ARTICLE IN PRESS

Progress in Oceanography xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Progress in Oceanography

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

# Wave hindcast in the North Pacific area considering the propagation of surface disturbances

Yukiharu Hisaki

*Department of Physics and Earth Sciences, University of the Ryukyus, 1-Aza Senbaru, Nishihara-cho, Okinawa 903-0213, Japan*

ARTICLE INFO

*Keywords:*
North Pacific Ocean
Interpolation
Wind
Cyclone
Wave model
Wave height
Wave period

ABSTRACT

Ocean surface waves in the North Pacific area are affected by storm winds. It is necessary to consider the movement of storms to predict waves. The impact of a time interpolation method for winds that considers the propagation of surface disturbances on ocean wave prediction from 2005 to 2006 in the North Pacific area is demonstrated. It is possible to interpolate surface winds, even when there are multiple cyclones and anticyclones moving in different directions at different distances. This method will be useful for wind fields with increasing amounts of spatial information. The predicted wave heights and periods from the linearly interpolated winds and the winds predicted using this new method are compared with in-situ observations from several moored buoys. The predicted wave heights are also compared with those from several drifting buoys in the northwestern Pacific. The improvement of the wave height and period prediction is evident in the case where the difference in the predicted wave parameters between the linear interpolation and the present method is large. The improvement of the wave height and period prediction is statistically significant at more than 95% in most cases. It is shown that the wave height and period prediction can be improved by improving the time interpolation method; however, the improvement of the wave direction prediction is not evident.

## 1. Introduction

Knowledge of the wave climate is important for ocean wave research and for practical applications such as ship navigation, offshore oil exploration, and the planning of marine operations and offshore and coastal structures. Wave heights are high during the winter in the North Pacific area, including the Bering Sea and the Sea of Okhotsk. Extratropical cyclones often occur and develop in the North Pacific area. These extratropical cyclones cause extremely high waves. A hindcast of ocean waves is important for climate studies and for practical applications such as scheduling ship navigation and maintaining fisheries. The prediction and hindcast of ocean waves is often used (e.g., Chawla et al., 2013; Chowdhury and Behera, 2017; Cox and Swail, 2001; Reguero et al., 2012; Sasaki, 2014; Wang and Swail, 2001; Yamaguchi and Hatada, 2002) for wave climate studies. Ocean wave models for hindcasts are driven by archived atmospheric reanalysis datasets. However, the time resolution of archived atmospheric reanalysis data $T$ is much longer than the time step required for wave prediction. Therefore, the surface wind is interpolated with respect to time.

It may be better to compute surface winds from atmospheric models incorporating observed data; however, this would result in a computational overload. A linear interpolation with respect to time is often used because it is simple and robust. However, a linear time interpolation cannot retrieve the atmospheric fields in the case of a moving cyclone. A moving tropical cyclone is expressed by a parametric form (e.g., Hisaki and Naruke, 2003; Hong and Yoon, 2003), and the surface wind field is deduced from the parametric model. A Rankine vortex is often used for the parametric model (e.g., Cheung et al., 2007; Phadke et al., 2003). This approach may be useful for case studies that investigate the ocean response to a moving storm. However, it is difficult to apply this method when both moving cyclones and stationary fields coexist. An interpolation using the parametric form is generally applied in the area near the moving cyclones for each cyclone, while linear interpolations are applied in other areas. The problem is how to decide which areas use the parametric interpolation and which areas use the linear interpolation.

It is also difficult to express moving extratropical cyclones using the parametric form, such as a Rankine eddy. Waves associated with extratropical cyclones are predicted not from the parametric form of the cyclone but from the interpolated wind of the gridded data (e.g., Businger et al., 2015; Pingree-Shippee et al., 2016). Cieślikiewicz and Graff (1997) reconstructed the wind fields using the empirical orthogonal function (EOF) method, in which the spatial patterns are fixed; however, a propagating pattern cannot be reconstructed using this method.

*E-mail address:* hisaki@sci.u-ryukyu.ac.jp.

https://doi.org/10.1016/j.pocean.2018.06.003
Received 7 July 2017; Received in revised form 22 April 2018; Accepted 6 June 2018

Hisaki (2016) developed a new and simple time interpolation method of an atmospheric field that can be applied to both moving and stationary disturbances. This method is called the Space Propagation Time Interpolation Method (SPTIM). The principle of SPTIM is similar to the interpolation method in Hisaki (2011), which can remove the Garden Sprinkler effect by interpolating a wave directional spectrum at higher frequency and direction resolution from a wave spectrum at low spectral resolution. Hisaki (2016) demonstrated that the predicted near inertial currents using winds interpolated from SPTIM are significantly different from those from linearly interpolated winds, even though the wind products for the prediction are the same. This method becomes obsolete with increasing amounts of temporal wind field information. However, it is useful with increasing spatial wind field information because the grid number difference in the position of a cyclone at a time $t$ with that at a time $t + T$ is larger with higher spatial resolution (Hisaki, 2016).

There are studies that have investigated the wave predictions from different wind products in the global ocean (e.g., Campos and Soares, 2016; Caires et al., 2004; Graber et al., 1995; Stopa and Cheung, 2014). The wind products in these studies have different time and spatial resolutions. There are few studies that investigate the impact of the time interpolation method on wave predictions using the same wind data products. Van Vledder and Akpınar (2015) showed that a finer time resolution in the wind fields does not significantly improve the accuracy of the wave predictions.

The objective of the study is to demonstrate SPTIM for ocean surface wave prediction from 2005 to 2006 in the North Pacific area. The predicted wave parameters are compared with in-situ observed data obtained from deployed buoys. The positions of the deployed buoys are geographically limited to the North Pacific near the US coast.

A few moored buoy datasets in the northwestern Pacific were used in Cox and Swail (2001) and Yamaguchi and Hatada (2002). However, these moored buoys were dismantled in 2000. There were no moored buoys in the northwestern Pacific around Japan during the analysis period used in this study. Most validation studies of wave hindcasts have not been compared to in-situ observations in the northwestern Pacific (Caires et al., 2004; Reguero et al., 2012; Stopa and Cheung, 2014), and validation studies of wave predictions using buoy datasets in the northwestern Pacific are rare. Comparisons of predicted wave parameters with other instruments are limited to satellite altimeter data. The validation of satellite altimeter wave height data in the northwestern Pacific is limited. For example, Zieger et al. (2009) validated satellite altimeter wave height data via comparisons to buoy data; however, there are no buoy data in the northwestern Pacific.

We did comparisons with drifting buoy data in the northwestern Pacific. Studies that compare predicted wave parameters with drifting buoy data are rare (Doble and Bidlot, 2013; Waseda et al., 2014).

The difference between linearly interpolated winds and winds interpolated by SPTIM is large in the storm track area of the northwestern Pacific (Hisaki, 2016). The storm track area is observed along the major oceanic frontal zones in the northwestern Pacific (Nakamura et al., 2004). The wave data from drifting buoys are suitable for demonstrating the ability of SPTIM to predict wave parameters because many of the drifting buoys have moved to the Kuroshio extension area.

This paper is organized as follows. Section 2.1 briefly reviews SPTIM. Section 2.2 describes the wave modeling and observations. Section 3.1 shows an example of a wave prediction. The wind and wave parameters are compared with moored buoy observations in Sections 3.2, 3.3, and 3.4. The wave heights are compared with drifting buoy observations in Section 3.6. The wave directions are compared in Section 3.5. The spatial and temporal variability of the predicted wave parameters from the linear interpolation and SPTIM are investigated in Section 3.7. The discussion and conclusions are presented in Section 4.

## 2. Methods

### 2.1. Interpolation method

The details of the interpolation method are described in Hisaki (2016). The outline of the method is briefly described here. We consider the interpolation of a scalar value $P = P_1(\mathbf{x})$ at a position $\mathbf{x}$ and a time $t$ and $P = P_2(\mathbf{x})$ at a position $\mathbf{x}$ and a time $t + T$. The value of $P$ at the time $t + \alpha_t T$ $(0 < \alpha_t < 1)$ is $P = (1-\alpha_t)P_1 + \alpha_t P_2$ in the case of linear interpolation. If we consider the movement of the disturbance, this is extended as

$$P(\mathbf{x} + \alpha_t \mathbf{a}) = (1-\alpha_t)P_1(\mathbf{x}) + \alpha_t P_2(\mathbf{x}_b), \tag{1}$$

where $\mathbf{x}_b = \mathbf{x} + \mathbf{a}$ and the vector $\mathbf{a} = \mathbf{a}(\mathbf{x})$ denotes the vector of the movement of the surface disturbance, which is called the propagation vector.

The propagation vectors $\mathbf{a}$ are estimated on all the grid points of the computational domain. We seek the centers of the surface disturbances at times $t$ and $t + T$. The centers are those of the anticyclones or cyclones, which are identified as local maximum or minimum values of the sea level pressure.

The cyclones and anticyclones are tracked using the sea level pressure at the times $t$ and $t + T$. The procedure for making pairs of (anti) cyclones is as follows. Consider that (anti) cyclones $C_t(i)$ $(i = 1, ..., M)$ and $C_{t+T}(j)$ $(j = 1, ..., N)$ are identified within the search window, where $C_t(i)$ denotes the (anti) cyclones at the time $t$ and $M$ and $N$ are the number of (anti) cyclones at the times $t$ and $t + T$, respectively. We seek $j_q(i) = j$ to minimize $|\mathrm{SLP}(C_t(i)) - \mathrm{SLP}(C_{t+T}(j))|$ for each $i$, where $\mathrm{SLP}(C_t(i))$ is the central sea level pressure of the (anti) cyclone $C_t(i)$.

If there exists no $k$ for $i$ $(i, k = 1, ..., M)$ that satisfies $j_q(i) = j_q(k)$ except $i \neq k$, a pair of (anti) cyclones $(C_t(i), C_{t+T}(j_q(i)))$ is identified. If there exists a $k$ for $i$ $(i, k = 1, ..., M)$ that satisfies $j_q(i) = j_q(k)$ and $i \neq k$, the distances $\mathrm{dist}(C_t(i), C_{t+T}(j_q(i)))$ and $\mathrm{dist}(C_t(k), C_{t+T}(j_q(k)))$ are compared, where $\mathrm{dist}(C_t(i), C_{t+T}(j))$ is the distance between the centers of the (anti) cyclones $C_t(i)$ and $C_{t+T}(j)$. If $\mathrm{dist}(C_t(i), C_{t+T}(j_q(i))) < \mathrm{dist}(C_t(k), C_{t+T}(j_q(k)))$, a pair of (anti) cyclones $(C_t(i), C_{t+T}(j_q(i)))$ is identified. The number of (anti) cyclone pairs cannot be larger than $M$ or $N$. There exists the possibility that (anti) cyclone pairs are overlooked. This method should therefore be improved by incorporating the track method in Neu et al. (2013).

The positions of the centers of the disturbances are $\mathbf{x}_p(n)$ and $\mathbf{x}_q(n)$ $(n = 1, ..., M_D)$ at times $t$ and $t + T$, respectively, where $M_D$ is the number of pairs of centers of anticyclones or cyclones. The positions $\mathbf{x}_p(n)$ and $\mathbf{x}_q(n)$ are considered to be the positions for the same anticyclones or cyclones. The propagation vectors $\mathbf{a}$ in Eq. (1) on $\mathbf{x}_p(n)$ $(n = 1, ..., M_D)$ are $\mathbf{x}_q(n) - \mathbf{x}_p(n)$.

The propagation vectors $\mathbf{a}$ on the other grid points are spatially interpolated from $\mathbf{a}$ at the positions $\mathbf{x}_p(n)$. If the area of the analysis is limited, the propagation vector $\mathbf{a}$ on the boundary is $\mathbf{0}$. Both position vectors $\mathbf{x}$ and $\mathbf{x} + \mathbf{a}$ are on grid points. In this case, the position $\mathbf{x} + \alpha_t \mathbf{a}$ in Eq. (1) is not on a grid point. Instead of the spatial interpolation of $P$ evaluated in Eq. (1) at positions $\mathbf{x} + \alpha_t \mathbf{a}$ to the grid points, we estimate the position $\mathbf{x}_a$ by solving the equation

$$\mathbf{x}_c = \mathbf{x}_a + \alpha_t \mathbf{a}(\mathbf{x}_a) \tag{2}$$

for a given grid position $\mathbf{x}_c$, where $\mathbf{a}(\mathbf{x}_a)$ is the bilinearly interpolated $\mathbf{a}$ from the propagation vectors $\mathbf{a}$ onto the grid points. The value of $P = P_1(\mathbf{x}_a)$ at the time $t$ is evaluated using the bilinear interpolation from $P_1$ on the grid points. The value of $P = P_2(\mathbf{x}_a + \mathbf{a}(\mathbf{x}_a))$ at the time $t + T$ is evaluated using the bilinear interpolation from $P_2$ on the grid points. Then, the value of $P$ at the time $t + \alpha_t T$ is evaluated using Eq. (1) by replacing $\mathbf{x}$ with $\mathbf{x}_a$. This interpolation is conducted in components for the wind vectors. In the case where the propagation vector $\mathbf{a}$ is $\mathbf{0}$, SPTIM is identical to the linear interpolation. An ad-hoc correction is conducted near the coast (Hisaki, 2016).