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Convolution based techniques for computing self attraction and loading in MOM6

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Abstract. Self Attraction and Loading (SAL), which accounts for the deformation of the solid Earth under the load of the ocean tide and the self-gravitation of the so-deformed Earth as well as of the ocean tides themselves, is an important effect to include in numerical models of the ocean tides. Computing the SAL potential and its gradient is a challenging problem that is often accomplished using the spherical harmonics transform (SHT), but that approach has drawbacks which limit its accuracy. This work employs an alternative approach based on computing the spherical convolution integral, utilizing two implementations of the SAL Green's function, a closed form approximation, and a tabular version regularized by Cesàro summation. The alternative approach is accelerated by the recently developed Cubed Sphere Fast Multipole Method (CSFMM). The convolution technique is implemented in the Modular Ocean Model, version 6, where it provides more accurate tides than those obtained with the SHT when measured against altimetry-based tides. Previous investigators have cited Gibbs phenomenon as a possible source of error in SHT calculations, and these errors, along with aliasing and finite differencing errors, are avoided by the convolution. The convolution approach has different sources of error including errors in the approximate SAL Green's function, quadrature error in computing the convolution integral, and interpolation error from the CSFMM. In addition to comparing the accuracy of the two approaches, we also present the runtime for parallel calculations using up to 1024 MPI ranks.

1 Introduction

Tides are an important component of the Earth system. In many open-ocean and coastal regions, tides dominate sea level and/or current variability. Tides are also implicated as a major element in the ocean mixing cycle, which contributes significantly to the background oceanic stratification in both the coastal and open ocean (Simpson and Hunter, 1974; Munk and Wunsch, 1998). Tides are a result of astronomical gravitational forcing, and this tidal forcing drives periodic changes in the sea surface height (SSH) and the currents. Hence an improved understanding of tidal dynamics is necessary for developing improved models.

Historically, tides were modeled separately from the rest of the ocean, primarily in barotropic tide models, which improved with increased computing power and data assimilation from satellite altimetry (Egbert et al., 1994; Le Provost et al., 1994; Parke and Hendershott, 1980; Ray, 1993; Schwiderski, 1980; Shum et al., 1997; Stammer et al., 2014). The first studies of tides in a baroclinic model were performed in regional configurations (Cummins and Oey, 1997; Kang et al., 2002; Merrifield et al., 2001). In the past two decades, as computers have improved, tides have been explicitly incorporated into ocean general circulation models (Arbic, 2022; Arbic et al., 2010; Müller et al., 2010; Schiller and Fiedler, 2007; Thomas et al., 2001; Rocha et al., 2016; Waterhouse et al., 2014). Running such models with combined tidal and atmospheric forcing at high spatial resolution

enables investigation of the interactions of barotropic and internal tides with oceanic phenomena across a wide range of scales, including mesoscale eddies, and other components of the Earth system including the cryosphere.

An important effect to capture when modeling the tides is Self Attraction and Loading (SAL). This encompasses the physical effects of the self gravitation of the oceanic tidal elevations, the elastic response of the Earth's crust to the loading of the ocean tide, and resulting changes in the Earth's gravitational potential due to the gravitation of the deformed solid Earth (Hendershott, 1972). SAL has a large effect on tides, changing their amplitude by up to 20 % and impacting their phase significantly as well (Gordeev et al., 1977). A simple computationally efficient approach to computing SAL uses the so-called scalar approximation (Accad and Pekeris, 1978), in which the SAL forcing term is approximated as a constant multiplied by the tidal elevation.

However, the scalar approximation is less accurate than a treatment using spherical harmonics, which properly account for the response of the ocean and solid Earth to harmonics of different scales (Ray, 1998). Many earlier studies that included the spherical harmonics SAL in tide models took an iterative approach using offline computations (Arbic et al., 2004; Egbert et al., 2004), where the SAL was calculated outside of the model run. The iterative approach is cumbersome. Early attempts to use the spherical harmonics SAL inline, as the model is running, found it to be too computationally expensive (Stepanov and Hughes, 2004). This is because calculating SAL requires global communication, in contrast to other terms in the momentum equations of numerical ocean models. More recent modeling using an inline spherical harmonics SAL has been aided by improvements in computational power (Barton et al., 2022; Brus et al., 2023; Schindelegger et al., 2018; Wang et al., 2024), yet this approach still encounters limitations on accuracy around coastlines (more below), and the fact that spherical harmonics, being global quantities, cannot easily be used in regional models.

Another approach to computing SAL, often used in the geodesy community, is based on a convolution of the sea surface height with a Green's function (Farrell, 1972; Schrama, 2005; Agnew, 2012; Martens et al., 2019). This approach has been explored in post-processing contexts, and past efforts at incorporating this method into an ocean model have faced difficulties with the expense of computing the convolution (Stepanov and Hughes, 2004). Here we employ the recently developed Cubed Sphere Fast Multipole Method (CSFMM; Chen and Krasny, 2025) to reduce the cost of computing the integral and enable efficient inline SAL calculations. The convolution SAL is implemented in the Modular Ocean Model, version 6, and the results show that it provides more accurate tides than those obtained with the spherical harmonics approach.

The paper is organized as follows. Section 2 presents the governing equations, describes the various methods for computing SAL, introduces our convolution SAL technique, and presents results comparing the different methods using a snapshot of the tidal sea surface height. Section 3 describes the model configuration used to test the convolution SAL. Section 4 presents results comparing tidal errors and computational efficiency using the convolution and spherical harmonics approaches. Conclusions are presented in Sect. 5.

2 Methods and Implementation

The Modular Ocean Model version 6 (MOM6) is a widely used open source numerical ocean general circulation model (Adcroft et al., 2019). The model is hydrostatic and solves either a Boussinesq or non-Boussinesq equation set. Here we use a single layer configuration in which the dynamical equations reduce to the shallow water equations on a sphere,

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} + \boldsymbol{f}\times\boldsymbol{u} = -g\nabla\eta + \mathcal{F}, \tag{1}$$

$$\frac{\partial \eta}{\partial t} + \nabla\cdot(h\boldsymbol{u}) = 0, \tag{2}$$

where t is time, $\boldsymbol{u}$ is the horizontal fluid velocity, $\boldsymbol{f} = f\boldsymbol{e}_{\mathrm{r}}$, where f is the Coriolis parameter and $\boldsymbol{e}_{\mathrm{r}}$ is the radial outward unit vector, η is the perturbation sea surface height, g is acceleration due to gravity, $\mathcal{F}$ are other forces (for instance, friction and tidal forcing terms), and h is the total water column thickness. If the ocean floor has height $b(\boldsymbol{x})$, then $\eta(t,\boldsymbol{x}) = h(t,\boldsymbol{x}) + b(\boldsymbol{x})$. Equation (1) expresses the balance of momentum, and Eq. (2) expresses the conservation of mass. For multi-layer configurations, this system can be supplemented with thermodynamic equations, and in that case it is often replaced by the more general Boussinesq or non-Boussinesq equations. The horizontal grid is based on a global tripolar discretization with an Arakawa C-grid. In this work the forcing term has several components,

$$\mathcal{F} = g\nabla(\eta_{\mathrm{EQ}} + \eta_{\mathrm{SAL}}) + \boldsymbol{F}_{\mathrm{wave}} + \boldsymbol{F}_{\mathrm{quad}} + \boldsymbol{F}_{\mathrm{h}}, \tag{3}$$

where η_{EQ} represents equilibrium tidal forcing corrected for the effects of solid earth body tides (Hendershott, 1972), η_{SAL} is the SAL potential, $\boldsymbol{F}_{\mathrm{wave}}$ is the linear wave drag, $\boldsymbol{F}_{\mathrm{quad}}$ is quadratic bottom boundary layer drag, and $\boldsymbol{F}_{\mathrm{h}}$ is horizontal viscosity. The linear wave drag includes a tunable parameter χ. Further details on the wave drag scheme are given by Jayne and St. Laurent (2001) and Buijsman et al. (2015). We refer to η_{SAL} as the SAL potential and $g\nabla\eta_{\mathrm{SAL}}$ as the SAL acceleration.

2.1 Spherical Harmonics for Computing SAL

Recent efforts to compute SAL inline (Schindelegger et al., 2018; Barton et al., 2022; Brus et al., 2023; Wang et al., 2024) have used spherical harmonics. In this technique, the spherical harmonics decomposition of the sea surface height η (i.e., the tidal mass anomaly) is computed, with spherical

harmonic coefficients $\widehat{\eta}_{n,m}$ given by

$$\widehat{\eta}_{n,m} = \int_0^{2\pi}\int_0^{\pi} Y_n^m(\theta,\phi)\eta(\theta,\phi)\cos\theta \mathrm{d}\theta\mathrm{d}\phi, \quad (4)$$

where Y_n^m is the degree n order m spherical harmonic, θ is the latitude, and ϕ is the longitude. In practice two approaches are available to compute these coefficients. One approach uses a fast spherical harmonics transform to reduce the operation count (Barton et al., 2022), but this approach faces challenges with parallel scaling, and additional interpolation steps are needed if the sea surface height is not given on a latitude-longitude grid. Another approach computes the integrals in Eq. (4) directly without using a fast transform as in Brus et al. (2023) and Wang et al. (2024). In this case the operation count is not reduced, but the direct calculation is better suited for parallelization.

Given the coefficients $\widehat{\eta}_{n,m}$, the SAL potential has the expansion

$$\eta_{\mathrm{SAL}}(\theta,\phi) = \sum_{n=0}^{\infty}\sum_{m=-n}^{n} \frac{3\rho_{\mathrm{w}}(1+k'_n-h'_n)}{\rho_{\mathrm{e}}(2n+1)}\widehat{\eta}_{n,m}Y_n^m(\theta,\phi), \quad (5)$$

where ρ_{w} and ρ_{e} are the average density of seawater and the Earth in kilograms per cubic meter, and k'_n and h'_n are the modified load Love numbers (LLNs) as discussed by Farrell (1972). We use average values for the real Earth, $\rho_{\mathrm{w}} = 1035\,\mathrm{kg\,m^{-3}}$, and $\rho_{\mathrm{e}} = 5517\,\mathrm{kg\,m^{-3}}$. When a multilayer model is used, the sea surface height is replaced with the bottom pressure anomaly and the coefficients $\widehat{\eta}_{n,m}$ are adjusted appropriately. In practice the sum in Eq. (5) is truncated, for example going up to degree $N = 40$ (Brus et al., 2023). Numerical experiments have found that using larger degrees has not significantly reduced the tidal error. The fact that tidal errors do not decrease past $N = 40$ can be attributed to Gibbs phenomenon and aliasing errors that occur when high wavenumber components in the solution are projected to low wavenumbers if the underlying spatial grid is not sufficiently fine (Sansò, 1990; Jekeli, 1996). These errors will be largest in coastal regions, and coastal tides have a significant back effect on the open ocean tides (Arbic et al., 2007, 2009; Arbic and Garrett, 2010). After computing the SAL potential η_{SAL}, the SAL acceleration $g\nabla\eta_{\mathrm{SAL}}$ is computed by finite differences, which can lead to additional errors by amplifying high wavenumber errors in η_{SAL}.

2.2 Gibbs Phenomenon

The Gibbs phenomenon occurs when truncating the Fourier series of a periodic function f with a jump discontinuity (Gottlieb and Shu, 1997). If f has a jump discontinuity, then finite truncations of the Fourier series of f will overshoot and undershoot around the discontinuity. This overshoot has a magnitude of approximately 9 %, and this oscillatory error does not diminish as more terms are used, but instead it becomes sharper and more concentrated around the discontinuity. In the context of computing SAL, the Gibbs phenomenon may arise from the finite truncation of a spherical harmonics series. When computing the spherical harmonic coefficients of the sea surface height $\widehat{\eta}_{m,n}$, the data field η is set to zero over land. While physically reasonable, this essentially introduces a jump discontinuity along coastlines, which adversely affects the convergence of the series. The presence of the Gibbs phenomenon in spherical harmonics calculations is a longstanding problem (Weyl, 1910; Gelb, 1997) and the geodesy community has advocated for an alternative based on convolution with a Green's function (Merriam, 1980; Schrama, 2005).

2.3 Cesàro Summation

Cesàro summation is a general method for improving the convergence properties of a series. In the case of the spherical harmonics series in Eq. (4), one defines the partial sums

$$S_J = \sum_{n=0}^{J}\sum_{m=-n}^{n} \frac{3\rho_{\mathrm{w}}(1+k'_n-h'_n)}{\rho_{\mathrm{e}}(2n+1)}\widehat{\eta}_{n,m}Y_n^m(\theta,\phi), \quad (6)$$

and then averages them to obtain the approximation

$$\eta_{\mathrm{SAL}}(\theta,\phi) \approx \frac{1}{N+1}\sum_{J=0}^{N} S_J, \quad (7)$$

which is equivalent to modifying the coefficients of the original series,

$$\eta_{\mathrm{SAL}}(\theta,\phi) \approx \sum_{n=0}^{N}\sum_{m=-n}^{n}\left(1-\frac{n}{N+1}\right) \cdot \frac{3\rho_{\mathrm{w}}(1+k'_n-h'_n)}{\rho_{\mathrm{e}}(2n+1)}\widehat{\eta}_{n,m}Y_n^m(\theta,\phi). \quad (8)$$

This technique can be implemented by modifying the existing spherical harmonics computation with no additional cost. Ideally, this technique will reduce the Gibbs phenomenon along coastlines, however at the same time, it introduces an error by modifying the LLNs. As far as we know, Cesàro summation has not previously been applied in spherical harmonics SAL computations.

2.4 Convolutions for Computing SAL

It is well known that the SAL potential can be computed as a convolution on the unit sphere S,

$$\eta_{\mathrm{SAL}}(\boldsymbol{x}) = \int_S G_{\mathrm{SAL}}(\boldsymbol{x}\cdot\boldsymbol{y})\eta(\boldsymbol{y})\mathrm{d}S(\boldsymbol{y}), \quad \boldsymbol{x},\boldsymbol{y}\in S, \quad (9)$$

where the SAL Green's function is

$$G_{\mathrm{SAL}}(\boldsymbol{x},\boldsymbol{y}) = \sum_{n=0}^{\infty}\frac{3\rho_{\mathrm{w}}(1+k'_n-h'_n)}{4\pi\rho_{\mathrm{e}}}P_n(\boldsymbol{x}\cdot\boldsymbol{y}), \quad (10)$$

and P_n is the nth degree Legendre polynomial (Farrell, 1972, 1973). Given a set of grid cells covering the sphere, the integral in Eq. (9) is computed using a numerical quadrature scheme. However, in order to use this Green's function, we cannot compute a truncated Legendre series in every single pairwise interaction in the discretized N-body sum, as this would be prohibitive in an ocean model where the SAL term is computed inline at every time step. There are two possible approaches that we can take. The first is to numerically sum the Green's function to a high degree outside of the model and tabulate the results, interpolating between values as needed. This approach has been taken previously (Farrell, 1972; Guo et al., 2004; Schrama, 2005; Martens et al., 2019). The other is to approximate the LLNs in order to find a closed form Green's function. Working with the LLNs in Wang et al. (2012), we empirically determined the following approximations,

$$k'_n \approx a_1/n, \quad h'_n \approx b_0 + b_1/n,$$
$$a_1 = -2.7, \quad b_0 = -6.21196, \quad b_1 = 6.1. \tag{11}$$

Then substituting in Eq. (10) and using the identities (Gradshteyn and Ryzhik, 2014),

$$\sum_{n=0}^{\infty} P_n(x) = \frac{1}{\sqrt{2(1-x)}},$$
$$\sum_{n=1}^{\infty} \frac{1}{n} P_n(x) = -\ln\left(\sqrt{\frac{1-x}{2}} + \frac{1-x}{2}\right), \tag{12}$$

a closed form approximation for the Green's function is obtained,

$$G_{\mathrm{SAL}}(\boldsymbol{x}, \boldsymbol{y}) \approx \frac{3\rho_{\mathrm{w}}}{4\pi\rho_{\mathrm{e}}}\left(\frac{1-b_0}{\sqrt{2-2\boldsymbol{x}\cdot\boldsymbol{y}}} - (a_1 - b_1)\ln\left(\sqrt{\frac{1-\boldsymbol{x}\cdot\boldsymbol{y}}{2}} + \frac{1-\boldsymbol{x}\cdot\boldsymbol{y}}{2}\right)\right). \tag{13}$$

From Eq. (3) we see that what is needed is the gradient of the SAL potential, $\nabla\eta_{\mathrm{SAL}}$. Assuming η_{SAL} has been computed, the gradient could be obtained by finite differences, but this could lead to large errors in coastal regions. Instead, taking the gradient of Eq. (9), one obtains

$$\nabla\eta_{\mathrm{SAL}}(\boldsymbol{x}) = \int_S \nabla G_{\mathrm{SAL}}(\boldsymbol{x}\cdot\boldsymbol{y})\eta(\boldsymbol{y})\mathrm{d}S(\boldsymbol{y}), \tag{14}$$

where the gradient falls on the $\boldsymbol{x}$-variable of the Green's function. The chain rule yields the gradient of the Green's function,

$$\nabla G_{\mathrm{SAL}}(\boldsymbol{x}\cdot\boldsymbol{y}) = \frac{\mathrm{d}G_{\mathrm{SAL}}(\cos\gamma)}{\mathrm{d}\cos\gamma}\nabla\cos\gamma(\boldsymbol{x}, \boldsymbol{y}), \tag{15}$$

where $\boldsymbol{x}\cdot\boldsymbol{y} = \cos\gamma(\boldsymbol{x}, \boldsymbol{y})$ and $\gamma(\boldsymbol{x}, \boldsymbol{y})$ is the great circle angle between $\boldsymbol{x}$ and $\boldsymbol{y}$. Then taking these derivatives yields

$$\nabla G_{\mathrm{SAL}}(\boldsymbol{x}, \boldsymbol{y}) = \frac{3\rho_{\mathrm{w}}}{4\pi\rho_{\mathrm{e}}R_{\mathrm{E}}\sqrt{1-x_3^2}} \cdot \begin{bmatrix} y_3(1-x_3^2) - x_3(x_1y_1 + x_2y_2) \\ x_1y_2 - x_2y_1 \end{bmatrix} \cdot \left(\frac{1-b_0}{(2-2\boldsymbol{x}\cdot\boldsymbol{y})^{3/2}} - \frac{(a_1-b_1)(2\boldsymbol{x}\cdot\boldsymbol{y} + \sqrt{2-2\boldsymbol{x}\cdot\boldsymbol{y}})}{2((\boldsymbol{x}\cdot\boldsymbol{y})^2 - 1)}\right), \tag{16}$$

where (x_1, x_2, x_3) and (y_1, y_2, y_3) are the Cartesian coordinates of $\boldsymbol{x}$ and $\boldsymbol{y}$. The convolution using this closed form Green's function will be referred to later on as the closed form convolution.

To use a tabular Green's function, we once again take the gradient of the Green's function, written as

$$\nabla G_{\mathrm{SAL}}(\boldsymbol{x}\cdot\boldsymbol{y}) = \nabla\cos\gamma(\boldsymbol{x}, \boldsymbol{y}) \cdot \sum_{n=0}^{\infty} \frac{3\rho_{\mathrm{w}}(1 + k'_n - h'_n)}{4\pi\rho_{\mathrm{e}}} P'_n(\boldsymbol{x}\cdot\boldsymbol{y}). \tag{17}$$

The series is truncated at $N = 46\,342$, which is the number of LLNs provided by Wang et al. (2012). The resulting finite sum is evaluated for $\boldsymbol{x}\cdot\boldsymbol{y}$ on the interval $[-1, 1]$, with a grid spacing of $\Delta x = 0.001$, for a total of 2001 evaluations. For $\boldsymbol{x}\cdot\boldsymbol{y} = \pm 1$, the sum is divergent, as $P'_n(1) = n(n+1)/2$ and $P'_n(-1) = (-1)^{n+1}n(n+1)/2$, and $1 + k'_n - h'_n$ does not decay to 0. Additionally, in the interval $(-1, 1)$, the sum is highly oscillatory and displays poor convergence. To remedy this, Cesàro summation is applied. At intermediate values where the sum was not computed, linear interpolation is used to find an approximate value. The convolution using this Cesàro regularized tabular Green's function will be referred to later on as the Cesàro tabular convolution. Several other techniques for computing this sum and regularizing the oscillations exist, including the use of Kummer's transformation as in Guo et al. (2004) and Martens et al. (2019). We also tested these techniques, but the resulting tide simulations perform worse than the Cesàro tabular convolution, which we will focus on. Even though the LLNs are exact from $N = 1$ to 46 342, this Green's function is still an approximation, as the Legendre series is truncated and the singularity at $\boldsymbol{x}\cdot\boldsymbol{y} = 1$ is not represented in a table. For both forms of the Green's function, tuning is possible by multiplying through by a scalar parameter. This can be used to match the acceleration magnitude with the acceleration computed using the SHT SAL.

2.5 Fast Summation for Accelerating Convolutions

We employ a midpoint discretization of Eq. (14) yielding an approximation for the gradient of the SAL potential,

$$\nabla\eta_{\mathrm{SAL}}(\boldsymbol{x}_i) \approx \sum_{j=1, j\neq i}^{N_0} \nabla G_{\mathrm{SAL}}(\boldsymbol{x}_i, \boldsymbol{x}_j)\eta(\boldsymbol{x}_j)A_j, \quad i = 1, \ldots, N_0, \tag{18}$$

where N_0 is the number of grid cells used in MOM6, $\boldsymbol{x}_i$ is the midpoint of a grid cell, and A_i is the grid cell area. As the SAL acceleration is computed at cell centers, interpolation is performed to obtain values at cell edges. The kernel singularity at $i = j$ is skipped, which is consistent with taking the Cauchy principal value of the integral. If the sums in Eq. (18) are computed directly using loops over the indices i and j, the operation count scales like $O(N_0^2)$, which is prohibitive for reaching high resolution. Various fast summation methods have been developed to accelerate the computation of such sums including the treecode (Barnes and Hut, 1986) and Fast Multipole Method (Greengard and Rokhlin, 1987).

Here we employ the recently developed Cubed Sphere Fast Multipole Method (CSFMM) to reduce the operation count to $O(N_0)$ (Chen and Krasny, 2025). The CSFMM applies barycentric Lagrange interpolation to approximate the kernel (Berrut and Trefethen, 2004), with proxy points defined by a tensor product grid of Chebyshev points in a quadtree of cubed sphere grid cells. The scheme introduces an error whose amplitude is controlled by two user-specified parameters: the interpolation degree n_0 of the barycentric Lagrange interpolation used in the approximations of the kernel, and a parameter θ_0 controlling the size and separation of the cubed sphere grid cells. In contrast to spherical harmonics approximations, the interpolation is local, and this approach does not encounter the Gibbs phenomenon. In addition, the quadtree structure of the cubed sphere grid cells naturally adapts to the irregular distribution of ocean grid points around coastlines. A detailed discussion of the error behavior of spherical convolutions and the CSFMM is presented in Chen and Krasny (2025).

2.6 Comparison of Methods

Before discussing the implementation of convolution SAL in MOM6, we compare the various methods for computing SAL without any confounding non-SAL factors. We compute the SAL acceleration on a MOM6 grid with 0.08° nominal grid spacing for the global snapshot of tidal sea surface height (SSH) shown in Fig. 1 using the various methods described in the previous sections. The SSH snapshot comes from a tidal MOM6 run, with SAL computed using the SHT with $N = 40$. In the following tests, the SHT is used with maximum degree $N = 40$ and $N = 200$, and the Cesàro SHT is used with $N = 200$, and $N = 400$. These are compared with the two convolution approaches, using the closed form Green's function and the Cesàro tabular Green's function. The CSFMM is used to accelerate the convolution, with CSFMM parameters $n_0 = 2$ and $\theta_0 = 0.9$. Global zonal and meridional accelerations are plotted in Figs. 2 and 3, and accelerations focused on the Northeast Atlantic are plotted in Figs. 4 and 5. Figure 6 plots the spectral density of the zonal acceleration in Fig. 2. As all the calculations are based on the same reference SSH snapshot, differences can be attributed to the different methods of computing SAL, as opposed to confounding effects from non-SAL factors in the model.

Looking first at the global zonal and meridional accelerations, there is general agreement among all the results. As the maximum degree increases from $N = 40$ to $N = 200$ in the SHT computation, one observes less large scale waviness in the contour lines, due to a reduction in truncation error. While differences between the $N = 40$ and $N = 200$ results may appear large, they are actually quite small, less than $10^{-8}\,\mathrm{m\,s^{-2}}$ in the open ocean. Additionally, the large scale patterns of the Cesàro SHT result broadly match the unmodified SHT result, with small differences. This is because Cesàro summation has the largest effect on small scales at high wavenumber, while the plots mainly depict the low wavenumber large scale structure. Lastly, there are some differences in the large scale structure between the closed form convolution result and the four SHT computations. This is because the LLN approximations used in deriving the closed form SAL Green's function are least accurate at low wavenumber and have the greatest impact at large scales.

Next consider the regional accelerations in Figs. 4 and 5. Clear differences can be seen between the SHT results with $N = 40$ and $N = 200$, where $N = 200$ resolves small scale features in coastal regions while predicting larger coastal amplitudes. As coastal regions are spanned by relatively few grid cells, aliasing of high degree spherical harmonics may contribute to these large amplitudes. Comparing the $N = 200$ SHT result with the $N = 200$ Cesàro SHT result, one sees the regularization effect of the latter as maximum amplitudes are smaller and the waviness in the contours is reduced. The $N = 400$ Cesàro result further reduces the waviness and resolves small scale features, but also increases the coastal amplitudes. The convolution results are similar to the high degree SHT results, but it feature smaller coastal amplitudes. The LLN approximations used in deriving the closed form SAL Green's function are most accurate at high wavenumber and small scales. Additionally, at this level of detail, we see that the Cesàro tabular convolution has some differences from the closed form convolution. While both feature smaller coastal amplitudes than the calculations with spherical harmonics, the Cesàro tabular convolution also has some waviness in the contour lines that is not present with the closed form. While the convolution approach has errors in the approximate SAL Green's function, quadrature error in computing the integral, and interpolation error from the CSFMM, it avoids the Gibbs phenomenon, aliasing error, and finite difference errors present in the SHT calculations.

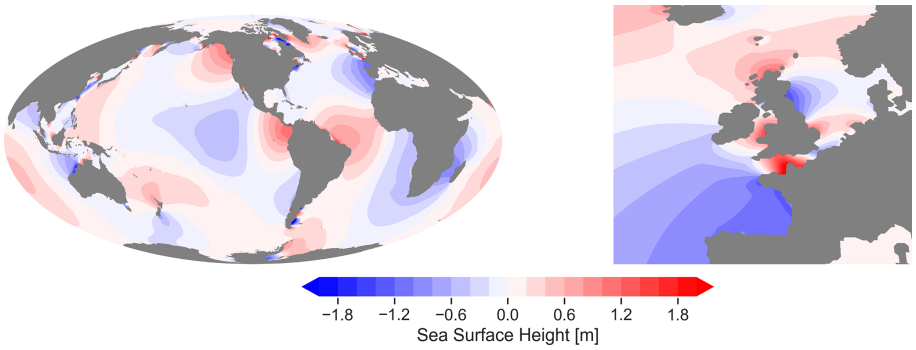


Figure 1. Global snapshot of tidal sea surface height used to compare different SAL computation methods. The right panel is a zoomed version of the left panel focusing on the Northeast Atlantic, a region of exceptionally large coastal tides. The SSH snapshot is on a MOM6 grid with 0.08° nominal grid spacing, taken from an existing MOM6 barotropic tidal simulation.

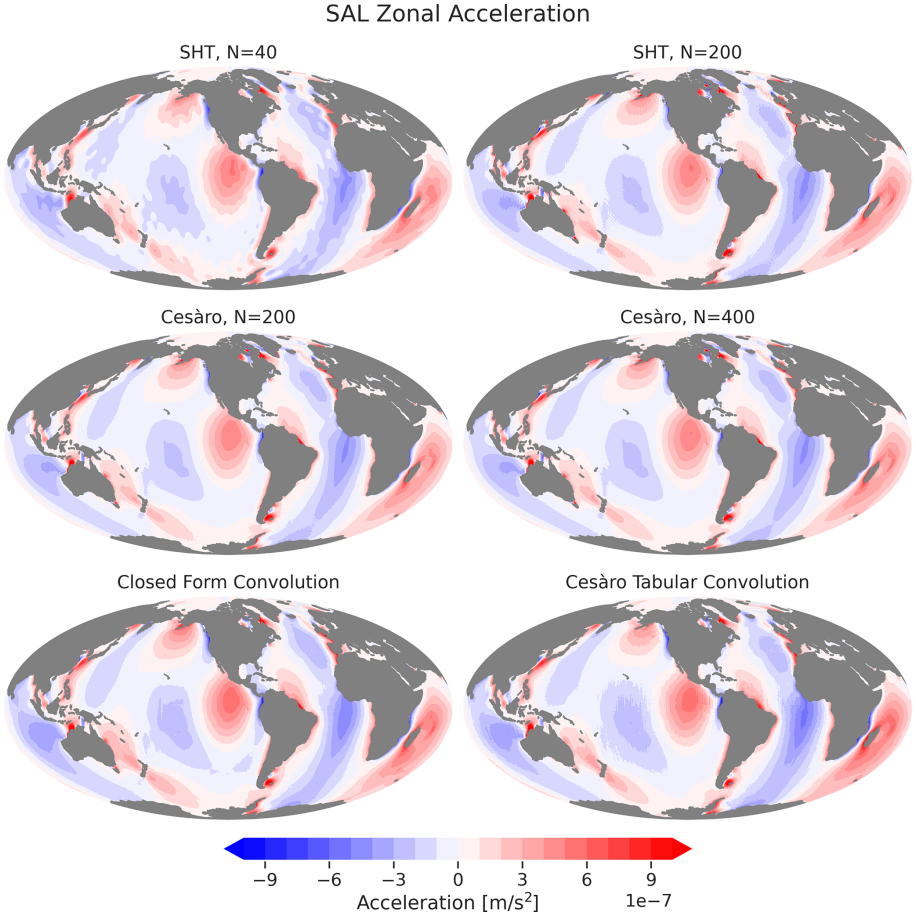


Figure 2. SAL zonal acceleration for the tidal sea surface height snapshot in Fig. 1, computed using spherical harmonics transform (SHT) with $N = 40$, $N = 200$, Cesàro regularized SHT with $N = 200$, $N = 400$, and both convolution approaches.

To gain further insight into the methods, Fig. 6 shows the normalized spectral density of the SAL zonal acceleration. There is general agreement among the four SHT results, which decay roughly as $O(N^{-1})$. Comparing the $N = 40$ SHT with the $N = 40$ Cesàro SHT, the latter spectrum falls off slightly faster at high wavenumber. A similar trend is seen at $N = 200$, but to a lesser degree. In contrast, the closed form convolution spectrum falls off significantly faster at high wavenumber, decaying like $O(N^{-2})$, which is consistent with the smoother acceleration fields seen in Figs. 4 and 5. However, the closed form convolution has a significant mismatch in the degree-1 spherical harmonic compo-

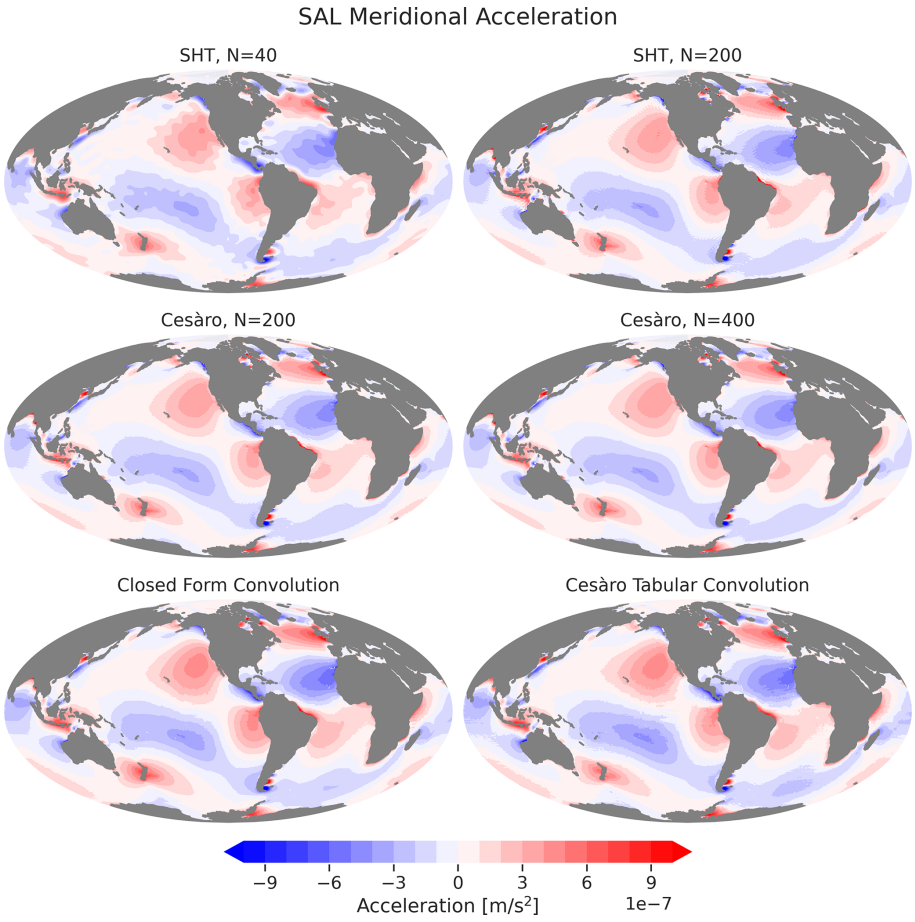


Figure 3. SAL meridional acceleration for the sea surface height snapshot in Fig. 1, computed using spherical harmonics transform (SHT) with $N = 40$, $N = 200$, Cesàro regularized SHT with $N = 200$, $N = 400$, and both convolution approaches.

nent, which relates to tidal geocenter motion (Desai and Ray, 2014). With the closed form convolution, it is likely that the approximations made in the derivation of the closed form Green's function cause this discrepancy. Additionally, with the Cesàro tabular convolution, the discrepancy at degree-1 is much smaller. However, we also observe that the tabular convolution has a spectra that decays in line with the spectra of the SHT calculations. This is consistent with the wavier contour lines seen in the acceleration maps.

3 Simulation Details

The convolution/CSFMM technique described above was implemented in MOM6. The model was run with zero initial velocity and M_2 tidal forcing for 20 d with time step $\Delta t = 180$ s. The SAL acceleration was computed inline at every time step and the last three days of output are used to evaluate the results. A single level configuration was used with two different grids, one with nominal spacing 0.36° (typical of long duration low-resolution climate simulations), and one with nominal spacing 0.08° (typical of short duration high-resolution simulations). The model was run on the Derecho computer system at NCAR (Computational and Information Systems Laboratory, 2023) and Vanda at NUS. The topography and wave drag are based on GEBCO 2023. Several configurations are tested: SHT with $N = 40$, 200, Cesàro SHT with $N = 40$, 200, 400, and the convolution, using both the closed form and Cesàro tabular Green's functions.

3.1 Measuring Error

To measure the error in the model tides, the model output is compared with the TPXO9 dataset (Erofeeva and Egbert, 2018), which comes from a hydrodynamical model that assimilates satellite observations of tidal sea surface heights. We first compute

$$D^2 = \frac{1}{2}(A^2_{\mathrm{TPXO}} - A^2_{\mathrm{MOM6}}) - A_{\mathrm{TPXO}} A_{\mathrm{MOM6}} \cos(\varphi_{\mathrm{TPXO}} - \varphi_{\mathrm{MOM6}}), \quad (19)$$

at each grid point, where A is the amplitude of the tidal constituent and φ is the Greenwich phase lag. The root mean

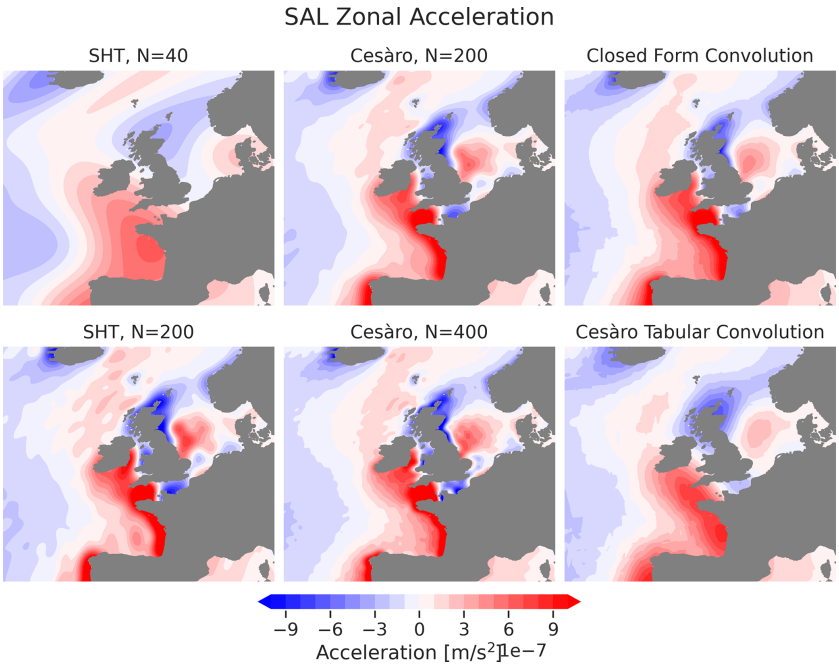


Figure 4. As in Fig. 2, focusing on the Northeast Atlantic.

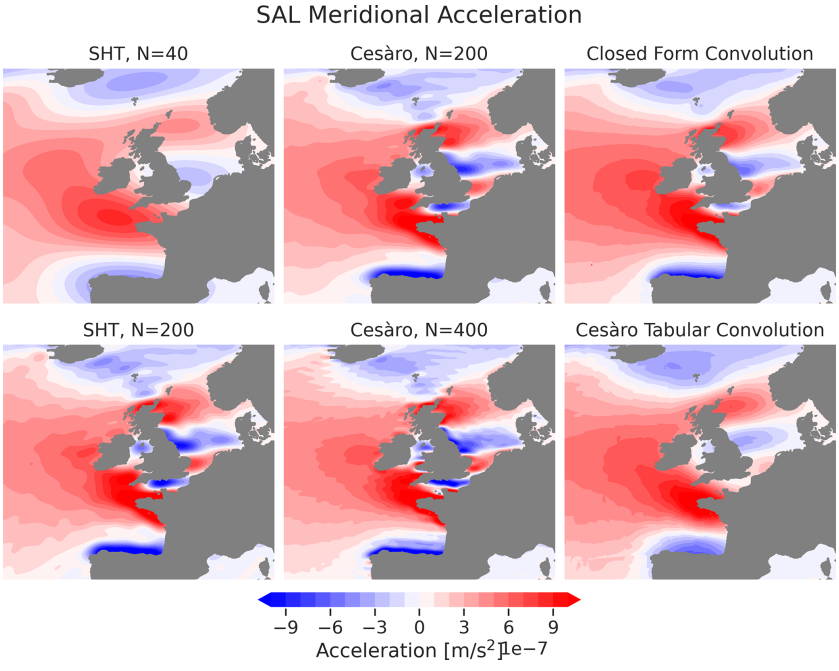


Figure 5. As in Fig. 3, focusing on the Northeast Atlantic.

square error (RMSE) is then defined as

$$\mathrm{RMSE} = \left(\frac{1}{4\pi R_{\mathrm{E}}^2} \int_S D^2 \mathrm{d}S \right)^{1/2}. \tag{20}$$

The RMSE can be decomposed into an amplitude error and a phase error (Shriver et al., 2012). The RMSE is also computed for two different domains: over the entire ocean, and over the deep non-polar ocean, restricting to grid points lying between 66° S and 66° N that have a depth of greater than 1000 m. The latter computation removes coastal regions and polar regions, where data-assimilative tide models such as TPXO are less accurate (Stammer et al., 2014).

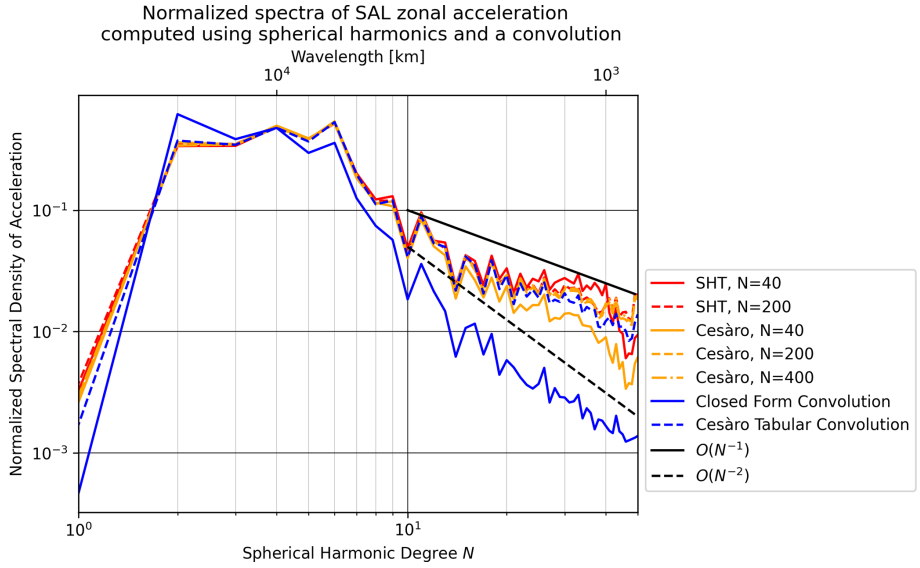


Figure 6. Normalized spectral density of the global SAL zonal acceleration field shown in Fig. 2. A spherical harmonic of degree N has wavelength $2\pi R_E/N$.

3.2 Tuning

The parameter χ in the wave drag scheme is tuned for each method of computing SAL in order to minimize the RMSE. One can understand the need for tuning using energy arguments (Arbic et al., 2004); if χ is too large, then too much energy is dissipated, and conversely if χ is too small, then not enough energy is dissipated. Both extremes adversely affect the accuracy of the modeled tides. The different methods of computing SAL yield accelerations of different amplitude and χ must change accordingly. The χ parameters used here are presented in Tables 1 and 2. Because of differences in how the wave drag was precomputed, the coefficient χ has a different order of magnitude at 0.36 and 0.08° grid spacing.

4 Results

4.1 TPXO9 Comparison

Error results are presented in Table 1 with 0.36° nominal grid spacing and in Table 2 with 0.08° nominal grid spacing, comparing the SHT, the Cesàro SHT, and the two convolution approaches. With 0.36° nominal grid spacing, the $N = 40$ SHT has a deep non-polar RMSE of 6.50 cm, with the phase error contributing 5.70 cm. The global RMSE of 8.65 cm is similarly dominated by the phase error of 7.31 cm. Using $N = 200$ yields only an error reduction of less than 1 %. The Cesàro SHT errors decrease from $N = 40$ to $N = 200$ and $N = 400$, yet even for $N = 400$ they remain larger than the $N = 40$ SHT errors. The convolution errors are smaller than the SHT errors in all cases, with the greatest reduction coming from the phase error. We note that the Cesàro tabular convolution and the closed form convolution have similar RMSEs, with the Cesàro tabular convolution featuring about a 0.05 cm improvement. With 0.08° nominal grid spacing, significant error reduction is achieved in all cases. The $N = 200$ SHT errors are the smallest among the five SHT test cases. The amplitude errors are slightly larger with the two convolutions than the $N = 200$ SHT, but this is compensated by smaller phase errors, so that the convolutions still have the smallest RMSE. As with the error results at 0.36° nominal grid spacing, the improvement that the Cesàro tabular convolution presents over the closed form convolution is small.

4.2 Discussion

The question arises – why are the SHT errors only slightly smaller for $N = 200$ than for $N = 40$? Figures 2 and 3 show that the $N = 40$ SHT results have small amplitude oscillations in the open ocean, while the $N = 200$ SHT results have similar structure but without the oscillations. The more significant difference is seen in Figs. 4 and 5, where $N = 200$ yields larger coastal accelerations than $N = 40$. Some of these large coastal accelerations are spurious overshoots due to Gibbs phenomenon, aliasing error, and finite differencing error. Similar considerations apply to the $N = 200$ and $N = 400$ Cesàro SHT results. Cesàro summation might mitigate the impact of Gibbs phenomenon, but it does nothing to remedy errors due to aliasing and finite differencing, and as a result, it also results in large coastal accelerations. Additionally, remedying Gibbs errors on the sphere is a subtle matter and Cesàro summation may not be sufficient (Gelb, 1997). By contrast as seen in Figs. 4 and 5, both convolutions predict smaller coastal accelerations, which we attribute to the

Table 1. Wave drag tuning parameter χ and errors for different methods of computing SAL with 0.36° nominal grid spacing.

		Deep non-polar ocean			Global ocean		
0.36° nominal grid spacing	Wave drag χ	RMSE	Amplitude error	Phase error	RMSE	Amplitude error	Phase error
SHT SAL, $N = 40$	0.8	6.50	3.18	5.70	8.65	4.63	7.31
SHT SAL, $N = 200$	0.8	6.45	3.09	5.66	8.54	4.61	7.18
Cesàro SHT SAL, $N = 40$	0.8	8.10	3.56	7.27	10.26	5.01	8.95
Cesàro SHT SAL, $N = 200$	0.8	6.76	3.17	5.98	8.86	4.68	7.52
Cesàro SHT SAL, $N = 400$	0.8	6.60	3.13	5.81	8.69	4.65	7.35
Closed Form Convolution SAL	0.7	4.10	2.78	3.01	6.53	4.43	4.80
Cesàro Tabular Convolution SAL	0.7	4.05	2.78	2.94	6.47	4.38	4.77

Table 2. As in Table 1, but with 0.08° nominal grid spacing.

		Deep non-polar ocean			Global ocean		
0.08° nominal grid spacing	Wave drag χ	RMSE	Amplitude error	Phase error	RMSE	Amplitude error	Phase error
SHT SAL, $N = 40$	8.0	2.71	1.59	2.20	5.32	3.54	3.96
SHT SAL, $N = 200$	8.0	2.67	1.55	2.17	5.22	3.53	3.84
Cesàro SHT SAL, $N = 40$	8.0	4.50	2.34	3.85	6.78	3.98	5.49
Cesàro SHT SAL, $N = 200$	8.0	3.01	1.68	2.49	5.48	3.61	4.13
Cesàro SHT SAL, $N = 400$	8.0	2.84	1.61	2.33	5.35	3.57	3.98
Closed Form Convolution SAL	8.1	2.36	1.70	1.63	5.06	3.64	3.52
Cesàro Tabular Convolution SAL	8.1	2.32	1.69	1.59	5.03	3.61	3.50

absence of Gibbs phenomenon, aliasing error, and finite differencing error.

Another question arises – why does the removal of Gibbs phenomenon and aliasing error in coastal regions reduce the error in the deep non-polar ocean? We speculate that the global improvement in the tides is due to the back effect of large resonant coastal tides upon open-ocean tides (Arbic et al., 2007, 2009; Arbic and Garrett, 2010). Thus it appears that improvements to the SAL in coastal regions as a result of using the convolution can drive improvements to the tides in the entire ocean. Further exploration into the role of the back effect in these calculations, as well as other potential reasons for the improvement, is left as a topic for future work.

4.3 Parallel Efficiency and Runtime

A strong scaling analysis is performed to examine the parallel efficiency and runtime of the convolution/CSFMM SAL. Figure 7 shows the single time step runtime (seconds) versus the number of MPI ranks for MOM6 running with 0.36° nominal grid spacing yielding $N_0 = 784\,000$ grid cells. The runtime is shown for the convolution/CSFMM SAL, $N = 40$ spherical harmonics SAL, and non-SAL portion of the calculation. The data was collected using the internal performance analysis tools in MOM6. The SHT and convolution/CSFMM are different algorithms with different operation counts and communication patterns, and this affects their parallel efficiency. From 1 to 16 ranks, the SHT scales better and is faster than the convolution/CSFMM, but from 16 to 1024 ranks the convolution/CSFMM scales better than the SHT. The SHT runtime increases at 512 and 1024 ranks, presumably due to communication costs, while the convolution/CSFMM continues scaling well. In this single layer simulation the convolution/CSFMM runtime is comparable to or smaller than the non-SAL portion of the calculation, and its impact in a multi-layer simulation will be much smaller. The closed form convolution is slightly faster than the Cesàro tabular convolution.

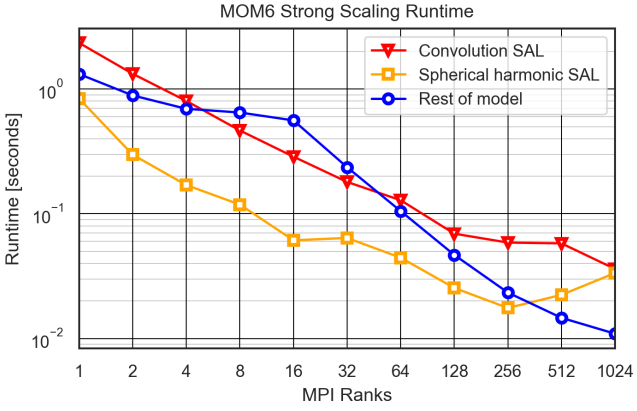


Figure 7. Single time step runtime (seconds) versus number of MPI ranks, MOM6 running with 0.36° nominal grid spacing, yielding $N_0 = 784\,000$ grid cells, results shown for convolution SAL, $N = 40$ SHT SAL, non-SAL portion of the calculation.

5 Conclusions

In the numerical modeling of ocean tides, capturing the effects of SAL is necessary for accurate prediction of tidal amplitude and phase. Many current models employ spherical harmonics to compute the SAL acceleration. This work presents an alternative where the SAL acceleration is computed by convolving the sea surface height with two Green's functions, one based on an asymptotic approximation of the Load Love Numbers, and another based on a precomputed table of values. The convolution integral is discretized on a set of grid cells covering the sphere and the sums are accelerated by the Cubed Sphere Fast Multipole Method. The convolution/CSFMM was implemented in the MOM6 ocean model and compared with the default SHT as well as a Cesàro modified SHT. Errors in tidal amplitude and phase were tabulated using the TPXO9 tidal atlas as the reference. In these tests the convolution approaches have smaller RMSE than the SHT. The larger SHT error is attributed to overshoots in coastal amplitude due to Gibbs phenomenon, aliasing error due to finite grid resolution, and finite difference error in computing the gradient of the SAL potential. In contrast to the global nature of spherical harmonics, the convolution/CSFMM uses local grid cell approximations which do not exhibit these errors. Parallel scaling results up to 1024 MPI ranks show that the runtime of the convolution/CSFMM is not prohibitive.

This work focused on global ocean models, but incorporating tides and SAL in regional models is also of interest (Irazoqui Apecechea et al., 2017). Spherical harmonics are poorly suited for that case, and in future work we plan to explore the convolution/CSFMM SAL in regional models. Similarly, the present work employed a simple discretization of the convolution integral Eq. (18) and more accurate schemes could be considered (Agnew, 2012). Finally, an integral equation method could bypass the load Love numbers and directly compute the SAL Green's function on a grid given a model of the Earth interior. Such an approach could possibly also incorporate the inhomogeneity of the Earth interior (Pagiatakis, 1990; Scherneck, 1991).

Code and data availability. The current version of MOM6 is available from https://github.com/noaa-gfdl/MOM6 (last access: 22 July 2026) under the GNU Lesser General Public License. The exact version of the model used to produce the results used in this paper is archived on repository under https://doi.org/10.5281/zenodo.18445619 (Chen and Wang, 2026), as are input data and scripts to run the model and produce the plots for all the simulations presented in this paper.

Author contributions. BKA and RK conceptualized the project. AC conducted the formal analysis and investigation. AC and HW produced the software. HW provided datasets. BKA and RK supervised the project. AC visualized the results and prepared the original draft. AC, HW, BKA, and RK assisted in reviewing and editing the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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