Ocean Modelling 99 (2016) 15–21

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Sensitivity of near-inertial internal waves to spatial interpolations of wind stress in ocean generation circulation models

Zhao Jing[a,b,*], Lixin Wu[b], Xiaohui Ma[a]

[a] Department of Oceanography, Texas A&M University, College Station, TX 77843, USA
[b] Physical Oceanography Laboratory, Qingdao Collaborative Innovation Center of Marine Science and Technology, Ocean University of China, Qingdao, PR China

ARTICLE INFO

Article history:
Received 20 August 2015
Revised 19 December 2015
Accepted 22 December 2015
Available online 31 December 2015

Keywords:
Near-inertial internal waves
Wind stress
Spatial interpolation
Ocean general circulation models

ABSTRACT

The oceanic near-inertial internal waves (NIWs) have been extensively studied using ocean general circulation models (OGCMs). Currently most OGCMs use the bilinear or bicubic interpolation to interpolate wind stress onto models' surface grids. In this study, we examine the influences of bilinear and bicubic interpolations on the wavenumber and frequency spectra of wind stress and on the simulated NIWs in the ocean. It is demonstrated that both the bilinear and bicubic interpolations are equivalent to spatial low-pass filters with the former leading to more significant loss of wind stress variance at high wavenumbers. When coarse (e.g., 2°) wind stress is used to force OGCMs, the bilinear and bicubic interpolations significantly damp the wavenumber spectrum of wind stress at mesoscales, leading to decreased near-inertial wind stress variance. Using the bilinear (bicubic) interpolation could weaken the near-inertial wind work by ~43% (22%) in the subtropical region (10°N–30°N) and by ~16% (4%) at the midlatitudes (30°N–50°N).

We propose a new interpolation method, i.e., the bi-*sinc*-function interpolation, which is able to retain all the wind stress variance within the Nyquist wavenumber. Compared to the bilinear and bicubic interpolations, the bi-*sinc*-function interpolation improves the simulations of NIWs and should be incorporated into OGCMs especially when coarse wind stress is used.

1. Introduction

Near-inertial internal waves (Garret, 2001), referred to as NIWs henceforth, form a pronounced peak in the ocean current frequency spectrum, containing half of the kinetic energy and a substantial portion of the shear in the internal wave field (Ferrari and Wunsch, 2009). They are of central importance to a variety of ocean processes, including the mixed layer deepening (Greatbatch, 1984; Price et al., 1986; Jochum et al., 2013), phytoplankton dispersion (Franks, 1995) and mesoscale eddy dissipation (Polzin, 2010). In addition, they are thought to provide an energy source for abyssal diapycnal mixing which affects uptake of heat and carbon by the oceans as well as climate changes (Munk and Wunsch, 1998; Wunsch and Ferrari, 2004; Jing and Wu, 2014). Due to the important role of NIWs in the climate system, they have been extensively studied using ocean general circulation models (OGCMs) forced by reanalysis wind products (Nagasawa et al., 2000; Furuichi et al., 2008; Rath et al., 2013 and 2014; Rimac et al., 2013; Simmons and Alford, 2012; Zhai et al., 2005, 2007 and 2009) or coupled to atmosphere general circulation models (AGCMs) (Komori et al., 2008; Jochum et al., 2013).

As a natural resonant frequency of fluids on a rotating planet, NIWs are efficiently forced by wind stress in the near-inertial frequency band (Pollard and Millard, 1970; Alford, 2003; Rath et al., 2013). The near-inertial wind stress is generated by atmospheric processes from mesoscales (e.g., fronts and tropical cyclones) to synoptic scales (e.g., midlatitude storms). Previous numerical studies revealed the sensitivity of simulated NIW strength in OGCMs to the horizontal resolution of wind forcing, pointing out the important role of mesoscale wind stress in powering NIWs (Jiang et al., 2005; Rimac et al., 2013). So far the horizontal resolution of AGCMs is typically coarser than 1°, which is not able to resolve all the mesoscale wind stress variability and underestimates the near-inertial wind work. Furthermore, as the horizontal resolution of OGCMs has been pushed to O(0.1°) to resolve mesoscale oceanic eddies, a spatial interpolation is required to interpolate the coarse wind stress derived from AGCMs onto the much finer grids of OGCMs. The bilinear and bicubic interpolations are two built-in options for most OGCMs and AGCMs. On one hand, the bicubic interpolation seems to be a better choice for interpolating wind stress in the sense that it produces continuous wind stress curl, which plays an essential role in the quasi-geostrophic dynamics. On the

* Corresponding author at: Department of Oceanography, Texas A&M University, College Station, TX 77843, USA. Tel.: +1 979 676 0762.
E-mail address: jingzhao198763@tamu.edu (Z. Jing).

http://dx.doi.org/10.1016/j.ocemod.2015.12.006
1463-5003/

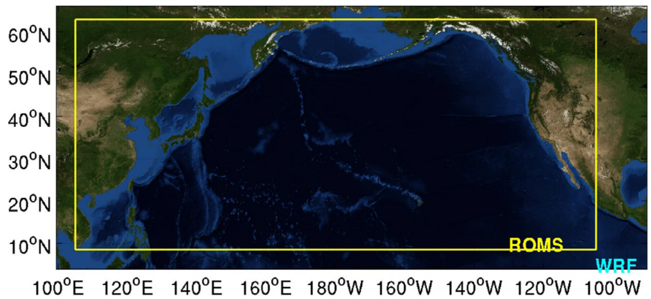

Fig. 1. CRCM computation domain in the North Pacific: the outer frame outlines the WRF computational region and the inner frame outlines the ROMS computational region.

other hand, using the bilinear interpolation is not unusual in previous NIW-modeling studies (e.g., Nagasawa et al., 2000; Furuichi et al., 2008; Rimac et al., 2013). So far it remains unclear how these interpolation methods may affect the simulation of NIWs.

Recently, Jing et al. (2015) applied a *sinc*-function interpolation to the time domain and found significant improvement in the simulated NIWs compared to the linear interpolation. In this study, we generalize the *sinc*-function interpolation to the two-dimensional spatial domain and propose a bi-*sinc*-function interpolation method (referred to as the bisinc interpolation henceforth). The performance of bisinc interpolation in simulating NIWs is analyzed and compared to those of bilinear and bicubic interpolations. The paper is organized as follows. The numerical model configurations are introduced in Section 2. In Section 3, we compare the bilinear, bicubic and bisinc interpolations especially their influences on the horizontal wavenumber spectrum and frequency spectrum of wind stress. Simulations of NIWs using different interpolations are presented in Section 4. Discussion is provided in Section 5 followed by conclusions. Comparisons of computational cost among different interpolations are provided in Appendix A.

2. Model configurations

A coupled regional climate model (CRCM) developed at Texas A&M University is used to study NIWs in the North Pacific. It includes the Weather Research and Forecasting (WRF) Model (Leung et al., 2006) as the atmospheric component and the Regional Ocean Modeling System (ROMS) (Moore et al., 2004; Shchepetkin and McWilliams, 2005) as the oceanic component. The CRCM is configured with ROMS and WRF both at ~0.1° horizontal resolution and thus is able to resolve mesoscale wind stress. The model domain covers the entire North Pacific with the WRF domain slightly larger than the ROMS domain (Fig. 1). The ROMS shares the same grids with WRF in the overlapped domain to avoid mismatch between land- and ocean-surface heat fluxes. The open boundaries of the ocean are forced by 5-day average Simple Ocean Data Assimilation (SODA) dataset. The 6-hourly National Centers for Environmental Prediction (NCEP) reanalysis data are used as the initial and boundary conditions for the atmosphere. In the CRCM simulation, WRF and ROMS are coupled every hour which is sufficiently fine to resolve wind stress variance in the near-inertial band.

The numerical simulations consist of five experiments. In the first experiment (E-Control), NIWs are simulated using the CRCM. The simulation is initialized on October 1, 2002 from a 6-year ROMS spin-up simulation (1997–2002) and integrated for one year. The period 2002–2003 is chosen as it is a relatively neutral year for both the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) which modulate the activities of midlatitude storms and tropical cyclones (Camargo and Sobel, 2005; Chang and Fu, 2002). This facilities the comparisons of the simulated NIW strength to the climatological mean derived from the surface drifters (Chaigneau et al., 2008; Elipot and Lumpkin, 2008).

The remaining four experiments (E-Linear, E-Cubic, E-Sinc, and E-Smooth) are the ROMS-only simulations with the hourly air-sea heat and momentum fluxes obtained from the E-Control. The starting date of these experiments is October 1, 2002 with the same initial and boundary conditions as those of E-Control. To examine the effects of different interpolation methods on the simulated NIWs, the $0.1^\circ \times 0.1^\circ$ wind stress derived from E-Control is first smoothed using a $2^\circ \times 2^\circ$ moving average and then subsampled onto $2^\circ \times 2^\circ$ grids (referred to as the 2° wind stress henceforth). The $2^\circ \times 2^\circ$ box is used here because it is comparable to the horizontal resolution of some widely used reanalysis wind products such as the NCEP and CORE-II (Coordinated Ocean-Ice Reference Experiments II) datasets. Finally, the 2° wind stress is interpolated back onto the original $0.1^\circ \times 0.1^\circ$ grids to force the ROMS using the bilinear interpolation for E-Linear, bicubic interpolation for E-Cubic, and bisinc interpolation for E-Sinc.

The difference of NIWs in E-Control from those in E-Linear, E-Cubic, and E-Sinc comes from two aspects. First, the $2^\circ \times 2^\circ$ moving average filters out part of the mesoscale wind stress variability, reducing the near-inertial wind stress variance. Second, the interpolations may lead to further reduction of mesoscale wind stress variability and cause additional loss of near-inertial wind stress variance. To isolate the influence of interpolations on the simulated NIWs, we perform a ROMS-only simulation forced by the $2^\circ \times 2^\circ$ moving averaged wind stress without subsampling and interpolations (referred to as E-Smooth). Performance of different interpolation methods in simulating NIWs can be evaluated based on the comparisons of E-Linear, E-Cubic, and E-Sinc to E-Smooth.

3. The influence of spatial interpolations on the wavenumber and frequency spectra of wind stress

Let $\tau(i, j)$ represent the zonal or meridional wind stress component with a grid size of $\Delta x$and Δyin the zonal and meridional direction, respectively. Introduce the zero-padding wind stress $\tilde{\tau}(\frac{i}{M}, \frac{j}{N})$:

$$\tilde{\tau}\left(\frac{i}{M}, \frac{j}{N}\right) = \begin{cases} \tau\left(\frac{i}{M}, \frac{j}{N}\right), & \frac{i}{M}, \frac{j}{N} \in Z \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where M and N are any positive integer and Z denotes the integer set. The interpolation of $\tau(i, j)$ onto finer grids with a grid size of $\Delta x/M$ and $\Delta y/N$ can be expressed by the 2-D convolution formula:

$$\tau_{\text{int}}\left(\frac{i}{M}, \frac{j}{N}\right) = \sum_{p=-\infty}^{\infty} \sum_{q=-\infty}^{\infty} \tilde{\tau}\left(\frac{i-p}{M}, \frac{j-q}{N}\right) g\left(\frac{p}{M}, \frac{q}{N}\right) \tag{2}$$

where g is called the impulse response function uniquely determined by the interpolation method (Bracewell, 1965). Introduce the wavenumber response function:

$$R(k_H) = \frac{\Phi^{\tau}_{\text{int}}(k_H)}{\Phi^{\tau}(k_H)} \tag{3}$$

where $k_H = \sqrt{k^2 + l^2}$ is the magnitude of horizontal wavenumber, Φ^{τ}_{int} and $\Phi^{\tau}$are the horizontal wavenumber spectra for τ_{int} and τrespectively. R measures the influence of interpolations in the horizontal wavenumber space. According to the 2-D convolution theorem, $R(k_H) = \frac{1}{2\pi} \int_0^{2\pi} |G(k_H \cos\alpha, k_H \sin\alpha)|^2 d\alpha$ for an isotropic wind stress field where $G(k, l)$ is the 2-D Fourier transform of $g(\frac{i}{M}, \frac{j}{N})$ and $\alpha = \arctan(l/k)$ is the azimuth of horizontal wavenumber.