Terr. Atmos. Ocean. Sci., Vol. 23, No. 4, 397-411, August 2012 doi: 10.3319/TAO.2012.03.02.01(A)

Possible Influences of ENSO on Winter Shipping in the North Pacific

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Received 22 July 2011, accepted 2 March 2012

ABSTRACT

Possible influences of the El Niño/Southern Oscillation (ENSO) on winter shipping in the North Pacific (NP) are investigated using marine observations contained in the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). Shipping frequency is interpreted using the number of ship reports accumulated in each 2° × 2° box-space throughout the winter season. Analyses reveal that shipping across the NP follows major "great circle" routes from the South China Sea (SCS) along the coasts of East Asia and Japan before heading eastward along the open ocean north of the Aleutian Islands toward the western coasts of North America. The above routes are shorter in navigational distance and avoid strong winds and high waves in the regions south of the Aleutian Islands caused by the Aleutian low.

In the far north NP, total shipping frequency exhibits evident interdecadal variability. El Niño tends to weaken ocean waves in these regions. Better maritime conditions facilitate shipping efficiency and result in decreases in navigation times and the number of ship reports, yielding a negative correlation between interannual components of Niño-3.4 SST and shipping frequency. In the Philippine Sea and the northern SCS, total shipping frequency also exhibits clear interdecadal variability. El Niño tends to weaken prevailing northeasterly flows and trade winds, leading to weakened ocean waves and decreased navigation times and ship-report numbers. Interannual components of Niño-3.4 SST and shipping frequency are negatively correlated. Overall, ENSO's influences on winter shipping in the western and northern NP are indiscernible in the aspect of total shipping frequency, but are notable in the interannual-variability aspect of shipping.

Key words: ENSO, ICOADS, Winter shipping, North Pacific

Citation: Chen, J. M., C. M. Hsieh, and J. S. Liu, 2012: Possible influences of ENSO on winter shipping in the North Pacific. Terr. Atmos. Ocean. Sci., 23, 397-411, doi: 10.3319/TAO.2012.03.02.01(A)

1. INTRODUCTION

Earth's climate system results primarily from ocean-atmosphere interactions. In contrast to the large amounts of observed atmospheric data, oceanic data are considerably rare. This is due to a lack of dense observational networks over the open ocean. To improve this situation, tremendous efforts have been made to compile surface meteorological observations from voluntary observation ships, fixed and drifting buoys, and ocean stations. The collected data are stored in the user-friendly format of the International Maritime Meteorological Archive (IMMA; Woodruff 2005). The data are referred to as the International Comprehensive Ocean-Atmosphere Data Set (ICOADS; e.g., Parker et al. 2004; Woodruff et al. 2005; Worley et al. 2005). This valuable data set dates back several centuries providing long-term observational records (greatly improved in recent decades) and the largest available spatial coverage of the earth's oceans even more so than satellite data and other observational sources. Also, it has served as the foundation for a variety of scientific applications in blended analyses and reanalyses (e.g., Kalnay et al. 1996; Rayner et al. 2003; Smith and Reynolds 2003, 2004). In general, instrument-measured variables (e.g., sea level pressure, surface wind, and others) are more reliable than those obtained by visual estimates (e.g., ocean wave, cloud, and others). As such, information from visual estimates is subject to limits in its quality control and must be evaluated before use (e.g., Worley et al. 2005). Shipping safety is significantly affected by maritime conditions such as ocean waves and surface winds. It is important to find objective methods for evaluating the quality of marine information revealed in the ICOADS data.

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Within the ICOADS data, wave observations have separate estimates for wind sea and swell. Wind sea is the direct result from wind traveling across a body of water. The fetch length of winds on the sea's surface determines the size of waves. Swell relates to factors beyond the fetch of the winds and features longer period and flatter crests. Gulev and Hasse (1999) found that wind sea is closely connected with local wind variability. Some observers tend to employ wind information to estimate ocean waves and vice versa, resulting in a highly coherent surface wind-ocean wave relationship in climatological descriptions of the sea state (e.g., Gulev and Hasse 1998; Gulev et al. 2003). For the ICOADS data, the most reliable information ought to be spatial location and the number of reports. The spatial distribution of ship-report numbers should provide reliable information for delineating shipping frequency and the major routes used. In general, shipping frequency and routes should vary in accordance with maritime conditions. This suggests that, in addition to economic factors, significant climate variability may also affect the variability of shipping frequency. This type of relationship on an interannual time scale, rather than climatological descriptions of sea states, may serve as a more sophisticated criterion for evaluating the relative accuracy of the ICOADS data. However, to date, this subject has not been studied comprehensively.

On an interannual time scale, the most striking variability feature in the Pacific is El Niño-Southern Oscillation (ENSO). It is characterized by strong sea surface temperature (SST) anomalies over the tropical central-eastern Pacific (e.g., Rasmusson and Carpenter 1982; Rasumusson and Wallace 1983; Philander 1990). These anomalies are maximal in winter and exert evident remote impacts on the East Asian (EA) winter climate via an atmospheric bridge connected by tropical Walker circulation anomalies (e.g., Wang 1992; Klein et al. 1999; Lau and Nath 2000, 2003; Alexander et al. 2002; Lau and Wang 2006) and Pacific-EA teleconnections (e.g., Wang et al. 2000; Wang and Zhang 2002). Previous studies have also found that ENSO can affect climatic conditions in the North Pacific (NP)-North American sectors via a meridional teleconnection pattern featuring a wave train emanating from the tropical Pacific (e.g., Shukla and Wallace 1983; Mechoso et al. 1987). At low latitudes, strong El Niño events cause a low-level anomalous anticyclone anchored in the Philippine Sea-South China Sea (SCS) region (e.g., Wang et al. 2000; Wang and Zhang 2002; Chou 2004; Chen et al. 2007, 2008). It induces anomalous southwesterly flows to suppress prevailing winter northeasterly monsoon flows over the SCS and East Asia, leading to a weakened winter EA monsoon (e.g., Zhang et al. 1996, 1997; Lau and Nath 2006; Wu et al. 2006). In the extratropics, the Aleutian low tends to be deepened with an eastward displacement during El Niño winters as it is modulated by the Pacific/North American (PNA) teleconnection pattern (e.g., Horel and Wallace 1981; Wallace and Gutzler 1981; Fritz 1982, 1985; Shukla and Wallace 1983). Changes in the position of the Aleutian low are more important in affecting climatic conditions in surrounding oceanic regions than changes in central pressure (e.g., Rodionov et al. 2005).

The above studies reveal that ENSO can cause noticeable surface circulation anomalies in the NP during winter. These circulation anomalies should further induce changes in surface winds and ocean waves by which shipping efficiency and safety in the NP may be affected. Consequently, shipping frequency and ENSO may exhibit certain patterns in the dynamics of their relationship. Efforts are thus made in this study to investigate the possible influences of ENSO on the interannual variability of NP shipping during winter. The major questions raised in this study are as follows:

- What are the general characteristics of winter surface climate and shipping routes in the NP depicted by the ICOADS data?
- Do the wind and wave parameters of the ICOADS data exhibit systematic variability features in association with ENSO?
- How does ENSO affect the NP winter shipping? What is the relative importance in comparison with economic factors?

The results of this study should provide a specific evaluation of ICOADS data quality, including that of the visually-estimated wave parameter. The study will provide a better understanding of the interannual variability of marine environments, which should be beneficial for marine safety, shipping, and marine meteorological research.

2. DATA

Two data sets are analyzed in this study. The first is the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) monthly reanalysis data (Kalnay et al. 1996). For this data, sea level pressure (*SLP*) and 10-m wind (*V*10) fields in a 2.5° × 2.5° grid are used to delineate surface circulation features associated with ENSO. This data set is hereafter referred to as the reanalysis data.

The second data set includes ICOADS observations, which contain reports from ships, buoys, and ocean stations. Because of its diversity of sources, ICOADS data exhibit random temporal and spatial distributions and inhomogeneous quality due to different measurement methods and recording practices throughout the period of its records (e.g., Minobe and Maida 2005; Kent et al. 2007). In general, uncertainty likely decreases with data collected more recently due to more coherent and accurate sampling processes (e.g., Worley et al. 2005). To reduce uncertainty problems regarding data quality, analyses in this study examine the winters of the recent period 1983 - 2008, where 1983 winter begins in December of 1982 through to January and February of 1983. This period is after the late-1970s abrupt climate change in the Pacific (e.g., Nitta and Yamada 1989; Trenberth 1990) and includes the most significant El Niño events of 1983 and 1998. Ocean wave and surface wind are important factors affecting shipping efficiency and safety. Thus, only records with both wave (represented by wind sea parameter) and wind observations are included in the analysis. Processes regarding quality control are applied to remove possible biases in the data. A value of 2.5 to 4.5 standard deviations is commonly used as the threshold to filter outliers from monthly or seasonal grid data (e.g., Gulev and Grigorieva 2006; Tokinaga et al. 2009). A threshold of 3.5 standard deviations is thus applied in this study, the same as that used in the monthly statistics of the ICOADS data (e.g., Worley et al. 2005). To have a uniform spatial distribution, the winter-mean gridded values are obtained by averaging individual parameters within each 2° × 2° box-space.

3. MEAN WINTER FEATURES OF THE ICOADS DATA

The mean winter patterns of the ICOADS data are analyzed and compared with the reanalysis data, aiming at surveying data characteristics and quality. Figure 1 shows the climatological (1983 - 2008) winter means of 10-m wind ($V10$) and its wind speed $[(u^2+v^2)^{1/2}, \text{WSP}]$ of the reanalysis data (upper two panels) as well as wind speed

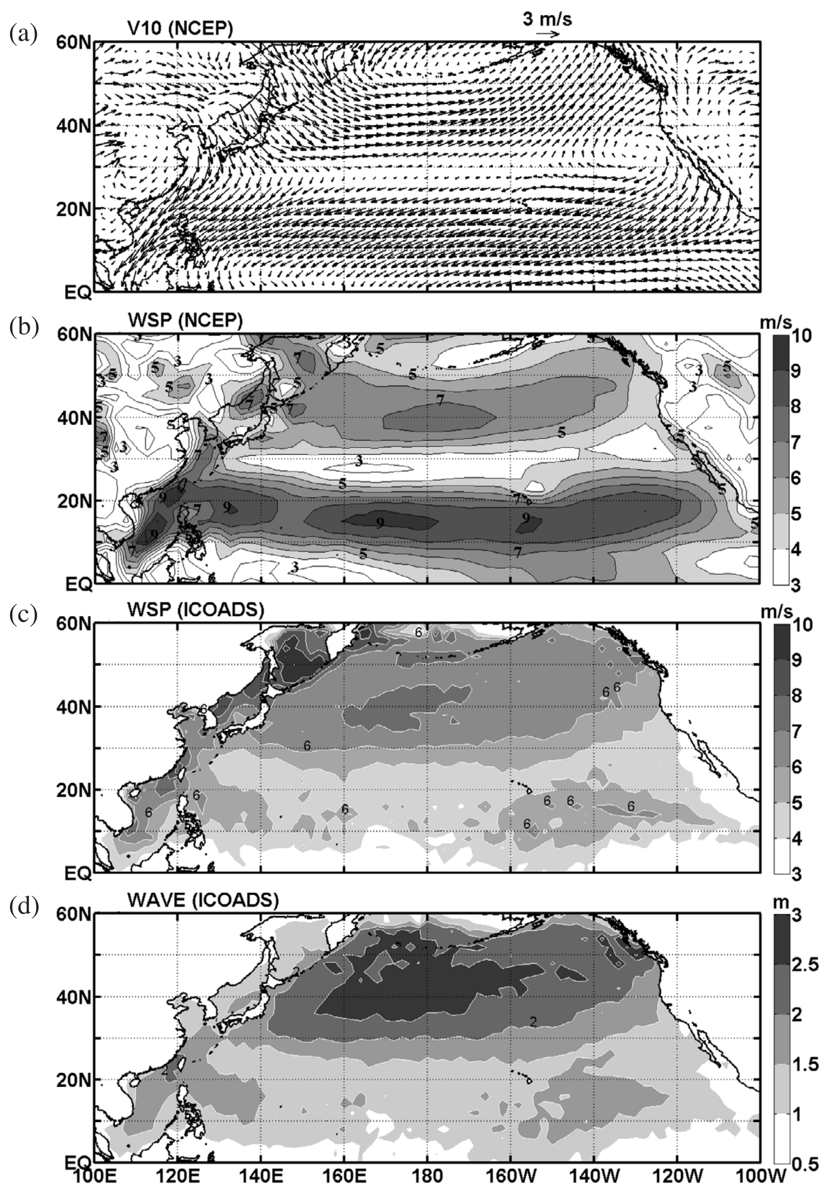

Fig. 1. The winter climatological (1983 - 2008) means of (a) 10-m winds, (b) 10-m wind speed $[(u^2+v^2)^{1/2}]$ of the reanalysis data, (c) wind speed, and (d) wave height of the ICOADS data. Contour intervals are 1 m s^{-1} in (b) (c) and 0.5 m in (d).

and height of wave of the ICOADS data (lower two panels). The reanalysis *V*10 (Fig. 1a) over the NP exhibit three salient features: the Aleutian low at the middle and high latitudes, northeasterly trade winds at the low latitudes, and monsoon northeasterly flows prevailing over the coastlines of East Asia. Subsequently, strong wind speed (WSP) occurs along the mid-latitude westerlies in the southern regions of the Aleutian low, the trade winds in the tropics, and the northeasterly monsoon flows off the EA coastlines (Fig. 1b). These three strong wind belts also appear clearly in the ICOADS WSP field (Fig. 1c). WSP magnitude of the ICOADS data is comparable with the reanalysis data for the mid-latitude westerlies and northeasterly monsoon flows but much weaker for the trade winds. Such a systematic error, as will be shown later, is likely associated with extremely poor coverage in the ICOADS data set in the tropics. The wave height in Fig. 1d shows a spatial pattern highly consistent with the WSP. Strong winds correspond to high waves. The winter-mean wave height is about 2 - 3 meters underneath the Aleutian low and about 1 - 2 meters in the SCS-Philippine sea regions, while those in the tropical Pacific exhibit values around 1 - 1.5 meters. These distributions are consistent with the climatological patterns shown by Gulev et al. (2003).

To delineate major shipping routes, Fig. 2 shows the 1983 - 2008 mean of the frequency patterns represented by the accumulation of ship-report numbers during winter. The analysis only includes reports from ships and therefore only reflects shipping activity. According to the frequency patterns, the shipping routes with large frequency (≧ 90) follow a great circle around the NP basin. The typical route from Asia to America emanates from the SCS and passes by the coasts of East Asia and Japan. It then heads northeastward along the Kuril Islands and turns eastward at a point southeast of the Russian Kamchatka Peninsula. The eastbound course mainly parallels the Aleutian Islands in the open oceans to the islands' north. The routes connect to the western coastlines of North America and further onward to Central America. The above high-latitude great circle routes are taken by both eastbound and westbound shipping for two important reasons. First, the navigational distance is shorter than via the lower latitudes due to the Earth's spherical shape; the evident saving in time and costs makes this route favorable. Second, the high-latitude route mainly penetrates the center of the Aleutian low where wind speed and wave height are smaller, while a lower-latitude route south of the low's center will encounter strong winds and high waves caused by mid-latitude westerly flows (see Fig. 1). Apparently, the high-latitude routes do have better marine safety. Overall, ICOADS observations are more intense in the open ocean to the north of Hawaii and to the west of 160°E. In the tropical central and eastern Pacific (160°E - 100°W, EQ-18°N), extremely few observations are collected in the ICOADS data, making analyses in these tropical regions highly questionable and not representative. We thus exclude these regions from our analyses. In this paper, the possible influences of ENSO on winter shipping and associated large-scale regulatory processes are focused on the western and northern NP.

4. ENSO-RELATED CIRCULATION AND WAVE VARIABILITY IN THE NP

ENSO is known to induce systematic changes in winter circulation over the NP (e.g., Shukla and Wallace 1983; Mitchell and Wallace 1996; Larkin and Harrison 2002). The associated variations in surface winds and ocean waves are assumed to influence shipping efficiency and safety in the NP. Before analyzing shipping variability features, it is necessary to examine the capability of ICOADS data in delineating the interannual variability of marine environments. This examination serves to justify the suitability of ICOADS data in conducting an interannual study.

The ENSO events are categorized by the Niño-3.4 (170 - 120°W, 5°S - 5°N) SST index compiled by the Climate Prediction Center (http://www.cpc.ncep.noaa.gov). A year in which the winter Niño-3.4 SST anomaly is higher (lower) than 0.5°C (-0.5°C) is classified as an El Niño (a La Niña) case. This classification results in nine El Niño and seven La Niña events as listed in Table 1. El Niño events are char-

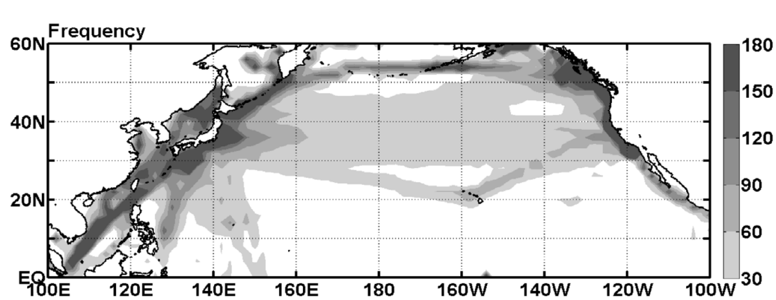

Fig. 2. The climatological-mean (1983 - 2008) shipping frequency represented by accumulated number of ship reports from the ICOADS data throughout the winter (December - February) season. The large frequency patterns indicate that major shipping routes connect Asia and North America via a great circle course through the high-latitude (about 54°N) North Pacific. The frequency is sparse in the tropical central and eastern Pacific.

Table 1. El Niño and La Niña winters defined by the Niño-3.4 SST index.

El Niño	1983, 1987, 1988, 1992, 1995, 1998, 2003, 2005, 2007
La Niña	1985, 1989, 1996, 1999, 2000, 2001, 2008

acterized by evident and elongated warm SST anomalies in the tropical central and eastern Pacific and cold anomalies in the western Pacific, while La Niña SST anomalies are largely of reverse polarity (e.g., Philander 1990). Equatorial SST anomalies can effectively modulate the overlying atmosphere via variability of the Walker circulation (e.g., Wang 1992; Klein et al. 1999; Chen et al. 2008). Anomalous warm (cold) SSTs induce an overlying low-tropospheric convergence (divergence) anomaly. Composite patterns of the reanalysis 850-hPa velocity potential (not shown) associated with ENSO characterize a pair of divergent-convergent anomalies with centers over the tropical eastern (around 140 - 120°W) and western Pacific (around 130 - 150°E) in response to underlying SST anomalies. These anomaly centers act as tropical forcing to excite a Rossby-wave-like response (e.g., Matsuno 1966; Gill 1980), which consists of a twin pairing of anomalous highs (lows) straddling the equator to the west of a divergent (convergent) center. To examine this response, composite SLP patterns of the reanalysis and ICOADS data for El Niño and La Niña cases are shown in Fig. 3. Hereafter, composite anomalies

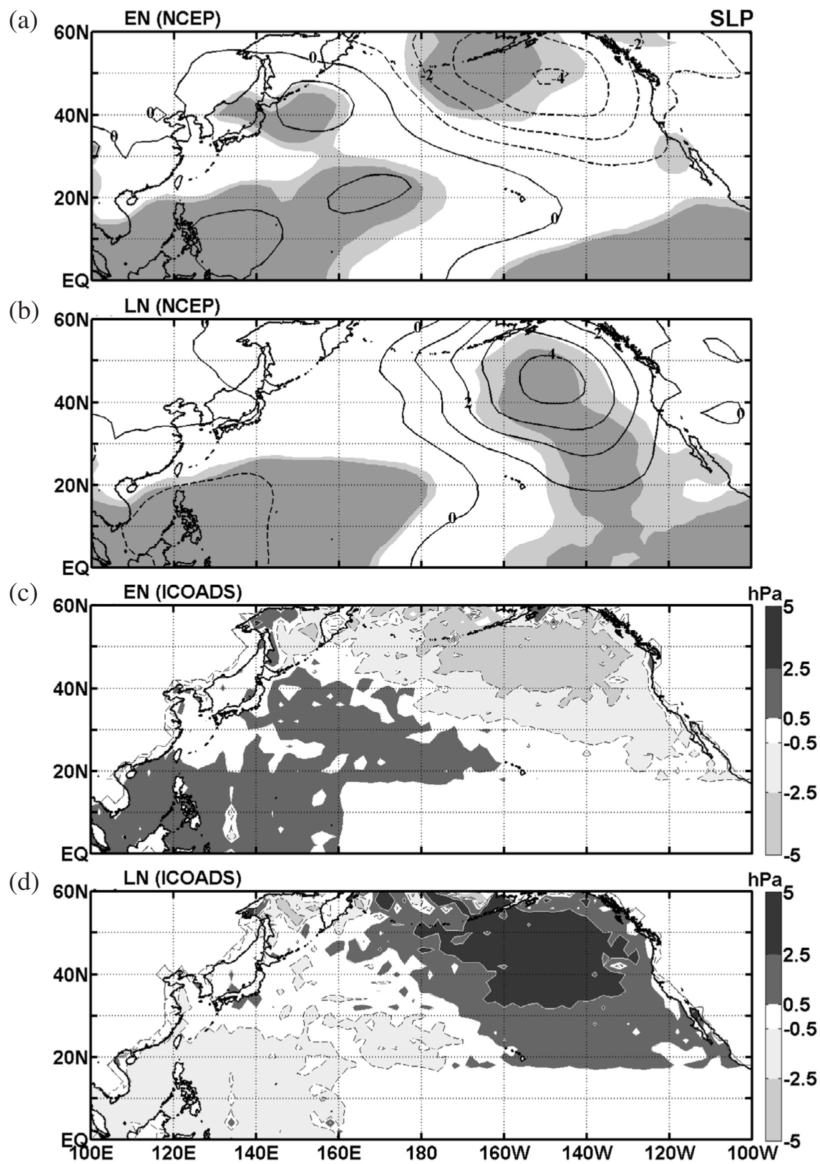

Fig. 3. Composite anomalies of sea level pressure for El Niño (EN)/La Niña (LN) cases constructed from (a) (b) the reanalysis data and (c) (d) the ICOADS data. In (a) and (b), contour intervals are 1 hPa and anomalies significant at the 0.1 (0.05) level are lightly (darkly) shaded. In (c) and (d), the data-sparse regions in the tropical central and eastern Pacific are not shown.

of the reanalysis data significant at the 0.1 (0.05) level are indicated by light (dark) shading.

As the significant patterns reveal, the reanalysis SLP anomalies associated with El Niño (La Niña) events exhibit an anomalous high (low) in the tropical western Pacific to the west of the divergent (convergent) center around the 150°E, while an anomalous low (high) appears in the northeastern NP. The above circulation variability indicates that the Aleutian low tends to intensify during El Niño but weaken during La Niña. This feature is in agreement with the analyses of Harrison and Larkin (1996) and Mitchell and Wallace (1996). For the ICOADS data, composite SLP anomalies exhibit coherent patterns with the reanalysis anomalies in terms of spatial structures and the magnitudes of major anomaly features in the western and northeastern NP.

Changes in surface winds in company with circulation variability are depicted by composite *V*10 anomalies in Fig. 4. For the El Niño cases (Fig. 4a), a significant anomalous anticyclonic (cyclonic) circulation stands out in the SCS-Philippine Sea region. Also noted is a wave train emanating from the tropical western Pacific that moves along the Pacific Rim, resulting in a significant and elongated cyclonic circulation anomaly in the northeastern NP. This wave train is a part of the PNA pattern (e.g., Horel and Wallace 1981; Wallace and Gutzler 1981; Shukla and Wallace 1983). The above anomaly features are largely reversed in La Niña cases (Fig. 4b).

The magnitude of surface wind anomalies is compared in terms of WSP between the reanalysis and ICOADS data in Fig. 5. For El Niño cases (Fig. 5a), significant WSP features of the reanalysis data include northwest-southeasterly oriented positive anomalies in the northern NP (160°E - 150°W, 30 - 50°N) and negative anomalies in the western Pacific (15 - 25°N). As indicated by the climatological flow patterns in Fig. 1a, these two features correspond to, respectively, the intensification of mid-latitude westerlies at the southern flank of the Aleutian low and the weakening of northeasterly monsoon flows and trade winds in the SCS and tropical western Pacific. The former is associated with an eastward displacement and intensification of the Aleutian low (e.g., Fritz 1985; Mitchell and Wallace 1996), while the latter reflects a weakening in the EA winter monsoon as suppressed by anomalous southwesterly flows associated with a low-level anomalous anticyclone centering in the SCS-Philippine Sea regions (e.g., Zhang 1996; Wang et al. 2000; Wang and Zhang 2002; Lau and Nath 2006; Wu et al. 2006; Chen et al. 2007). The WSP anomalies of La Niña cases (Fig. 5b) exhibit a pattern more or less opposite to that of El Niño cases. WSP variability features for the mid-latitude westerlies and the subtropical northeasterly monsoon flows and trade winds depicted by the ICOADS data in Figs. 5c - d are consistent with that depicted by the reanalysis data in Figs. 5a - b with respect to spatial structure and anomaly magnitude. The above SLP and surface wind analyses clarify that the ICOADS observed data can adequately delineate the influence of ENSO on surface circulations in the northern and western NP.

Variability in surface wind should affect the magnitudes of local ocean waves. Composite wave patterns for El Niño cases (Fig. 6a) exhibit positive anomalies across the 30 - 50°N zone of the NP in concurrence with enhanced mid-latitude westerlies in the southern sections of the Aleutian

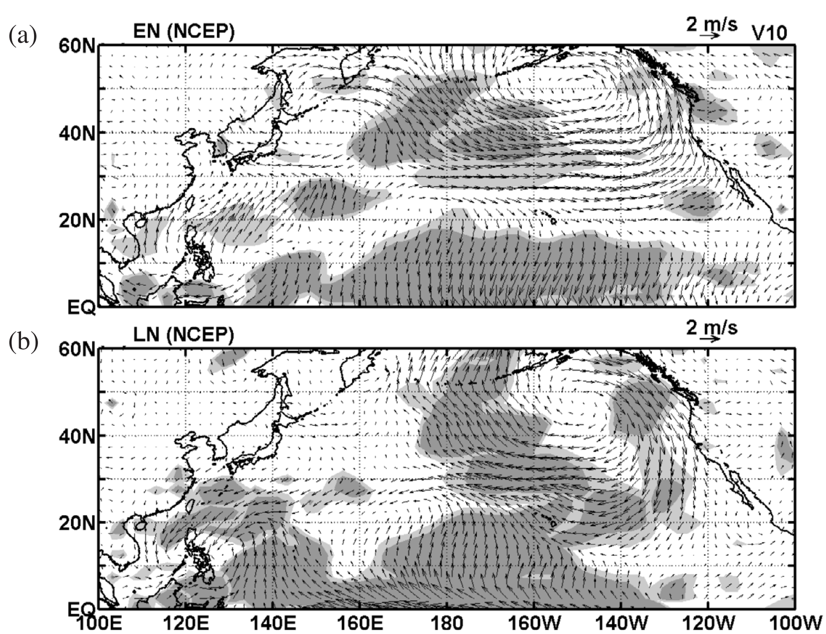

Fig. 4. As in Fig. 3, except for composite anomalies of 10-m wind fields of the reanalysis data for (a) El Niño and (b) La Niña cases. Composite anomalies significant at the 0.1 (0.05) level are lightly (darkly) shaded.

low (see Fig. 5a). In the northern sections, negative anomalies appear in the regions north of 50°N, covering the major routes across the Aleutian Islands. Negative anomalies also appear in the SCS-Philippine Sea region in association with suppressed northeasterly monsoon flows. Composite wave anomalies of La Niña cases (Fig. 6b) exhibit features largely opposite to that of El Niño cases in the SCS-Philippine Sea region. In the northern NP, the anomalous anticyclonic circulation associated with the weakened Aleutian low results in intensified (weakened) wave anomalies to the north (south) of 40°N. In general, the major wave anomalies shown in Fig. 6 are highly coherent with the variability patterns of surface winds in Fig. 5.

Analyses in this section demonstrate clearly that ENSO can induce systematic variability in winter surface winds and ocean waves in the northern and western NP, through which the major shipping routes pass. The ICOADS data are suitable for delineating interannual variability features. Moreover, ENSO is likely to affect NP shipping via marine environmental changes; therefore, the ENSO-NP shipping relationship is of continuing interest and worthy of further investigation.

5. RELATIONSHIP BETWEEN ENSO AND NP SHIPPING

Shipping is the primary means of transporting goods from one region of the world to another; therefore, demand

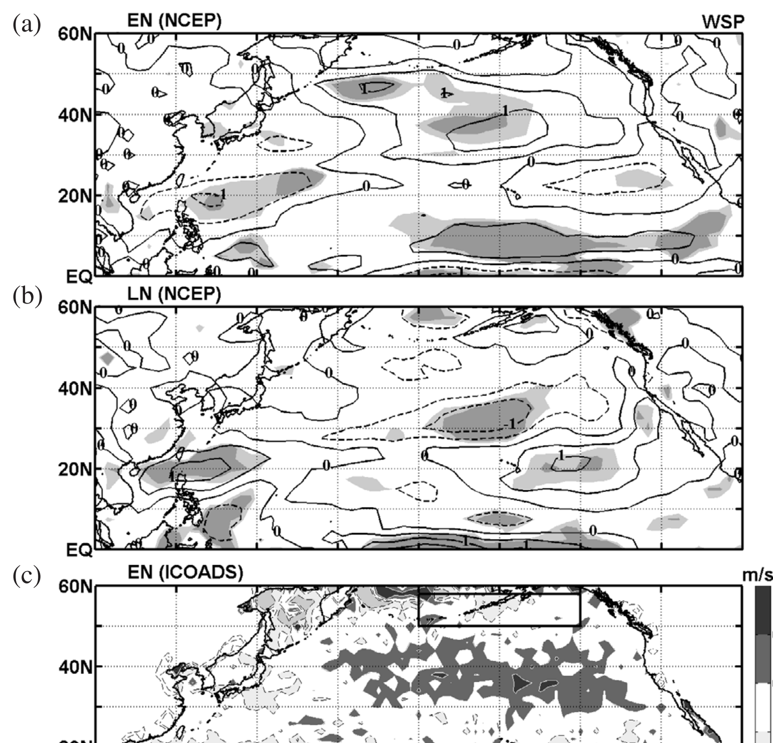

Fig. 5. As in Fig. 3, except for the wind speed anomalies of 10-m winds for (a) (b) the reanalysis data and (c) (d) the ICOADS data. In (a) and (b), contour intervals are 0.5 m s^{-1} and anomalies significant at the 0.1 (0.05) level are lightly (darkly) shaded. In (c) and (d), three regions with strong wind anomalies along the major shipping routes are indicated by the rectangular boxes: the northern NP (180 - 140°W, 50 - 58°N), the Philippine Sea (120 - 140°E, 10 - 20°N), and the northern SCS (110 - 120°E, 12 - 20°N).

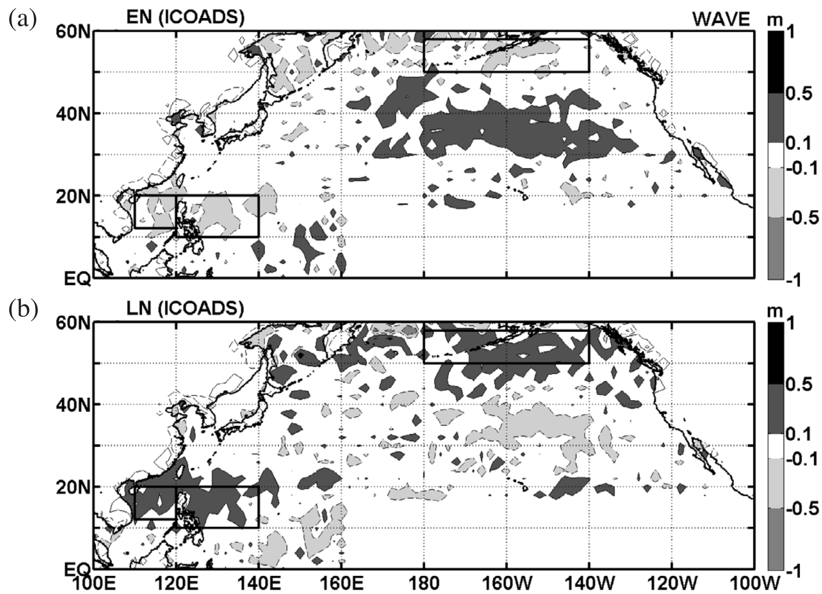

Fig. 6. As in Fig. 3, except for composite anomalies of the wave height of the ICOADS data for (a) El Niño and (b) La Niña cases. Three rectangular regions with strong wave anomalies have the same domains as those shown in Fig. 5.

for shipping should reflect world economic activity and interconnectedness. The relative influences of economic activity and ENSO on NP shipping are thus examined. As discussed previously, the impact of ENSO on marine environments is particularly evident in the western and northern NP, where major shipping routes also pass (see Fig. 2). One may anticipate that the ENSO-shipping relationship could be more systematic and better illustrated in these regions. As such, three regions in the western and northern NP with strong anomalies of wind speed and ocean wave heights induced by ENSO and also along the major shipping routes are thus selected for analysis: the northern NP (180 - 140°W, 50 - 58°N), the Philippine Sea (120 - 140°E, 10 - 20°N), and the northern SCS (110 - 120°E, 12 - 20°N). These selected regions are indicated by the rectangular boxes in Figs. 5c - d and Fig. 6. Shipping-frequency time series data given by accumulated ship-report numbers averaged for these regions are used to delineate the temporal features of NP shipping. The averaged results are compared with international trade data and winter Niño-3.4 SSTs to examine the relative influence of economic activity and ENSO on the features of shipping variability. Trade data are based on the sum of the total value of imports and exports given by the Trade Indicators Database of the Taiwan WTO center under the Chung-Hua Institution for Economic Research (http://db.wtocenter.org.tw/tradeQuery.asp). This database provides trade data from 1993 to the present. International trade amounts between three East Asian (EA) countries (China, Japan, and Taiwan) and the USA, Australia-Indonesia, and Singapore are compared with shipping frequency in the northern NP, the Philippine Sea, and the northern SCS, respectively.

5.1 The Northern NP

Figure 7a compares the 1993 - 2008 time series of monthly-accumulated ship-report numbers averaged from the winter season (thin solid line) and the entire year (thick dashed line) over the northern NP region with annual trade data between three EA countries and the USA (dotted line). The winter and yearly means of frequency time series exhibit relatively coherent interdecadal variability with a strong increase after 2004. The annual trade amounts are notable by an increasing trend with fast increases from the early 2000s. The dominant trends of annual trade amounts and winter-mean frequency are estimated by linear regression and second-order regression, respectively (Fig. 7b). After removing the linear trend, the de-trended time series of annual trade amounts evolve more coherently with the time series of the winter-mean frequency (Fig. 7c). Their correlation coefficient is 0.71, statistically significant at the 0.05 level. Total shipping frequency in the northern NP via the Aleutian-Islands region appears to be strongly controlled by international trade between East Asia and the USA on an interdecadal time scale, while ENSO-related interannual signature is indiscernible. To further examine the ENSO-shipping relationship, interannual components of Niño-3.4 SST and winter-mean shipping frequency are extracted by excluding interdecadal components (estimated by second-order regression) from the respective time series. The resultant SST and frequency time series shown in Fig. 7d tend to vary inversely on an interannual basis. Their correlation coefficient is -0.51, significant at the 0.05 level. This indicates that interannual variability in shipping frequency (giv-

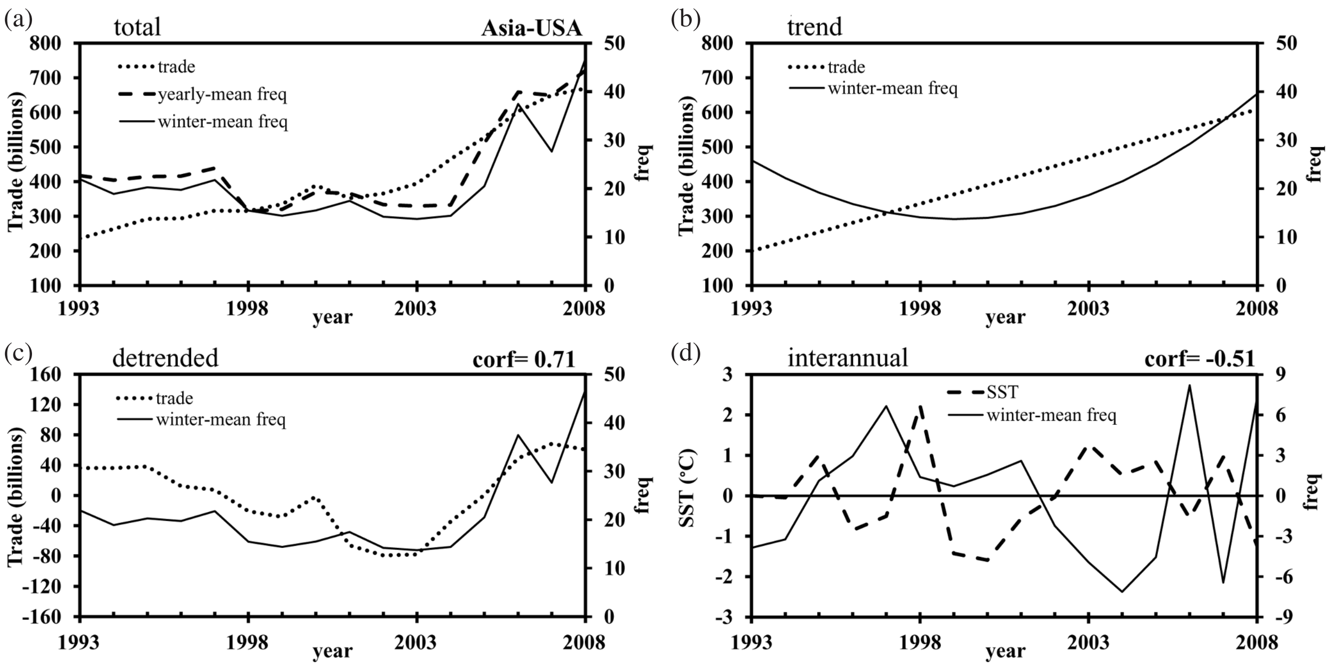

Fig. 7. Time series of international trade amounts (in US dollars) between three East-Asian countries (China, Japan, and Taiwan) and USA, shipping frequency represented by monthly-accumulated ship-report numbers in the northern NP (180 - 140°W, 50 - 58°N), and winter Niño-3.4 SST: (a) annual trade amounts and total shipping frequency averaged from winter and the entire year, (b) trends of annual trade amounts and winter-mean shipping frequency, (c) de-trended annual trade amounts and winter-mean total shipping frequency, (d) interannual components of winter Niño-3.4 SST and winter-mean shipping frequency.

en by accumulated ship-report numbers) tends to decrease (increase) during El Niño (La Niña) winters in the northern NP. As shown in Fig. 7a, El Niño weakens ocean waves in the northern NP with better maritime conditions leading to better shipping efficiency and shorter navigation times. Ship-log reports are routinely recorded every four hours and hence shorter navigation times correspond to fewer reports and a decrease in shipping frequency (Fig. 7d). Overall, total shipping frequency through the major routes in the northern NP is predominantly affected by economic activity, evidenced by the strong interdecadal relationship. ENSO, on the other hand, is much less important than economic activity although its influence can be seen on an interannual time scale with a negative correlation between interannual variability of Niño-3.4 SST and shipping frequency in the northern NP.

5.2 The Philippine Sea

Time series of winter and yearly means of shipping frequency averaged from the Philippine Sea and annual trade data between three EA countries and Australia-Indonesia are shown in Fig. 8a. Annual trade amounts display an increasing trend with strong increases in recent years. Their temporal features resemble closely time series of trade amounts between East Asia and the USA shown in Fig. 7a. Both time series of winter-mean and yearly-mean frequency exhibit salient interdecadal variability with a decreasing trend. Also, they do not exhibit any interannual signature associated with ENSO. The interdecadal trends (estimated by second-order regression) of winter-mean frequency and trade amounts are largely inverse (Fig. 8b). What the economic reasons are for a reduction in total shipping frequency in the Philippine Sea under growing world trade would likely be of interest to economists but are beyond the scope of this study. On an interannual time scale, the frequency-trade relationship becomes more coherent. After filtering out the interdecadal trend using second-order regression, interannual time series of winter-mean frequency tend to vary positively with that of annual trade amounts (Fig. 8c) with a correlation coefficient of 0.64, significant at a 0.05 level. Interannual time series of winter-mean frequency and Niño-3.4 SST (Fig. 8d) show an inverse relationship, with a -0.56 correlation coefficient significant at a 0.05 level. The negative correlation suggests that weakened (intensified) ocean waves in the Philippine Sea during El Niño (La Niña) events (see Fig. 6) tend to facilitate shipping efficiency and thus reduce navigation times and the number of ship reports on an interannual time scale. In brief, interannul variability of winter shipping in the Philippine Sea is closely regulated by international trade between East Asia and Australia-Indonesia. For ENSO, its impact is indiscernible in total shipping frequency and only notable and significant in the interannual variability of shipping frequency.

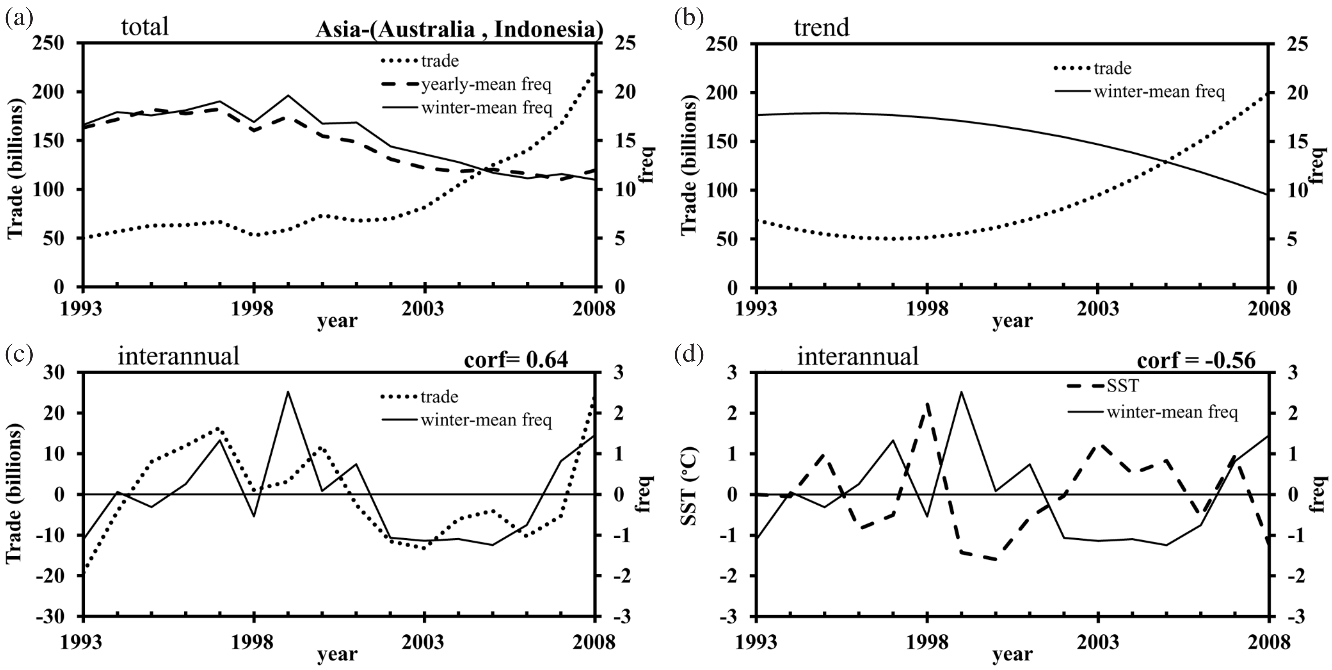

Fig. 8. Time series of international trade amounts (in US dollars) between three East-Asian countries (China, Japan, and Taiwan) and Australia-Indonesia, shipping frequency represented by monthly-accumulated ship-report numbers in the Philippine Sea (120 - 140°E, 10 - 20°N), and winter Niño-3.4 SST: (a) annual trade amounts and total shipping frequency averaged from winter and the entire year, (b) trends of annual trade amounts and winter-mean shipping frequency, (c) interannual components of annual trade amounts and winter-mean shipping frequency, (d) interannual components of winter Niño-3.4 SST and winter-mean shipping frequency.

5.3 The Northern SCS

Figure 9a shows time series of winter and yearly means of shipping frequency averaged from the northern SCS and annual trade amounts between EA countries and Singapore. Similar to Fig. 8a, annual trade amounts increase with time, but both the winter and yearly means of total shipping frequency decrease. As shown in Fig. 9b, their interdecadal trends (estimated by second-order regression) well resemble those found in the Philippine Sea (see Fig. 8b). By removing the above interdecadal trend, interannual components of the winter-mean frequency and annual trade amounts tend to vary positively with a 0.54 correlation coefficient which is significant at a 0.05 level (Fig. 9c). Interannual components of winter-mean frequency and Niño-3.4 SST, however, vary less consistently (Fig. 9d). Their correlation coefficient is negative but insignificant at only -0.26. The insignificant correlation indicates that ENSO's influence on interannual shipping variability is less important in the northern SCS than in the northern NP and the Philippine Sea.

5.4 ENSO-Shipping Frequency Relationship During 1983 - 2008

The relative effects of economic activity and ENSO on NP shipping are only examined for the period 1993 - 2008 due to the limited trade data. The analyses reveal a significant inverse relationship between ENSO SST and interannual variability of shipping frequency in the Philippine Sea and the northern NP, but not in the northern SCS. Are these relationships also valid and significant for the entire analysis period of 1983 - 2008? This extended period includes strong ENSO events in the 1980s. To answer this question, the interannual components (by removing interdecadal trend estimated by second-order regression) of Niño-3.4 SST and winter-mean shipping frequency in the northern NP, the Philippine Sea, and the northern SCS are shown in Fig. 10. SST and shipping frequency time series are largely in an inverse phase. Their correlation coefficients are -0.42 and -0.43 for the northern NP and the Philippine Sea, respectively. Both correlations are significant at a 0.05 level given the degrees of freedom of 25. On the other hand, the SST-shipping frequency correlation has an insignificant value of -0.15 for the northern SCS. These results are consistent with the previous findings using the 1993 - 2008 data. This indicates that ENSO-shipping frequency relationship over the NP is systematic and statistically meaningful. One thus may apply this relationship to the shipping management for the crossing-NP lines according to different ENSO climate conditions.

6. CONCLUDING REMARKS

Surface oceanic and atmospheric observations of the

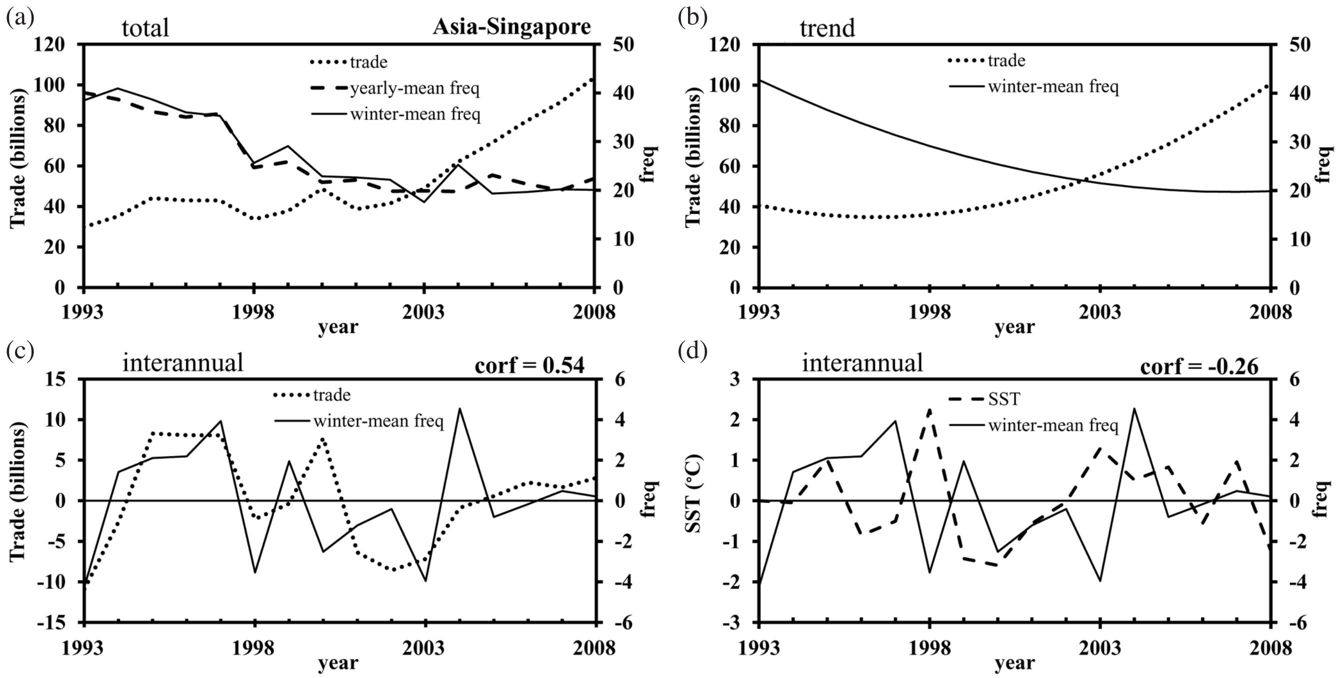

Fig. 9. As in Fig. 8, except for time series of international trade amounts between three East-Asian countries and Singapore, shipping frequency in the northern SCS (110 - 120°E, 12 - 20°N), and winter Niño-3.4 SST.

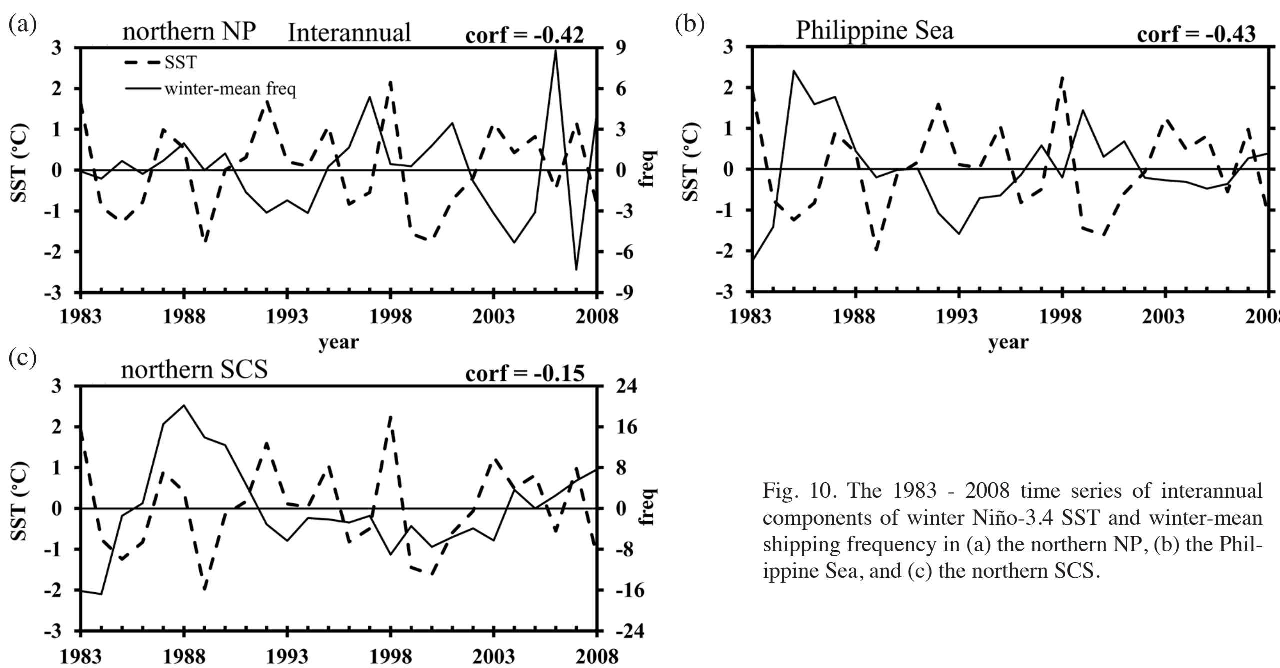

Fig. 10. The 1983 - 2008 time series of interannual components of winter Niño-3.4 SST and winter-mean shipping frequency in (a) the northern NP, (b) the Philippine Sea, and (c) the northern SCS.

open ocean contain precious and important information for marine meteorological research. However, some observed parameters (such as ocean waves) are visually estimated, embedding uncertainty into data quality. Characteristics of these observations, as compiled by the ICOADS data, need to be systematically studied before one can broadly utilize their associated information. The spatial position and number of ICOADS ship reports ought to be highly accurate. An attempt is made in this study to use ICOADS data to examine the possible influences of ENSO on winter (December - February) shipping in the NP. The dynamics of the coherent relationship between shipping-frequency variability and the sea state as influenced by surface winds is used to justify data quality of visually-estimated observations.

Shipping frequency is interpreted from the accumulated number of ship reports for each 2° × 2° box-space in the study regions for the winters of 1983 to 2008. Climatological (1983 - 2008) frequency patterns reveal that major shipping routes across the NP follow a great circle around the Pacific Rim. The routes start from the SCS and pass by the coasts of East Asia and Japan along a northeastward course toward the Kuril Islands. Shipping then turns east at a point southeast of the Kamchatka Peninsula (Russia) and takes a path through the open oceans north of the Aleutian Islands toward the western coastlines of North America. The path north of the Aleutian Islands avoids strong winds and high waves caused by the Aleutian low in the regions south of the islands. Moreover, the navigational distance is shorter than the lower-latitude route due to the Earth's spherical shape.

As defined by the Niño-3.4 SST index, there are nine El Niño and six La Niña events during the period 1983 - 2008. Composite analyses reveal that ENSO systematically affects surface marine environments during winter, especially in the northern and western NP. In these two regions, total shipping frequency over the major routes exhibits evident interdecadal variability. In the northern NP, interdecadal variability of shipping frequency is in close connection with international trade between East Asia and the USA. On the other hand, ENSO's relationship with total shipping frequency on an interdecadal time scale is indiscernible; however, the relationship is notable and statistically significant based on interannual variability. Their dynamic connections are described below. In the northern NP, El Niño events induce an eastwardly-displaced Aleutian low by which surface winds and ocean waves are intensified in the 30 - 50°N zone, but weakened in the section north of 50°N. Along the major routes in the northern NP (180 - 140°W, 50 - 58°N), weakened surface winds and ocean waves facilitate better maritime conditions. This allows for greater shipping efficiency and shortened navigation times, resulting in fewer numbers of shipping reports (shipping reports are made every four hours) and corresponding decreased shipping frequency. An El Niño event (represented by positive Niño-3.4 SST anomaly) thus corresponds to negative shipping frequency anomaly. In this case, interannual components of Niño-3.4 SST and winter-mean frequency show a significantly negative correlation, demonstrating a systematic ENSO-shipping relationship in the northern NP. In the western NP, El Niño events induce an anomalous anticyclone and anomalous southwesterly flows to suppress prevailing northeasterly monsoon flows and trade winds. Weakened surface winds lessen ocean waves along the major shipping routes in the Philippine Sea (120 - 140°E, 10 - 20°N) and the northern SCS (110 - 120°E, 12 - 20°N), providing better marine environments to increase shipping efficiency. Subsequently, shorter navigation times and fewer numbers of ship reports result in decreased shipping frequency counts. An El Niño event thus tends to associate with decreased shipping frequency. As such, the ENSO-shipping relationships in the Philippine Sea and the northern SCS feature a negative correlation between interannual components of Niño-3.4 SST and winter-mean frequency.

Analyses in this study show a dynamic relationship between interannual variability of winter shipping and ENSO-related marine environmental changes (surface wind, ocean wave) in the western and northern NP. These results demonstrate the reliability of using ICOADS data in studying interannual variability features in the NP. Shipboard observations contribute most ICOADS data. Consequently, caution needs to be taken when analyzing this type of data. First, for safety's sake, ships base their route on maritime conditions. Observed winds and waves in the ICOADS data are likely to be underestimated because the defensive nature of shipping leads to extreme sea states being observed less frequently. Therefore, when employing ICOADS data, qualitative features are more relevant than quantitative values. Second, the ICOADS data provide very few observations of tropical central and eastern Pacific. As shown in Figs. 1b and c, climatological surface winds in these tropical regions are strong in the reanalysis data but much weaker in the ICOADS data. This discrepancy deserves future attention on how representative and reliable observations are in these data-sparse regions.

As shown in Figs. 7 - 9, international trade exhibits coherently increasing trends between the three EA countries and USA, Australia-Indonesia, and Singapore. The possible reasons for the increasing trends of trade include inflation of currency and highly-growing economic activities throughout the world. On the other hand, total shipping frequency exhibits a positive trend in the Asia-USA routes, but negative trends in the other two routes. It seems that increasing international trade does not necessarily correspond with more shipping frequency. With the help of modern ship-building technology, the newly-built ships become larger and faster to save shipping costs. For example, the economic cruising speed of modern containers increases from 20 to 27 Knots with larger tonnage. As such, the shipping frequency, as represented by the number of routine 4-hour reports, can carry more goods with faster speed (or less cruise numbers). This factor may lead to a different tendency between international trade values and ship-report numbers. In addition, the portion of valuable cargoes carried by airplanes is another factor which will affect total amounts of international trade. Due to the factors of currency inflation, modern ship-building technology, and the portion of air cargoes, the international trade and shipping frequency may behave differently on their trend variability. All the above three factors are economic and non-climatic. Only after removing these dominant and non-climatic factors, the possible influences of climatic factors (e.g., ENSO) on the variability of winter shipping may become notable. ENSO can change oceanic (wave) and atmospheric (wind speed) conditions to modulate marine environments which in turn affect shipping efficiency, leading to a variability of shipping frequency. Specifically, the artificial economic factors are dominant in the long-term trend variability, while the detailed effects of climate factors are secondly important and only systematically influence winter shipping on an interannual time scale (i.e., ENSO scale).

Acknowledgements The authors would like to thank two anonymous reviewers for their valuable comments which improved this paper. This study was supported by Grant: NSC 100-2623-E-022-001-D of the National Science Council, Taiwan.

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