The effect of wind variability on the air–sea CO_2 gas flux estimation

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Abstract. The CO_2 gas transfer velocity at the air-sea interface is determined by various studies based on different mechanisms, such as turbulence and wave breaking, which are closely related with wind speed. The global marine data sets of wind speed are distributed by various types as re-analysis, assimilation, and satellite data. In order to clarify the effects of wind variability on the global CO_2 gas flux estimation, global air-sea CO_2 gas flux was estimated by using the CO_2 transfer velocity proposed by Wanninkhof (1992) together with different time and spatial resolutions of wind speeds. NCEP reanalysis 2 (6 hourly and daily, Gaussian grid) and QuikSCAT (0.25 x 0.25 grid), IFREMER-QuikSCAT (0.5 x 0.5 grid) and J-OFURO-QuikSCAT (1 x 1 grid) daily data sets were used. The difference of annual global air-sea CO_2 gas flux was 0.37 PgC/year between different time resolutions, and the difference was small on different spatial resolution. In the equatorial regions and the southern ocean, the annual air-sea CO_2 gas flux of each spatial resolution showed larger or equal values compared with each time resolution. This shows that the effects of wind variability in different time and spatial resolution data sets are significant for the estimation of air-sea CO_2 gas flux.
Key Words: global CO_2 gas flux, wind speed, time-spatial resolution

1. Introduction

It is necessary to solve the CO_2 budget over the whole earth, atmosphere, ocean and biosphere, in order to accurately predict future trends in the concentration of CO_2 in the lower atmosphere. The oceans occupy about 71 % of the Earth's surface and play an important role in the CO_2 budget due to the enormous reservoir for CO_2 in their deep waters. Therefore, the accurate evaluation of the air-sea CO_2 gas flux is very important to the estimation of total CO_2 budget over whole earth. However, the CO_2 circulation mechanism between atmosphere and ocean has not yet been completely resolved. In order to better understand the CO_2 circulation across the air-sea interface, it is necessary to estimate the CO_2 flux transferred at the sea surface. Historically, several models (Tans (1990), Wanninkof (1992), Liss and Merlivat (1986), etc.) have been proposed to determine the CO_2 exchange at the sea surface. These models are closely related with wind speed. The data sets of global wind speed are distributed by various time resolution types as re-analysis, assimilation, and composite data with their characteristic wind variabilities. By knowing the difference of the air-sea CO_2 gas flux using the different data sets, we can explore the effect of wind variability on the annual global air-sea CO_2 gas flux. Consequently, in order to clarify the effects of wind variability on the global CO_2 gas flux estimation, global air-sea CO_2 gas flux was estimated using the different time-resolutions such as 6 hourly and daily, and the different spatial resolutions of wind speed.

2. Estimation of the air-sea CO_2 flux

The air-sea CO_2 gas flux F was estimated by

$$F = k_L S(\Delta pCO_2), \qquad (2.1)$$

where k_L (m/s) is the CO_2 transfer velocity, ΔpCO_2 (μatm) is the partial pressure difference between atmosphere and ocean and S (‰) is the solubility in sea water. The CO_2 transfer velocity is generally expressed as a function of the wind speed at 10 m above the sea surface, U_{10} (m/s). Wanninkhof (1992) compared the several transfer velocity equations with water tank and field data and proposed that gas transfer velocity is related with a quadratic dependence on wind speed as:

$$k_L = 0.31 U_{10}^2 (Sc/660)^{-1/2} \qquad (2.2)$$

for short-term steady wind speed,

$$k_L = 0.39 U_{10}^2 (Sc/660)^{-1/2} \qquad (2.3)$$

for long-term averaged wind speed, where Sc is Schmidt number for CO_2 which is estimated from sea surface temperature. Weiss (1974, 1980) provided an empirical formula to estimate the CO_2 gas solubility S on the basis of data fitting among the solubility, temperature and salinity. ΔpCO_2 is taken from the global monthly climatology by Takahashi *et al*. (2009).

3. Data sets

In order to estimate the CO_2 transfer velocity, 5 types of wind speed data sets were used: 6 hourly and daily (Gaussian grid) data sets of NCEP (US National Center for Environmental Prediction) reanalysis 2, QuikSCAT scatterometer L3 daily (0. 25 x 0. 25 grid) data set distributed by PO. DAAC/Jet Propulsion Laboratory/NASA , QuikSCAT daily (0. 5 x 0. 5 grid) data set by IFREMER (French Research Institute for Exploitation of the Sea) and QuikSCAT daily (1 x 1 grid) data set by J-OFURO (Japanese Ocean Flux Data sets with Use of Remote Sensing Observations/Tokai University). The calculation of CO_2 transfer velocity was used Eq. (2.2) for short-term. The sea surface temperature of NCEP reanalysis 2 data was used. We assumed that salinity is 35 ‰ constant. The data period is one year for 2001 - this year does not include El Niño or La Niña events.

4. Results

The global air-sea CO_2 gas flux for 2001 on NCEP 6 hourly and daily, QuikSCAT, IFREMER-QuikSCAT, and J-OFURO-QuikSCAT data sets were -1. 8, -1.4, -1.1, -1.3, and -1.4 PgC/year, respectively. The air-sea CO_2 gas flux using NCEP 6 hourly data has the biggest value and the result using QuikSCAT daily data has the smallest value. The difference between air-sea CO_2 gas flux for NCEP 6 hourly and daily data was 0.37 PgC/year using the same equation. Although the

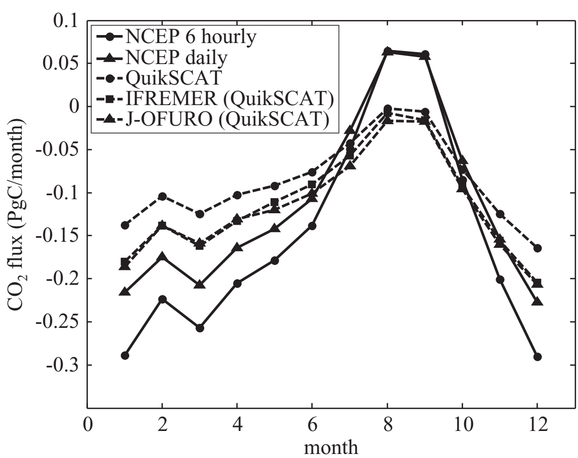

Figure 1 Distribution of the estimated monthly global air-sea CO_2 gas flux for NCEP 6 hourly and daily, QuikSCAT, IFREMER-QuikSCAT, and J-OFURO-QuikSCAT data sets.

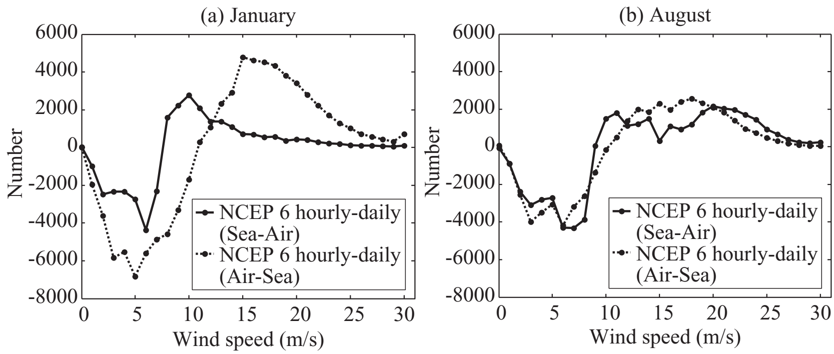

Figure 2 Difference between number of NCEP 6 hourly and daily wind speeds for CO_2 from sea to air and air to sea on (a) January, (b) August.

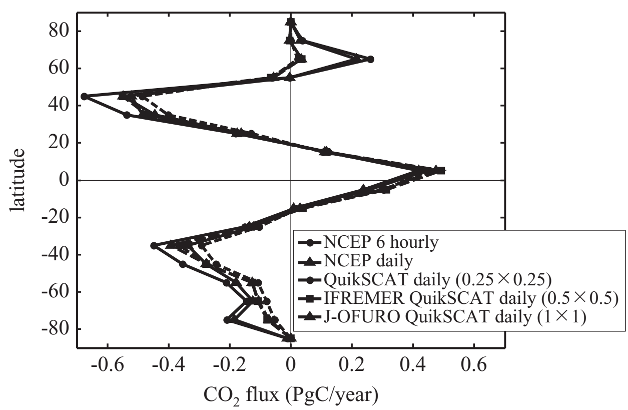

Figure 3 Plot of annual air-sea CO_2 gas flux in 10 degree latitude bands for NCEP 6 hourly and daily, QuikSCAT, IFREMER-QuikSCAT, and J-OFURO-QuikSCAT data sets.

grid sizes of the QuikSCAT daily data sets are different, the result using IFREMER-QuikSCAT daily and J-OFURO-QuikSCAT daily data has almost the same value, while the result from the QuikSCAT daily data is significantly more positive. This may be due to the rain gaps in the QuikSCAT only data set. In table 1, the regional estimates of air-sea CO_2 gas flux by each spatial resolution data compare well except that the QuikSCAT daily data is 23% lower in magnitude.

Figure 1 shows the monthly global air-sea CO_2 gas flux from each data set. We can see that the difference between the results of 6 hourly and daily is small in the period July-October, and large in the other months. About these differences: we investigated the total number of 1 m/s wind speed bins for the NCEP data set. Figure 2 shows the difference between the number of NCEP 6 hourly and daily for

CO_2 from sea to air and air to sea. In January, the difference between number of sea to air and air to sea is large, and in August, the difference is small.

Figure 3 shows the air-sea CO_2 gas flux in 10 degree latitude bands. In Figure 3, the result of each data set shows that the tendency is similar. In mid-latitude, the difference between the result of NCEP 6 hourly and daily is large. Especially, the difference is also large in January, although it is not shown here. The difference of each data set is very small at low latitude.

We estimated the local air-sea CO_2 gas flux in 8 areas; north Pacific, equator (Pacific), south Pacific, north Atlantic, equator (Atlantic), south Atlantic, equator (Indian ocean), and south Indian ocean. Table 1 shows the results of the estimated air-sea CO_2 gas flux in the above 8 areas. In the North Pacific and North Atlantic, the differences among data sets have the same pattern as the annual global air-sea CO_2 gas flux in Figure 1. In the equatorial region and southern hemisphere, the results of IFREMER-QuikSCAT and J-OFURO-QuikSCAT have larger or equal values compared with the results of NCEP 6 hourly and daily. As a tendency, the differences are small in the equatorial region, and large in the southern hemisphere. This is probably due to the higher wind speed variability in the southern oceans compared to the equatorial regions. The quadratic dependence of the gas transfer velocity on wind speed biases the mean flux to higher winds in areas of high variability.

In Figure 4 is shown the monthly air-sea CO_2 flux in the north Pacific, south Pacific, south Atlantic, and south Indian Ocean. In the north Pacific, the tendency is similar to the monthly global air-sea CO_2 gas flux in Figure 1. The difference between NCEP 6 hourly and daily is small in period July to October, the same as in Figure 1 in the south Pacific, south Atlantic and south Indian Ocean. In this period, the difference between NCEP and QuikSCAT, IFREMER-QuikSCAT, J-OFURO-QuikSCAT is large except in the north Pacific, and the air-sea CO_2 gas fluxes in QuikSCAT, IFREMER-QuikSCAT and J-OFURO-QuikSCAT have a negative value, although NCEP 6 hourly and daily have a small positive value. Thus, in the southern ocean, the difference of annual air-sea CO2 flux of

Table 1 The local air-sea CO_2 gas flux separated into 8 areas: (1) north Pacific, (2) equator (Pacific), (3) south Pacific, (4) north Atlantic, (5) equator (Atlantic), (6) south Atlantic, (7) equator (Indian ocean), (8) south Indian ocean.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NCEP 6 hourly	−0.69	0.57	−0.46	−0.57	0.16	−0.21	0.11	−0.42
NCEP daily	−0.53	0.53	−0.40	−0.47	0.15	−0.16	0.10	−0.36
QuikSCAT	−0.42	0.63	−0.44	−0.36	0.14	−0.23	0.11	−0.35
IFREMER-QuikSCAT	−0.54	0.68	−0.50	−0.43	0.14	−0.26	0.13	−0.42
J-OFURO-QuikSCAT	−0.56	0.65	−0.51	−0.44	0.14	−0.25	0.11	−0.42

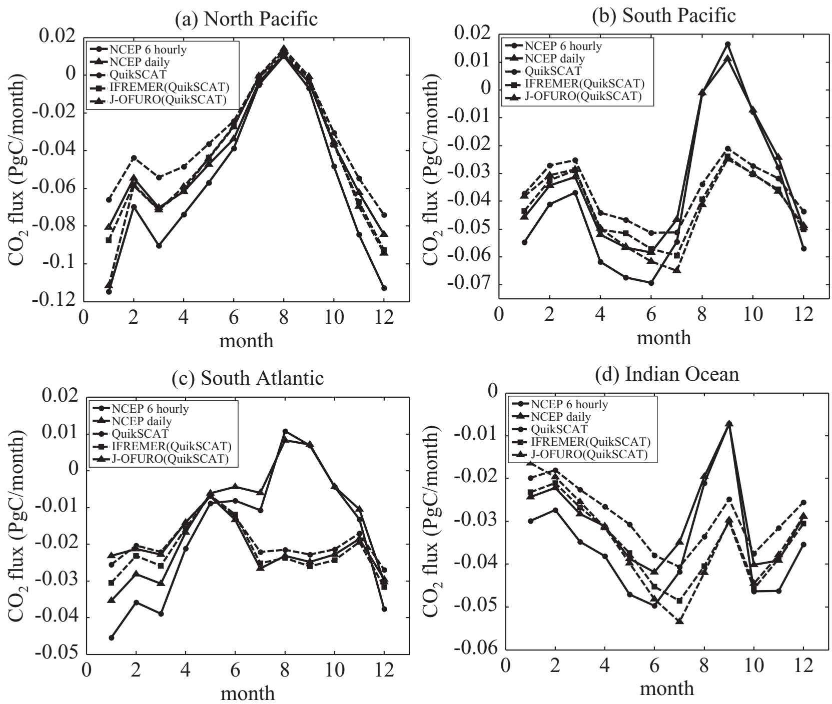

Figure 4 Distribution of the estimated monthly air-sea CO_2 flux for NCEP 6 hourly and daily, QuikSCAT, IFREMER-QuikSCAT, and J-OFURO-QuikSCAT data sets in North Pacific, South Pacific, South Atlantic, and South Indian Ocean.

QuikSCAT, IFREMER-QuikSCAT, J-OFURO-QuikSCAT is larger or equal compared with NCEP.

5. Summary

In this study, in order to investigate the effects of wind variability on the global air-sea CO_2 gas flux estimation, global air-sea CO_2 gas flux was estimated using wind speeds of different time and spatial resolutions: NCEP reanalysis 2 (6 hourly and daily, Gaussian grid), QuikSCAT scatterometer L3 daily (0.25 x 0.25 grid) data set distributed by PO.DAAC/Jet Propulsion Laboratory/NASA , QuikSCAT daily (0. 5 x 0. 5 grid) data set by IFREMER (French Research Institute for Exploitation of the Sea) and QuikSCAT daily (1 x 1 grid) data set by J-OFURO (Japanese Ocean Flux Data sets with Use of Remote Sensing Observations/Tokai University). The difference of annual global air-sea CO_2 gas flux was 0. 37 PgC/year on different time resolutions, although the difference was smaller (~ 0.1 PgC/year) on different spatial resolutions. By month, the differences on different time resolutions are small in the period July-October, and in other months are large, although the difference on different spatial resolution was small throughout the year. By locality and annually, in mid latitude and the North Pacific and North Atlantic regions, the differences on different time resolutions are large. And in the equatorial region and the southern ocean, the air-sea CO_2 gas flux of each spatial resolution also showed larger or equal values compared with each time resolution. By month, in the southern ocean, the value for each NCEP data set is positive in the period July-October, but the value for each QuikSCAT satellite data is negative. It was shown that there is a significant difference between the NWP model and the satellite data and the effects of wind variability on the different time and spatial resolution data sets are significant for the estimation of air-sea CO_2 gas flux.

Acknowledgments

The first author (Suzuki) is partially supported by Grant-in-Aid for Scientific Research (B) No.20360223 of Japan Society for the Promotion of Science (JSPS).

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