Verification of the Wind-driven Transport in the North Pacific Subtropical Gyre using Gridded Wind-Stress Products Constructed by Scatterometer Data

Kunihiro Aoki[1)] and Kunio Kutsuwada[2)]

1) Email: aoki@ees.hokudai.ac.jp, Graduate School of Environmental Earth Science, Hokkaido University

2) E-mail: kkutsu@scc.u-tokai.ac.jp, School of Marine Science and Technology, Tokai University

Abstract: Using gridded wind-stress products constructed by satellite scatterometers (ERS-1, 2 and QSCAT) data and those by numerical weather prediction(NWP) model(NCEP-reanalysis), we estimate wind-driven transports of the North Pacific subtropical gyre, and compare them in the central portion of the gyre (around 30°N) with geostrophic transports calculated from historical hydrographic data (World Ocean Database 2005). Even if there are some discrepancies between the wind-driven transports by the QSCAT and NCEP products, they are both in good agreement with the geostrophic transports within reasonable errors, except for the regional difference in the eastern part of the zone. The difference in the eastern part is characterized by an anticyclonic deviation of the geostrophic transport resulting from an anti-cyclonic anomalous flow in the surface layer, suggesting that it is related to the Eastern Gyral produced by the thermohaline process associated with the formation of the Eastern Subtropical Mode Water. We also examine the consistency of the Sverdrup transports estimated from these products by comparing them with the transports of the western boundary current, namely the Kuroshio regions, in previous studies. The net southward transport, based on the sum of the Sverdrup transports by QSCAT and NCEP products and the thermohaline transport, agrees well with the net northward transport of the western boundary current, namely the Kuroshio transport. From these results, it is concluded that the Sverdrup balance can hold in the North Pacific subtropical gyre.

KEY WORDS: wind-driven transport, scatterometer, subtropical gyre

1. Introduction

The upper oceanic circulation field in the interior ocean is related to surface wind distribution based on the Sverdrup balance (Sverdrup, 1947), which in the steady state, gives a relationship between wind stress curl and volume transport. In the North Pacific subtropical gyre, Hautala et al.(1994) presented that the Sverdrup balance in nearly the entire basin was considerably valid except two large-scale regions: in the western and eastern parts of the gyre. We can find two crucial problems for the data sets used in their study. One is that the surface meteorological data set (COADS) used in their estimations of wind-driven transport is considered to have questionable reliability, because it has not only inhomogeneous data density due to spatial dependence on ship routes but can involve much wind speed data measured by anemometers at higher levels than 10m, leading to over-estimations in wind stress(Kutsuwada,1994; Iwasaka et al., 2006). The other is hydrographic data based on the World Ocean Circulation Experiment (WOCE) used for estimations of the upper-oceanic transport, because the WOCE data obtained only by one-time measurements (spring 1985) along 24°N might not be appropriate to calculate the long-term averaged geostrophic transport. In order to solve these problems, we attempt to use the following data sets for surface winds with homogeneous spatial distribution as well as higher spatial resolution and long-term averaged hydrographic data.

We use two types of surface wind data sets: one is our gridded products constructed by satellite scatterometers: the Europe Remote Sensing satellites (ERS) covering from Oct 1991 to Dec 2000 and SeaWinds on board the QuikSCAT (QSCAT) covering a period since Aug 1999. The other is surface wind product based on the NWP models. Using new data sets of sea surface wind-stress and hydrographic measurements, we estimate the wind-driven geostrophic transport in the North Pacific subtropical gyre, and compare between the transports around 30°N. The wind-driven trans- ports are estimated by the 9-year(1992-2000) and 6-year (2000-2005) averaged wind products using the ERS and QSCAT, respectively. For both periods, the NWP products supplied by the European Centre for Medium-Range Weather Forecasts(ECMWF) and

National Centre for Environmental Prediction (NCEP) are used to compare between the wind-driven transports. The geostrophic transports are calculated from the 2005 version of the World Ocean Database (WOD05). This data set constructed by all historical hydrographic data allows us to estimate the long-term averaged geostrophic transport.

2. Data

2-1. Satellite products (ERS and QSCAT)

The ERS and Qscat/SeaWinds have continuously supplied wind data over the whole ocean in the period from August 1991 to the present. Validation studies demonstrated that the data are highly reliable by comparing with in-situ measurements such as buoys in the tropical and near-coastal regions (Ebuchi et al.,2002; Kasahara et al.,2003). The wind-stress magnitude on the sea surface is calculated for each 1° x 1° grid point for each day from 10-m wind speed by the scatterometers using the bulk formula based on Large and Pond (1981). These procedures are shown in detail in Kutsuwada(1998) and Kubota et al.(2002).

2.2. NWP products (NCEP-Reanalysis and ERA40)

We use wind(-stress) products in the operational global reanalysis provided by NCEP(Kalnay et al., 1996). They consist of two versions, NCEP reanalysis 1 and 2(NCEP-1,2). Both products provide quarter-daily surface wind data with 2.5° x 2.5° spatial resolution. Using the wind data, daily wind-stress vectors are calculated based on the same bulk formula as that used with ERS data (NCEP1 and 2/win). Further, we also use the original outputs of wind-stress in NCEP1 and 2(NCEP1 & 2/flux). We also use another operational global reanalysis(ERA40) of wind supplied by ECMWF with same spatial resolution. Using 10-m wind data every 12-hours, we calculate daily-averaged wind- stress using the same bulk formula.

2.3. World Ocean Database

We use the annual mean version of objectively analyzed historical hydrographic data of WOD05 (Boyer, 2006) supplied by the National Oceanographic Data Center (NODC internal report, http://www.nodc.noaa.gov) in order to calculate geostrophic transports. Its spatial resolution is 1° x 1° horizontally and 33 standard depth levels extending from the sea surface to 5500m depth vertically.

3. Results

3.1 Sverdrup transport for different wind products

The Sverdrup transports are estimated by various wind-stress products. An example is shown for zonally-integrated Sverdrup transports by the Qscat product(Fig.1). The transport has a maximum at about 30°N near the boundary between the westerly and trade wind regions. At the western boundary of 30°N, the values by the ERS's are the smallest, while those by the NCEP1/win the largest. The differences between these estimates are about 10 Sv ($1Sv=10^6$ m^3s^{-1}), corresponding to 20-30% of these transports. Mean wind-driven transport during 1992-2000 estimated by the NCEP2/flux product is not so far from that during 2000-2005 estimated by the same product, meaning that there is no significant difference in the Sverdrup transport field between the two periods.

4.2 Comparison of zonally integrated wind-driven transports with geostrophic transport

We compare the wind-driven transports estimated by different wind products with the geostrophic transport along 30°N estimated by the WOD05 hydrographic data. In this latitudinal zone, the Sverdrup transport difference becomes a maximum and then there are relatively large observation numbers in the WOD-05. Preliminarily, we investigate the dependency of the geostrophic transport on different two lower limits ($26.5\sigma_\theta$ and $27.5\sigma_\theta$) of vertical integration at three reference levels (1000, 2000 and 3000 db). Figure 2 shows zonal profiles of the geostrophic transports zonally-integrated from the eastern boundary for different reference levels and vertical integration ranges. These transports depend on the vertical integration range rather than the reference level. West of 155°E, the geostrophic transports change in the zonal direction with ranges of 5-10 Sv. This is artificially produced by spatial averaging over a thousand kilometers scale adopted in the WOD05 and related to a recirculation centered at 143°E, 32°N. For these discrepancies based on the different vertical integration ranges, it is difficult to select the best values which are most applicable for the comparison with the wind-driven transport, because the wind-driven circulation field in the upper ocean cannot be separated essentially from the thermohaline circulation field. Thus, we consider that the geostrophic transport field associated with the wind-driven circulation has an uncertainty shown by the range between its upper and lower values, and will represent the range in comparison with the wind-driven ones later

Figure 3a shows zonal profiles of the wind-driven transports zonally-integrated from the eastern boundary, estimated by various wind-stress products during 1992-2000, together with the range of the geostrophic transports. The wind-driven transports in the western boundary region are different among wind-stress products, ranging from 34 to 47 Sv with differences of about 13 Sv. Note that the estimated values by the ERS and ERA-40 products are significantly smaller than the geostrophic transport; while the estimates by the NCEPs are closer to the geostrophic transport west of 150°W, though they are rather different from the geostrophic transport in the eastern part. Wind-driven transport is also estimated using the new wind-stress product obtained by the QSCAT data during 2000-2005(Fig.3b), together with those by the NCEP2/flux and the geostrophic transport range. The QSCAT wind-driven transport is not so different from that for NCEP2/flux having a difference of about 5 Sv. The two values are within the range of the geostrophic transport in a large portion west of 150°W, and are rather close to the geostrophic transport integrated up to $26.5\sigma_\theta$. When we compare between the two zonal profiles of the wind-driven transports in Figs.3, we can find that the wind-driven transports for NCEP2/flux have almost the same values near the western boundary, meaning that there is little difference in the wind-driven transport between the two periods. These results imply that the Sverdrup balance can hold if the transports estimated by the QSCAT and NCEP data are valid.

In the eastern portion, there are deviations from the wind-driven transport (Figs.3), as similar to the result by Hautala et al.(1994). When we notice local transports in the eastern part, the southward geostrophic transport forms an anti-cyclonic deviation, being significantly smaller around 150°W and larger around 125°W. The geostrophic transport deviation around 150°W and 125°W may be due to the Eastern Gyral (Sverdrup et al., 1942). A recent numerical study (Toyoda et al., 2004), demonstrated that the Eastern Gyral is an anticyclonic circulation caused by the input of low-potential vorticity water associated with the formation of the Eastern Subtropical Mode Water (ESTMW)(Hautala and Roemmich, 1998). The structure in the geostrophic transport field in the eastern portion is suggested to be related to the ESTMW.

4. Discussion

We verify the wind-driven transports by comparing with the transport in the western boundary current namely Kuroshio, obtained by previous studies. Lee et al.(2001) estimated mean Kuroshio transport east of Taiwan using moored measurement data from WOCE and tide-gage data, and concluded that the net northward transport corresponding to the Kuroshio is about 36 Sv. The net southward transports which is sum of the Sverdrup transport estimated in this study and thermohaline transport of the North Pacific mode water(3Sv) (e.g.Yu et al., 2003) are shown in Table 1. The estimates for QSCAT and NCEP (34-39Sv) are within the reasonable error of the net northward transport, while those for ERS and ERA-40 are underestimated. Imawaki et al. (2001), on the Affiliated Surveys of the Kuroshio off Cape Ashizuri (ASUKA) observational line, derived 39-45Sv as mean Kuroshio throughflow transport (recirculation transports are removed) up to 1000m depth during 1992-99, using data by satellite altimeter and moored measurements. The transport would be consistent with the Sverdrup transport at the southern end of ASUKA-line (26°N, 136°E) if all of the Kuroshio flow reaches the south of Japan. However, since some portion (0-5 Sv) of the Kuroshio transport passes through the Tsushima Strait (Isobe, 1999), we can consider that the net northward transport west of 136°E at 26°N is about 39-50 Sv. At 24°N, the estimates for QSCAT and NCEP(38-48 Sv) are similar to that of the net north- ward transport although that for QSCAT is somewhat small. ERS and ERA-40 clearly under- estimate the transport also in this latitude.

5. Summary

We have verified the wind-driven transports for different wind-stress products. The Sverdrup transports have large differences of 10 Sv among wind-stress products at about 30°N. The wind-driven transports by the QSCAT and NCEP products are good agreement with the geostrophic transport with reasonable error, while those by the ERS and ERA-40 products were significantly smaller than the geostrophic transport. In the eastern part, there are significant differences between the wind-driven and geostrophic transports. This deviation in the region is not considered as a wind-driven flow field, and is suggested that it is due to the thermohaline effect, relating to the ESTMW formation. We also compared the Sverdrup transport with the Kuroshio transport in the WBC region. The net northward transports estimated by previous studies are in good agreement with the wind-driven southward transports by the QSCAT and NCEP. From our results, we can conclude that the Sverdrup balance can hold in the North Pacific subtropical gyre.

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Table 1. Zonally-integrated Sverdrup transport for different wind-stress products at 127°E, 24°N and at 136°E, 26°N plus thermohaline transport of 3Sv, and absolute difference of the transport between the latitudes (Sv).

	127E, 24N	*136E, 26N*	*Difference*
ERS	-28	-33	5
ERA-40	-28	-34	6
QSCAT	-34	-38	4
NCEP1/win	-37	-46	9
NCEP1/flux	-35	-42	7
NCEP2/win	-35	-43	8
NCEP2/flux	-39	-46	7

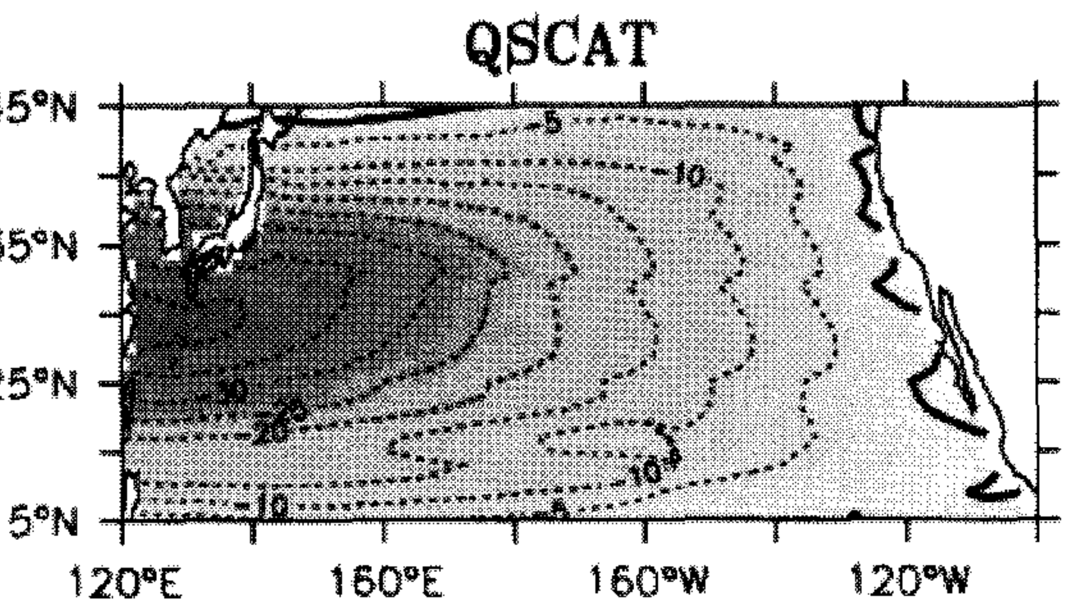

Fig.1. Zonally-integrated Sverdrup transports in the subtropical gyre estimated by Qscat wind-stress products in the 9-year mean field from 2000-2005. Contour interval is 5 Sv.

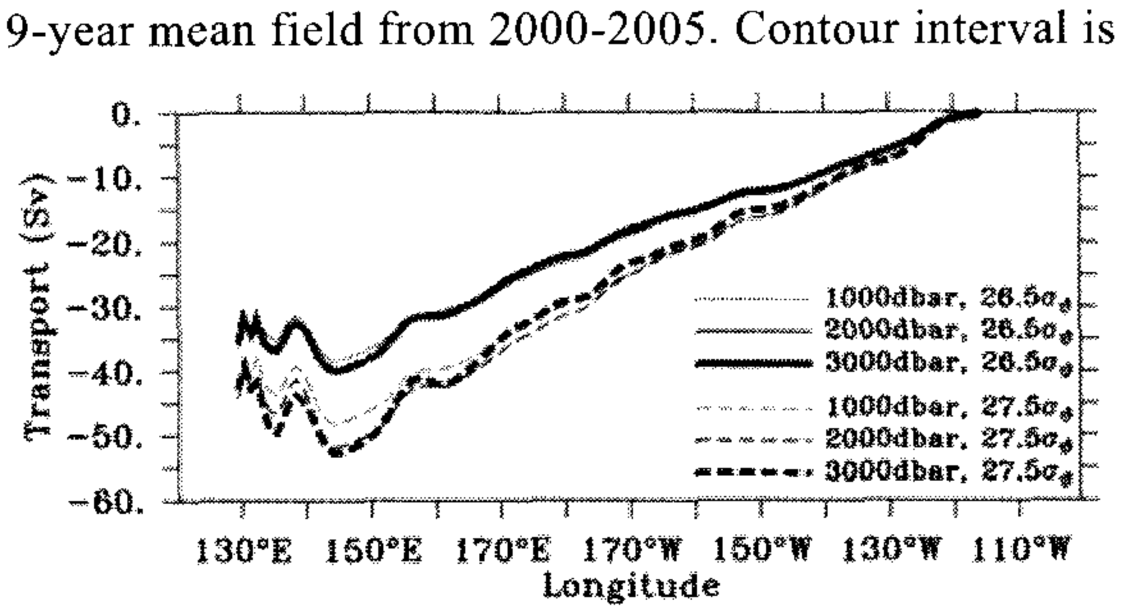

Fig.2. Zonally-integrated geostrophic transports for the reference levels(1000-3000db), with vertical integration ranging up to 26.5 and 27.5σ_θ surfaces along 30°N.

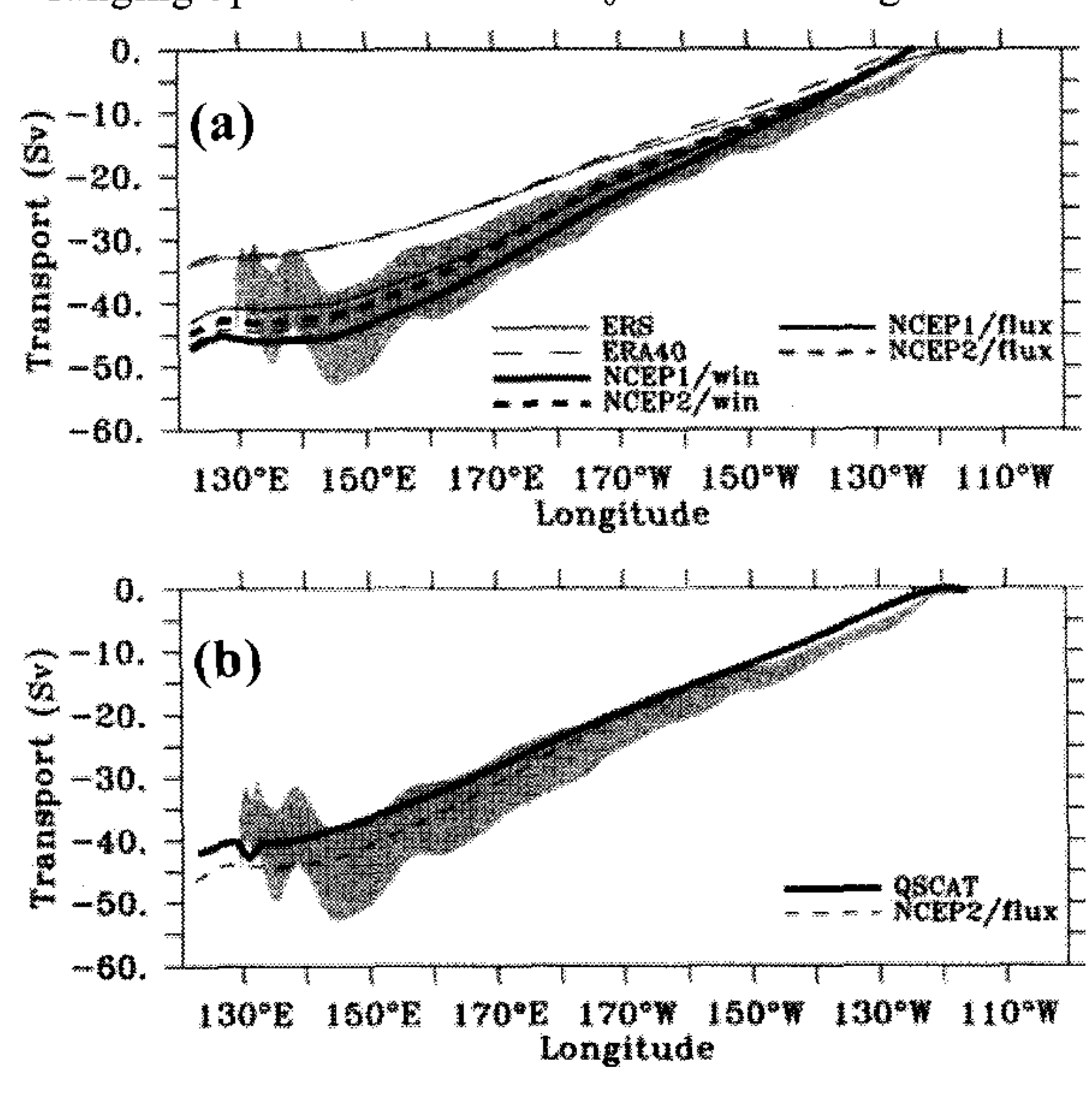

Fig.3. Zonally-integrated wind-driven transports estimated by (a):ERS & NCEPs during 1992-2000 and (b):Qscat & NCEP2s during 2000-2005. The range of zonally-integrated geostrophic transports by WOD05 along 30°N are shaded.