in Herrington *et al.*, 2018, for *pg3*; exactly the same methods can be used for *pg2*].

As compared to the *pg3* configuration, the extra complication of the *pg2* setup is that tracer state needs to be mapped from the tracer grid to the physics grid and tracer tendencies need to be mapped from the physics grid to CSLAM grid. In order to describe the algorithm some notation needs to be introduced.

The mapping algorithm is applied to each element  $\Omega$  (with spherical area  $\Delta\Omega$ ) so without loss of generality consider one element. Let  $\Delta A_k^{(pg)}$  and  $\Delta A_\ell^{(nc)}$  be the spherical area of the physics grid grid cell  $A_k^{(pg)}$  and CSLAM control volume  $A_\ell^{(nc)}$ , respectively. The physics grid cells and CSLAM cells respectively span the element without gaps or overlaps

$$\bigcup_{k=1}^{pg^2} A_k^{(pg)} = \Omega \text{ and } A_k^{(pg)} \cap A_\ell^{(pg)} = \emptyset \quad \forall k \neq \ell, \quad (1)$$

$$\bigcup_{k=1}^{nc^2} A_k^{(nc)} = \Omega \text{ and } A_k^{(nc)} \cap A_\ell^{(nc)} = \emptyset \quad \forall k \neq \ell. \quad (2)$$

The overlap areas between the  $k$ -th physics grid cell and CSLAM cells is denoted

$$A_{k\ell} = A_k^{(pg)} \cap A_\ell^{(nc)}, \quad (3)$$

so that

$$A_k^{(pg)} = \bigcup_{\ell=1}^{nc^2} A_{k\ell}. \quad (4)$$

This overlap grid is also referred to as an exchange grid.

## 2.1 Mapping tracers from CSLAM to $pg$

For mapping tracer state from the CSLAM grid to any physics grid can be done using existing CSLAM technology, i.e. do a high-order shape-preserving reconstruction of mixing ratio and dry air mass inside each CSLAM control volume and integrate those reconstruction functions over the overlap areas [Lauritzen *et al.*, 2010; Nair and Lauritzen, 2010]. This algorithm retains the properties of CSLAM: inherent mass-conservation, mixing ratio shape-preservation and linear-correlation preservation.

In mathematical terms the remapping is given by

$$\Delta M_{\ell}^{(pg)} \Delta A_{\ell} = \sum_{k=1}^{nc^2} \Delta M_{k\ell}^{(nc)} \Delta A_{k\ell}, \quad (5)$$

$$\Delta M_{\ell}^{(pg)} m_{\ell}^{(pg)} \Delta A_{\ell} = \frac{1}{\Delta M_{\ell}^{(pg)}} \sum_{k=1}^{nc^2} [\Delta M m]_{k\ell}^{(nc)} \Delta A_{k\ell}, \quad (6)$$

where

$$\Delta M_{k\ell}^{(nc)} = \frac{1}{\Delta A_{k\ell}} \int_{A_{k\ell}} \Delta M(x, y) dA. \quad (7)$$

$$[\Delta M m]_{k\ell}^{(nc)} = \frac{1}{\Delta A_{k\ell}} \int_{A_{k\ell}} [\Delta M m](x, y) dA. \quad (8)$$

The tendencies from the parameterizations are computed on the physics grid. The tracer tendency in physics grid cell  $k$  is denoted  $f_k^{(pg)}$ . The problem is how to map  $f_k^{(pg)}$  to the CSLAM control volumes  $f_{\ell}^{(nc)}$  satisfying the following constraints:

### 1. Local mass-conservation

$$f_k^{(pg)} \Delta p_k^{(pg)} = \cup_{\ell=1}^{nc^2} \Delta A_{k\ell} \Delta p_{\ell}^{(nc)} f_{\ell}^{(nc)}, \quad (9)$$

where  $\Delta p_k^{(pg)}$  is the pressure level thickness in physics grid cell  $k$  and similarly for  $\Delta p_{\ell}^{(nc)}$ .

2. **Shape-preservation in mixing ratio:** The forcing on the CSLAM grid should not produce a value smaller than the new physics grid mixing ratio,  $m_k^{(pg)} + \Delta t f_k^{(pg)}$  or a value smaller than the existing CSLAM mixing ratios over the overlap areas  $m_{k\ell}^{(nc)}$

$$m_k^{(min)} = \min \left( m_k^{(pg)} + \Delta t f_k^{(pg)}, \left\{ m_{k\ell}^{(nc)} | \ell = 1, nc^2 \right\} \right), \quad (10)$$

where  $\Delta t$  is the physics time-step. Similarly for maxima

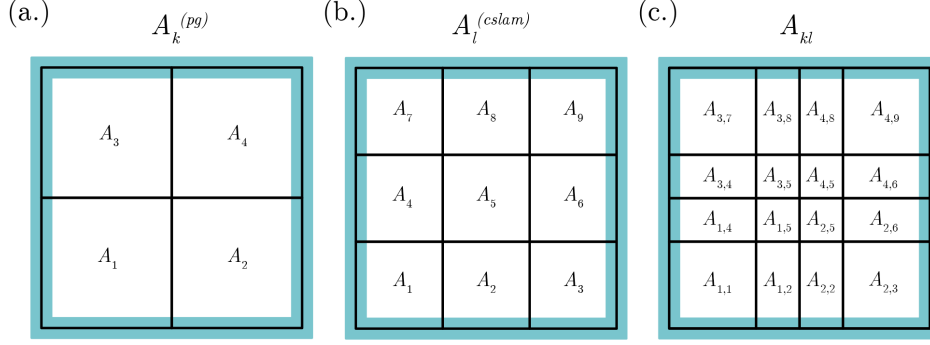
$$m_k^{(max)} = \max \left( m_k^{(pg)} + \Delta t f_k^{(pg)}, \left\{ m_{k\ell}^{(nc)} | \ell = 1, nc^2 \right\} \right), \quad (11)$$

3. **Linear correlation preservation:** The physics forcing must not disrupt linear tracer correlation between species on the CSLAM grid [see, e.g., Lauritzen and Thuburn, 2012].
4. **Consistency:** A constant mixing ratio tendency,  $cnst$ , on the physics grid,  $f_k^{(pg)} = cnst \forall k$ , must result in the same (constant) forcing on the CSLAM grid,  $f_{\ell}^{(nc)} = f_k^{(pg)} = cnst \forall \ell$ .

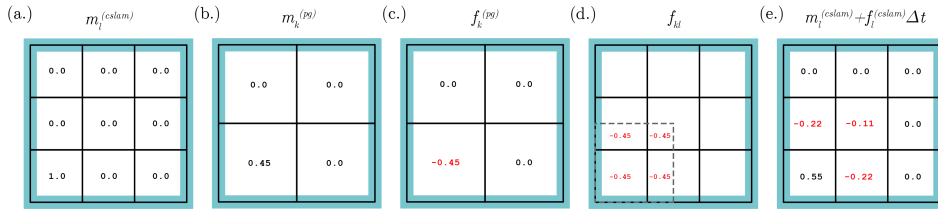
To motivate the algorithm that will simultaneously satisfy 1-4 it is informative to discuss how ‘standard’ mapping algorithms will violate one or more of the constraints.

- Conservative remapping:
- Interpolation:

some text about how challenging it is to satisfy 1-3 simultaneously



**Figure 1.** Indice notation for the (a)  $pg2$  grid, (b),  $pg3$  grid and (c) their exchange grid. **Peter - do you think you will use this figure?**



**Figure 2.** Make captions stand-alone while being concise

## 2.2 Algorithm

Preserving linear correlations in mapping to and from the CSLAM and  $pg2$  grids requires additional considerations; one such problem is depicted schematically in Figure 2. Consider a single element of CSLAM control volumes, containing only a single cell with mixing ratio 1.0, and 0.0 everywhere else ( $m_l$ ; Figure 2a). Assume that the mixing ratios mapped to the  $pg2$  grid ( $m_k$ ; Figure 2b) results in a negative tracer tendency from the physics ( $f_k$ ; Figure 2c). The non-zero values of the tendencies for  $pg2$  areas overlapping CSLAM grid cells originally containing a mixing ratio of zero ( $f_{k,l}$ ; Figure 2d), are driven negative by the mapped tendency (Figure 2e). Preserving linear correlations in mapping to and from grids with different degrees of freedom can not be guaranteed without additional modifications to the mapping procedure.

**Describe algorithm here**

**Peter - I think the results of the terminator tests should be mentioned here. We could just put in a sentence saying it passes. But I'm assuming that if we don't use the algorithm that weights the tendency by the amount of available mixing ratio, it will fail. If that's the case, we could just do a two panel plot showing the iCLy at day 15 for with and without the algorithm.**

### 2.3 Model Configurations

Two model configurations using the Community Earth System Model, version 2.1 (CESM2.1; <https://doi.org/10.5065/D67H1H0V>) are chosen to carry out the objectives discussed in Section 1. To test the hypothesis, that the *pg2* grid reduces spurious grid-noise over mountainous regions, a Held-Suarez configuration [FHS94 compset; Held and Suarez, 1994] modified to include real world topography is analyzed. H18 indicate that this configuration tends to have more grid-noise over steep terrain than in a more complex configuration using CAM, version 6 moist physics [CAM6; ], and is therefore a conservative choice for evaluating any change in grid imprinting between *pg3* and *pg2*.

To understand whether the resolved scales of motion are influenced by a coarser resolution physics grid, a suite of aqua-planet simulations [Neale and Hoskins, 2000; Medeiros *et al.*, 2016] are carried out over a range of spectral-element grid resolutions, using CAM6 physics (QPC6 compset). The aqua-planet is an ocean covered planet in perpetual equinox, with fixed, zonally-symmetric sea surface temperatures idealized after present day Earth [QOBS in Neale and Hoskins, 2000]. While the dynamics time-step,  $\Delta t_{dyn}$ , varies with resolution according to a CFL criterion, there is no established standard for how the physics time-step,  $\Delta t_{phys}$ , should vary across resolutions. This is further complicated by several studies indicating a high sensitivity of solutions to  $\Delta t_{phys}$  in CAM [Williamson and Olson, 2003; Williamson, 2013; Wan *et al.*, 2015; Herrington and Reed, 2018].

Here, a scaling for  $\Delta t_{phys}$  across resolutions is proposed, based on results of the moist bubble test [Herrington and Reed, 2018] using CAM-SE-CSLAM and detailed in Appendix A: . The basis for the scaling is to alleviate truncation errors that arise in the moist bubble test when  $\Delta t_{phys}$  is too large. The scaling is linear in grid-spacing,

$$\Delta t_{phys} = \Delta t_{phys,0} \times \frac{N_e}{N_{e,0}} \text{ s}, \quad (12)$$

where  $\Delta t_{phys,0}$  is taken to be the standard 1800s used in CAM-SE-CSLAM at low resolution,  $N_{e,0} = 30$  (equivalent to a dynamics grid-spacing of 111.2km).  $N_e$  refers to the horizontal resolution of the grid; each of the six panels of the cubed-sphere are divided into  $N_e \times N_e$  elements. Throughout the paper, spectral-element grid resolutions are denoted by an *ne* followed by the quantity  $N_e$ , e.g., *ne30*.

The only other parameter varied across resolutions modulates the strength of explicit numerical dissipation. The spectral element method is not implicitly diffusive, so fourth-order hyper-viscosity operators are applied to the state to suppress numerical artifacts. The scaling of the hyper-viscosity coefficients,  $\nu$ , across resolutions is defined as,

$$\nu_T = \nu_{vor} = 0.30 \times \left( \frac{30}{N_e} 1.1 \times 10^5 \right)^3 \frac{m^4}{s}, \quad (13)$$

$$\nu_p = \nu_{div} = 0.751 \times \left( \frac{30}{N_e} 1.1 \times 10^5 \right)^3 \frac{m^4}{s}, \quad (14)$$

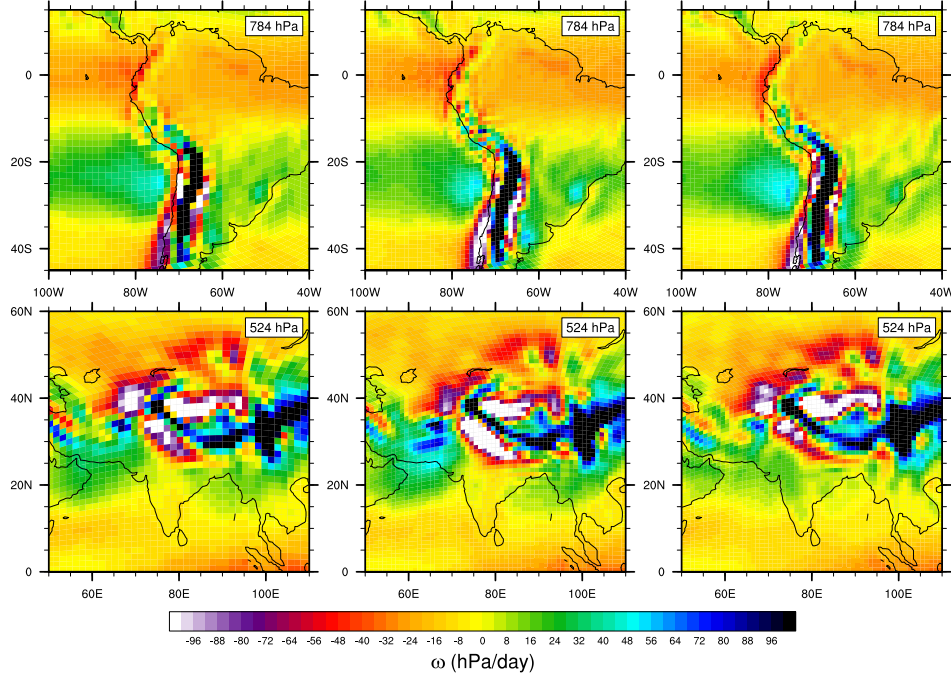
where subscripts *T*, *vor*, *p*, *div* refer to state variables the operators are applied to, temperature, vorticity, pressure and divergence, respectively. The scaling reduces the coefficient by an order of magnitude for each doubling of the resolution [as in Lauritzen *et al.*, 2018]. No explicit dissipation of tracers (e.g., water vapor) is required since the semi-Lagrangian numerics in CSLAM are diffusive.

## 3 Results

### 3.1 Held-Suarez with Topography

Flow over topography can result in significant grid imprinting using the spectral element method [Lauritzen *et al.*, 2015, H18]. Figure 3 shows the results of the Held-Suarez





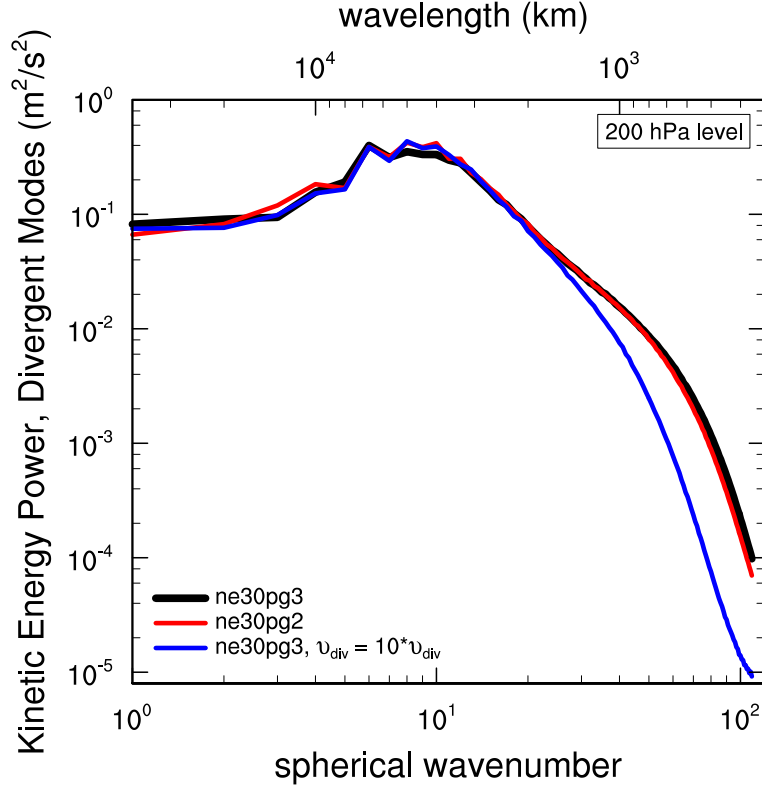
**Figure 3.** Mean  $\omega$  at two model levels in the middle troposphere, in a Held-Suarez configuration outfitted with real world topography. (Left) *ne30pg2* (Middle) *ne30pg3* and (Right) *ne30pg3* with the divergence damping coefficient increased by an order of magnitude. The  $\omega$  fields are computed a two-year simulation. The data are presented on a raster plot in order to identify individual grid cells

with topography simulations. The middle panel is the vertical pressure velocity,  $\omega$ , averaged over two years, over the Andes and Himalayan region at two different levels in the mid-troposphere, using the *ne30pg3* grid. The fields are displayed as a raster plot on the physics grid, so that individual extrema, which characterize the flow over the Andes between about  $10^\circ - 20^\circ$  S, may be identified as spurious. Near the foot of the Himalayas, between about  $20^\circ - 30^\circ$  N, there are stripes of extrema aligned with the mountain front that appear to be spurious  $2\Delta x$  oscillations.

As discussed in H18, grid imprinting over mountainous terrain tends to occur in regions of weak gravitational stability, causing extrema to extend through the full depth of the troposphere as resolved updrafts and downdrafts. Thus, grid imprinting over mountains may be alleviated through increasing the divergence damping in the model. Figure 3 (right panel) repeats the *ne30pg3* simulation through increasing  $\nu_{div}$  by an order of magnitude. The spurious noise over the Andes and the Himalayas are damped, and grid point extrema tend to diffuse into neighboring grid cells. The wavenumber-power spectrum of the kinetic energy due to divergent flow (Figure 4) confirms that divergent modes are damped at higher wavenumbers (greater than 30), by about an order of magnitude relative to the default *ne30pg3* simulation.

The  $\omega$  field of the *ne30pg2* simulation is provided in Figure 3 (left panel). Grid cell extrema over the Andes is less prevalent than in the *ne30pg3* simulation, as seen by the reduction in large magnitude  $\omega$  (e.g., red grid cells). The spurious oscillations at the foot of the Himalayas appear to have been entirely eliminated. This improvement in grid imprinting is due to the consistent numerical properties of the control volumes in the *pg2* grid compared with the *pg3* grid discussed in Section 1, and these results are consistent





**Figure 4.** Kinetic energy power spectrum arising from divergent modes in *ne30pg3*, *ne30pg2* and *ne30pg3* with the divergence damping coefficient increased by an order of magnitude, in the Held-Suarez with topography simulations. Spectra computed from five months of six-hourly winds.

with our hypothesis. The divergent modes are marginally damped relative to *ne30pg3* for wavenumbers greater than about 50, but are an order of magnitude larger than in the enhanced divergence damping *ne30pg3* run (Figure 4). From a model development standpoint, the *pg2* configuration is preferable to placing additional constraints on  $v_{div}$  in a *pg3* configuration, since this coefficient is one of only a handful of free parameters available to tune CAM-SE.

### 3.2 Aqua-planets

The Tropical regions are very sensitive to horizontal resolution, primarily due to the scale dependence of resolved updrafts and downdrafts at hydrostatic scales [Herrington and Reed, 2017, 2018]. The vertical velocity of updrafts and downdrafts is related to the horizontal length scales of buoyancy the model is able to support. A scale analysis of the Poisson equation [Jeevanjee and Romps, 2016] at hydrostatic scales shows that the ratio of the scale of  $\omega$  at two resolutions, due to their respective buoyancies is,

$$\frac{\omega_{\Delta x_1}}{\omega_{\Delta x_2}} = \frac{D_{\Delta x_2}}{D_{\Delta x_1}}, \quad (15)$$

where  $D_{\Delta x}$  is a characteristic buoyancy length scale for grid-spacing  $\Delta x$  (hereafter referred to as the *forcing scale*), and it is presumed that the magnitude of the buoyancy and the vertical scale of the buoyancy is unchanged or compensating across the two resolutions. Equation 15 indicates that the magnitude of the vertical velocity scales like the inverse of the forcing scale, which was verified in a simple moist bubble configuration using CAM-

**Table 1.**  $\Delta x$  and  $\Delta t$  for the physics and dynamics in the low resolution simulations

Grid name	$\Delta x_{dyn}$	$\Delta t_{dyn}$	$\Delta x_{phys}$	$\Delta t_{phys}$
ne20pg3	166.8km	300s	166.8km	1800s
ne30pg2	111.2km	300s	166.8km	1800s
ne30pg3	111.2km	300s	111.2km	1800s

SE and the CAM finite-volume dynamical core [CAM-FV; *Herrington and Reed, 2018*] and using CAM-SE-CSLAM (Appendix A: ). It is by no means trivial that equation 15 holds for the moist bubble test, since the scaling is derived from the dry anelastic equations.

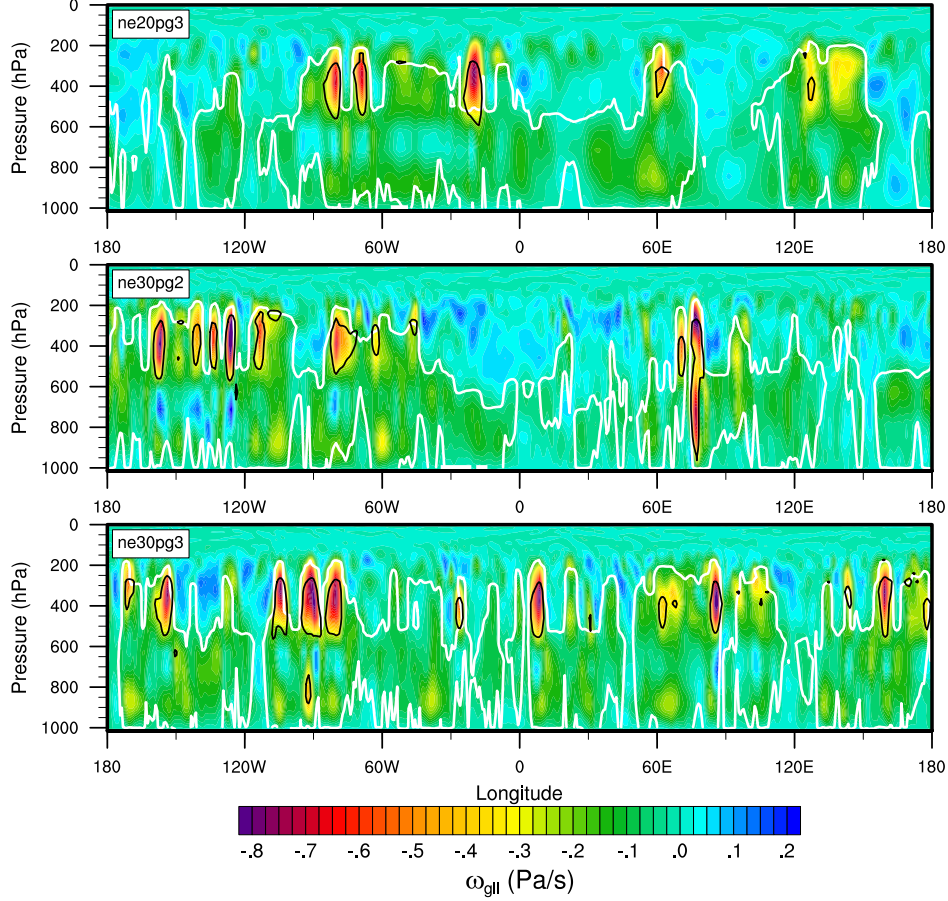
In aqua-planet configurations, the forcing scale varies with resolution in the range of five to ten times the grid-spacing in CAM-SE [*Herrington and Reed, 2018*], which from equation 15 explains why the updrafts and downdrafts are so sensitive to horizontal resolution. The forcing scale is analogous to an effective resolution, which is the characteristic length scale below which the solution is contaminated by numerical dissipation, and the features are overly damped. The effective resolution may be inferred from kinetic energy spectra as the wavenumber where the slope of the spectrum becomes steeper than the observationally determined slope [*Skamarock, 2011*]. In the CESM2 release of CAM-SE, this criterion occurs near wavenumber 60 [see Figure 6 in *Lauritzen et al., 2018*], a length scale of about six times the grid spacing, and overlapping with the forcing scale estimated by [*Herrington and Reed, 2018*] using a slightly older version of the model.

When the physics and dynamics grids are of different resolutions, which grid determines the models characteristic forcing scale? The remainder of section 3 attempts to address this question using spectral element grids at low resolution (Section 3.2.1), high resolution (Section 3.2.2) and across all resolutions typical of present day General Circulation Models (Section 3.2.3).

### 3.2.1 Low Resolution

The question posed above may be addressed through comparing *ne30pg2*, where  $\Delta x_{phys} = 166.8km$ ,  $\frac{3}{2}$  times larger than the dynamics grid spacing,  $\Delta x_{dyn} = 111.2km$ , to a simulation where both are equal to the physics grid resolution,  $\Delta x_{dyn} = \Delta x_{phys} = 166.8km$  (*ne20pg3*), and another simulation where both are equal to the dynamics resolution,  $\Delta x_{dyn} = \Delta x_{phys} = 111.2km$  (*ne30pg3*). The resolvable scales in the *ne30pg2* solution are expected to be bounded by the *ne20pg3* and *ne30pg3* solutions. Although according to equation 12,  $\Delta t_{phys}$  for *ne20* grids should be different from *ne30* grids, here it is set to the *ne30* value (see Table 1) in order to reduce the differences between the three configurations, and justified because lower resolution runs aren't very sensitive to this range of  $\Delta t_{phys}$  (Figure A.3).

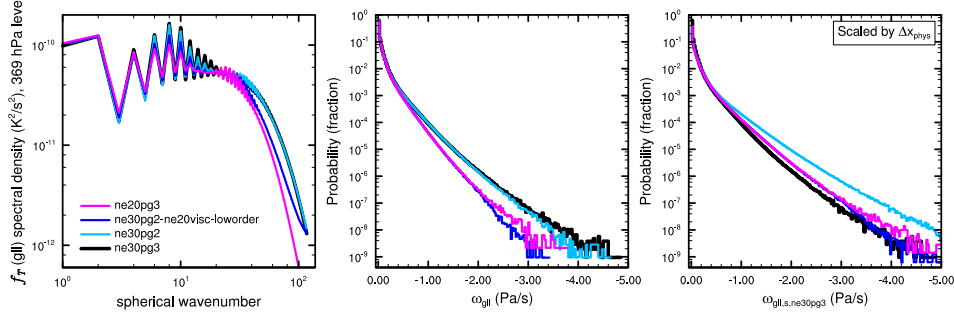
Figure 5 shows a snapshot of the  $\omega$  field in the Inter-Tropical Convergence Zone (ITCZ) in the pressure-longitude plane, in the three simulations. The  $\omega$  field is overlain with the  $\pm 15K/day$  contour of the physics temperature tendencies (black), which are primarily due to stratiform cloud formation. Since the component of  $\omega$  due to buoyancy is determined by the physics temperature tendencies mapped to the GLL grid, the tendencies and  $\omega$  are shown on the GLL grid,  $f_T^{(gll)}$  and  $\omega_{gll}$ , respectively. The white contour is intended to outline regions where the deep convection scheme is fairly active, set to the  $0.0075kg/m^2/s$  value of the convective mass fluxes (note the convective mass fluxes have not been mapped to the GLL grid, and are instead shown on the *pg* grid). The figure indicates that large regions of the ITCZ are comprised of upward  $\omega$  that balance the



**Figure 5.** Snapshots in the longitude-pressure plane of  $\omega_{gll}$  through the ITCZ region in the *ne20pg3*, *ne30pg2* and *ne30pg3* configurations. Black is the  $\pm 15K/day$  contour of the physics tendencies, and the white contour is the  $0.0075 kg/m^2/s$  contour of the parameterized deep convective mass fluxes.

warming due to compensating subsidence produced by the deep convection scheme. Much larger magnitude  $\omega$  are comprised of resolved updrafts driven by the buoyancy of stratiform clouds, and resolved downdrafts due to evaporation of condensates produced by overlying clouds [Herrington and Reed, 2018]. These large buoyancy stratiform clouds tend to form in the middle-to-upper troposphere due to detrainment of moisture by the deep convection scheme [Zhang and McFarlane, 1995].

It is not obvious from the snapshots in Figure 5 whether the characteristic length scale of the stratiform clouds, assumed here to be equal to the forcing scale, is any different across the three simulations. Analogous to determining the effective resolution [Skamarock, 2011], the forcing scale may be inferred from the wave-number power spectrum of  $f_T^{(gll)}$  as the maximum wavenumber prior to the steep, un-physical decline in power that characterizes the near-grid scale (hereafter  $f_T^{(gll)}$  is referred to as the *forcing*). The wave-number power spectrum of the forcing in the middle-to-upper troposphere is shown in Figure 6a. The slope of the *ne20pg3* spectrum begins to steepen at smaller wavenumbers than in the *ne30pg3* spectra. Additionally, the *ne30pg2* spectra is remarkably similar to the *ne30pg3* spectra, for all wavenumbers. These spectra indicate that the forcing scale for *ne30pg2* and *ne30pg3* are similar, and that both are less than the *ne20pg3* forcing scale.



**Figure 6.** (Left) Wavenumber-power spectrum of the temperature tendencies from the moist physics, near the 369 hPa level, (Middle) probability density distribution and (Right) the scaled probability density distribution of upward  $\omega$  everywhere in the model. The scaled distributions are scaled to *ne30pg3* using  $\Delta x_{phys}$ .  
need to add a, b, c labels

From equation 15, it is expected that the magnitude of the vertical motion is larger in the *ne30pg2* and *ne30pg3* simulations.

The probability density function (PDF) of upward  $\omega_{gll}$  everywhere in the simulations is shown in Figure 6b. Larger magnitude  $\omega_{gll}$  are more frequent in the *ne30pg2* run, compared to *ne20pg3*, and the PDF is actually more similar to the *ne30pg3* distribution, consistent with their similar forcing scales. This may be further illustrated through scaling the PDF's,

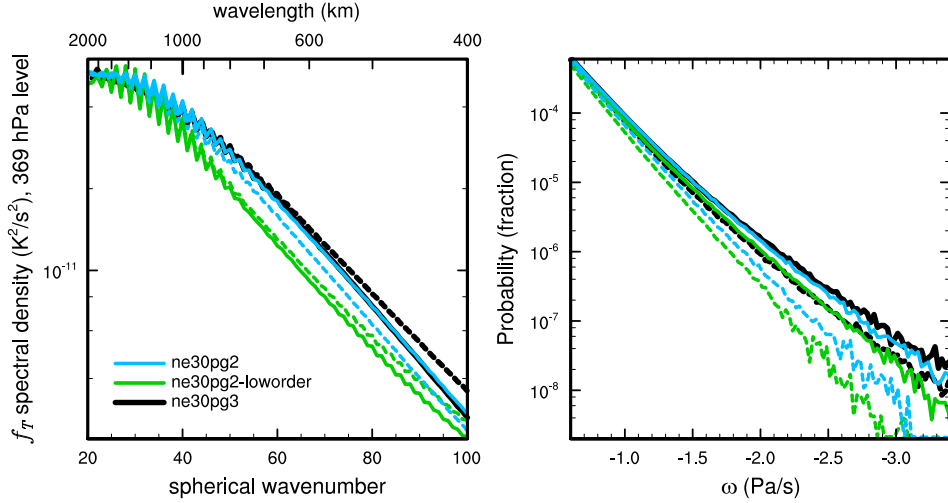
$$P_s(\omega) = \alpha \times P(\omega/\alpha), \quad (16)$$

where  $P_s(\omega)$  is the scaled PDF of  $\omega$  and  $\alpha$  is the ratio of  $\omega$  to  $\omega_{target}$ , the  $\omega$  associated with the target grid resolution,  $\Delta x_{target}$ . If one assumes the forcing scale is linear in  $\Delta x$ , then from equation 15,  $\alpha = \Delta x_{target}/\Delta x$ . The target resolution is taken here to be  $\Delta x$  of the *ne30pg3* grid.

If the forcing scale of *ne30pg2* is in fact determined by  $\Delta x_{phys}$ , then one sets  $\Delta x = \Delta x_{phys}$  in  $\alpha$ . This scaled PDF, however, severely overestimates the frequency of upward  $\omega$  of the target resolution, *ne30pg3* (Figure 6c). It is clear from the similarity of the unscaled PDF's of *ne30pg2* and *ne30pg3*, and their forcing spectra, that the forcing scale is determined by  $\Delta x_{dyn}$ , rather than  $\Delta x_{phys}$ . Additionally, the scaled *ne20pg3* PDF fits the *ne30pg3* distribution quite well, indicating that the linear framework used to approximate  $\alpha$  is valid across these two resolutions, and that the forcing scale of *ne20* grids are about  $\frac{3}{2}$  times that of the *ne30* grids.

There are two reasons the forcing scale is determined by the *GLL* grid, and not the *pg* grid. The first being that the hyper-viscosity coefficients are a function of the *GLL* grid resolution (equation 14). The fourth-order hyperviscosity is very scale selective, targeting near grid-scale features more so than, e.g., a second-order operator. The difference in  $\Delta x_{phys}$  between *pg2* and *pg3* are small enough that the hyperviscosity operators render this distinction somewhat ambiguous, and the forcing scale is not all that sensitive to the coarser physics. Through increasing  $\nu$  in *ne30pg2* to *ne20* values, the forcing spectrum begins to steepen at lower wavenumbers compared with the standard *ne30pg2* run, although still at a higher wave-number than in the *ne20pg3* run (not shown).

The other reason the forcing scale is determined by the *GLL* grid, is that high-order mapping of the forcing from the *pg2* grid, to the *GLL* and *CSLAM* grids helps reconstruct scales that are not supported on the *pg2* grid. Figure 7a shows a close-up of the wavenumber power spectrum of the forcing on the *pg* grid (dotted), where it is computed,



**Figure 7.** (Left) Wavenumber-power spectrum of the temperature tendencies from the moist physics, at the 369 hPa level, and (right) probability density distribution of upward  $\omega$ , everywhere in the model, for three year-long aqua-planet simulations. Solid lines refer to values of on the *GLL* grids, and dashed lines, the fields on the *pg* grids. See text for details regarding the three simulations.

and on the *GLL* grid (solid), where it has been mapped. In *ne30pg3*, the magnitudes are similar on both grids, except the mapping tends to damp the high wavenumbers of the forcing on the *GLL* grid (larger than 65). For *ne30pg2*, the magnitude of the forcing is actually greater after mapping to the *GLL* grid, and more similar to the forcing in the *ne30pg3* simulations. The high-order mapping can therefore replicate the scales of the physics tendencies that occur in the *pg3* simulation, even though the physics are evaluated on a coarser *pg2* grid.

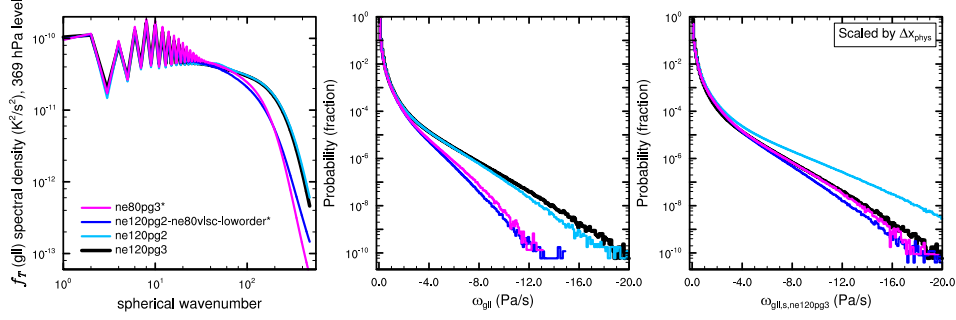
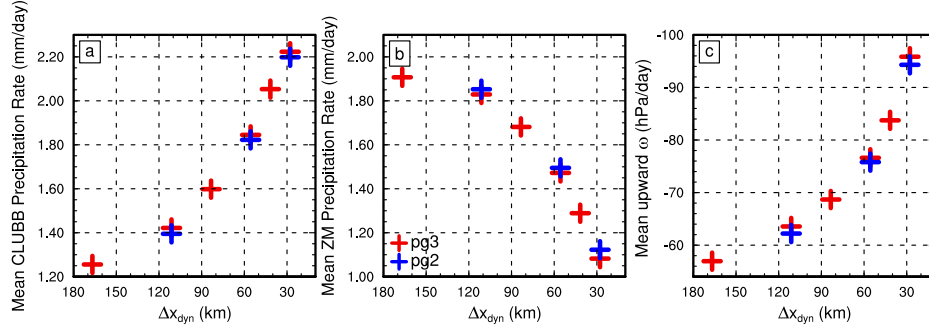
The importance of the high-order mapping can be shown with an additional *ne30pg2* simulation, using low-order mapping (*ne30pg2 – loworder* in Figure 7). Specifically, low-order mapping refers to piecewise constant mapping from *pg2* to *CSLAM* and bilinear mapping from *pg2* to *GLL*. The forcing spectrum is now similar on both the *pg2* and *GLL* grids, although the low-order mapping tends to damp the forcing on the *GLL* grid for wavenumbers greater than about 60 (Figure 7a). A close up of the PDF of  $\omega_{gll}$  is provided in Figure 7b (solid lines). As expected, the frequency of large magnitude  $\omega_{gll}$  in the low-order run is less compared to the default *ne30pg2* simulation.

The dotted lines in Figure 7b show the PDF of  $\omega$  on the *pg* grids. The frequency of large magnitude  $\omega$  is reduced on the *pg* grids, compared to the state on the *GLL* grids. This is primarily due to the smoothing effect of integrating the nodal point values over control volumes (H18). The larger  $\omega$  values are even less frequent on the *pg2* grid due to integrating over control volumes  $\frac{9}{4}$  times greater than the *pg3* control volumes.

In sum, at low resolution, the default *pg2* configuration does not degrade the resolution of the model since (1) the *GLL* resolution is unchanged and (2) the high-order mapping is able to reproduce a state similar to what occurs in a *pg3* configuration. Increasing the hyper-viscosity coefficients is akin to reducing the resolution of the *GLL* solution. The combined effect of these two factors can be illustrated through an *ne30pg2* simulation that uses low-order mapping, and with hyper-viscosity coefficients set to *ne20* values (*ne30pg2 – ne20visc – loworder* in Figure 6). The simulation more closely resembles

**Table 2.**  $\Delta x$  and  $\Delta t$  for the physics and dynamics in the high resolution simulations

Grid name	$\Delta x_{dyn}$	$\Delta t_{dyn}$	$\Delta x_{phys}$	$\Delta t_{phys}$
ne80pg3	41.7km	112.5s	41.7km	625s
ne120pg2	27.8km	75s	41.7km	450s
ne120pg3	27.8km	75s	27.8km	450s

**Figure 8.** As in Figure 6, but for the high resolution simulations. Asterisks indicate that the physics time-step in these simulations are  $\Delta t_{phys} = 675s$ , which is larger than that used for the default *ne120* runs (see Table 2). **need to add a, b, c labels.** And why is there so many spaces around the equal sign?**Figure 9.** Global mean, time-mean (a) CLUBB precipitation rate, (b) parameterized deep convective precipitation rate and (c) upward  $\omega$ . All computed from the final 11 months of one-year simulations, and upward  $\omega$  is computed using 6-hourly output.

the *ne20pg3* run. In this case, the forcing scale is more accurately determined by  $\Delta x_{phys}$ , since the scaled PDF matches the *ne30pg3* simulation quite well (Figure 6c).

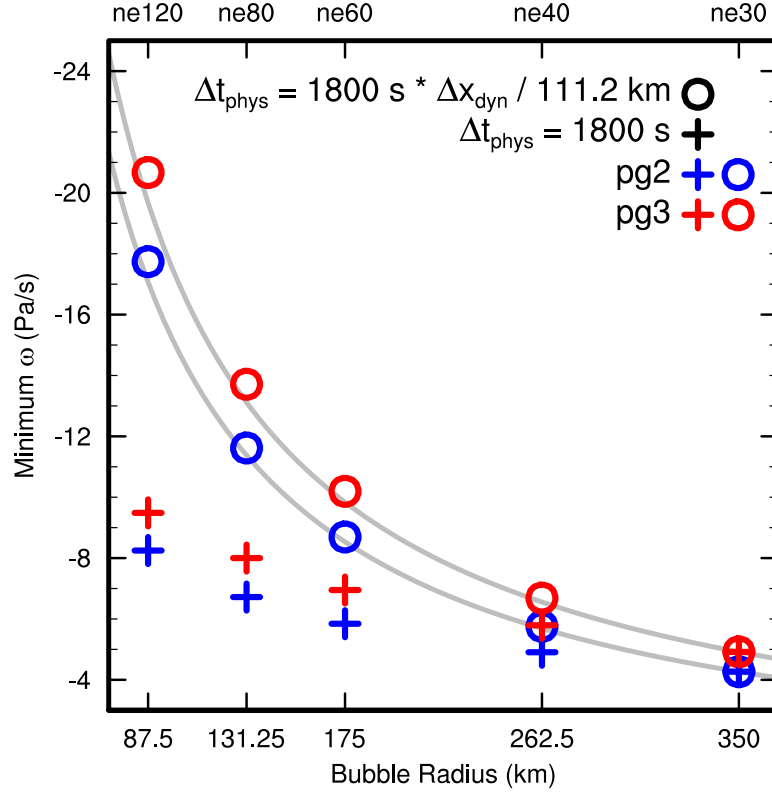
### 3.2.2 High Resolution

### 3.2.3 Across Resolutions

## 4 Conclusions

Mitigating grid-imprinting through increasing the divergence damping coefficient an order of magnitude greater than is required for numerical stability is not ideal from a model development perspective. The hyper-viscosity coefficients are one of the only a





**Figure A.1.** The magnitude of  $\omega$  in the *pg3* solutions are systematically larger than the *pg2* solutions, which is primarily a result of the damping effect of integrating the basis functions over a larger control volume.

**Figure A.2.**

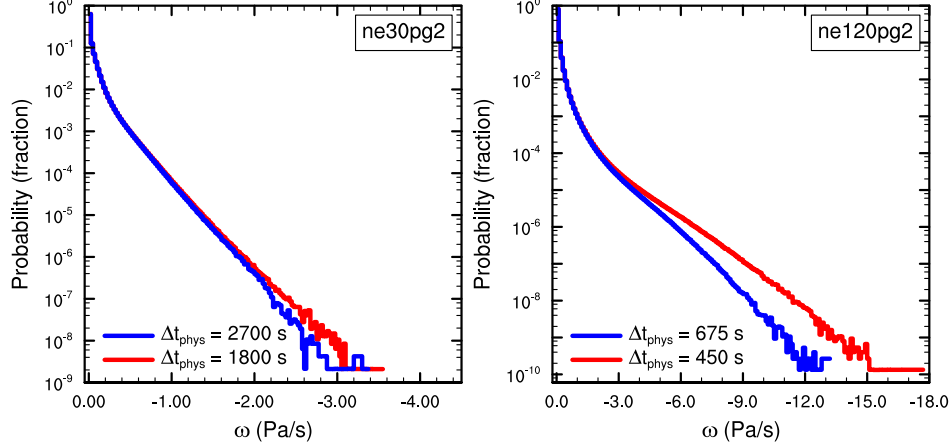
handful of free-parameters in CAM-SE to tune the kinetic energy spectrum to match observations [Skamarock *et al.*, 2014; Lauritzen *et al.*, 2018].

#### A: Defining $\Delta t_{phys}$ across resolutions

Herrington and Reed [2018] developed a moist bubble test, which indicate that time-truncation errors are large at high resolution (roughly 50km and less), and may provide insight on a reasonable scaling of  $\Delta t_{phys}$  across resolutions in more complex configurations. In the test a set of non-rotating simulations are initialized with a super-saturated thermal bubble, and the grid spacing and bubble radius are simultaneously reduced by the same factor in each run through varying the planetary radius. The test was designed to mimic the reduction in buoyancy length scales that occur when the model resolution is increased in more complex configurations [Hack *et al.*, 2006; Herrington and Reed, 2018].

The moist bubble test is performed with CAM-SE-CSLAM and coupled to the simple condensation routine of Kessler [1969] across five different resolutions (pertaining to the *ne30*, *ne40*, *ne60*, *ne80*, and *ne120* grids). The results are expressed as the minimum  $\omega$  throughout each one day simulation, and shown in Figure A.2. Two sets of simulations are performed with both *pg3* and *pg2*, one with  $\Delta t_{phys}$  determined by equation 12, and an equivalent set of simulations with  $\Delta t_{phys} = \Delta t_{phys,0}$  for all resolutions.





**Figure A.3.** Probability density distribution of upward  $\omega$  everywhere in the model in the aqua-planets using the *ne30pg2* grid (Left) and the *ne120pg2* grid (Right). Figure computed for one year of 6-hourly data. The different colors indicate the physics time-steps used in the runs.

Since the diameters of the bubbles,  $D$ , are set proportional to  $\Delta x_{dyn}$ , *Herrington and Reed* [2018] has shown that  $\omega$  converges to the scaling of equation 15 in the limit of small  $\Delta t_{phys}$ , where small  $\Delta t_{phys}$  is defined as  $\Delta t_{phys} = \Delta t_{dyn}$ , where  $\Delta t_{dyn}$  is the CFL limiting time-step. Equation 15 is overlain as grey lines in Figure A.2, with *ne30* being the reference resolution. The solutions using  $\Delta t_{phys}$  from equation 12 follow the scaling, whereas fixing  $\Delta t_{phys} = 1800$ s across resolutions damps the solution relative to the analytical solution, progressively more so at higher resolutions. If  $\Delta t_{phys}$  is too large, the solution has non-negligible error, which is avoided through scaling  $\Delta t_{phys}$  according to equation 12.

It is not clear if the results of the idealized test extend to the results of more complex configurations. To get a handle on whether the test is useful for understanding more realistic configurations, four aqua-planet simulations are performed with CAM6 physics. A pair of *ne30pg2* simulations, one in which  $\Delta t_{phys}$  is set to the appropriate value from equation 12 (1800s), and one where it is set to the  $\Delta t_{phys}$  corresponding to the *ne20* resolution (2700s). Similarly, a pair of *ne120pg2* simulations are performed, one with  $\Delta t_{phys}$  set to the value from equation 12 (450s), one with  $\Delta t_{phys}$  set to the *ne80* value (625s).

Figure A.3 shows the PDFs of  $\omega$  from a year of six-hourly data in the simulations. At lower resolution,  $\Delta t_{phys}$  has only a very small effect on the solution, near the tail-end of the distributions (Figure A.3a). At high-resolution, values of  $\omega$  less than about  $3\text{ Pa/s}$  are more frequent in the small  $\Delta t_{phys}$  run, with the discrepancy growing more for larger magnitudes of  $\omega$  (Figure A.3b). These results are similar to the aqua-planet results in *Herrington and Reed* [2018] using a prior version of CAM physics, version 5, and show that solutions are more sensitive to  $\Delta t_{phys}$  at higher-resolution. The progressively larger errors with increasing resolution also manifests in the moist bubble tests, indicating that truncation errors arising from large  $\Delta t_{phys}$  do exist in more complex configurations.

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