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Intrinsic error in the air-sea CO_2 exchange coefficient resulting from the use of satellite wind speeds

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ABSTRACT

This paper is aimed at justifying the use of satellite wind speed measurements for the determination of the carbon dioxide exchange coefficient at the air-sea interface. We relate it to the wind speed using a relationship determined by Liss and Merlivat, which enables us to monitor the spatio-temporal variations of the CO_2 exchange coefficient on a global scale, using satellite measurements of the wind speed. Yet these measurements integrate the wind speed over areas having a diameter ranging from 25 to 100 km. Moreover, a satellite has a global coverage only after a few days and samples a given place every few days (usually 3 days). We simulate the spatial integration and temporal sampling of spacecraft measurements from in-situ wind speed measurements to infer the errors induced. While the space integration results in a negligible error (a few tenths of cm h^{-1} at most), a caveat should be given about the sampling error. It is of the order of the statistical error of a normal distribution, depending on the standard deviation and number of measurements. An example of the statistical error resulting from the use of 1 month of SEASAT scatterometer data is shown. Provided this caution about the statistical error is kept in mind and the space and time integration is properly chosen, satellite data, after careful validation of the wind speed retrieval, are well suited for long-term global survey of the CO_2 exchange coefficient space and time variations. The use of a relationship between the exchange coefficient and the wind speed, which accuracy is presently discussed, is the only way to access these variations.

1. Introduction

The carbon dioxide released in the atmosphere by human activity is partly absorbed by the ocean. The flux exchanged between the two media is the product of the exchange coefficient and the CO_2 partial pressure gradient at the air-sea interface. Recently Liss and Merlivat (1986) established a relationship between the sea surface wind speed and the transfer velocity, thus allowing to describe the spatio-temporal evolution of this quantity using wind speed fields. Etcheto and Merlivat (1988) showed that the dependence of the exchange coefficient on the sea surface temperature is negligible and that the exchange coefficient is proportional to the transfer velocity at 20°C. Satellite wind speed measurements provide a unique mean for monitoring the transfer velocity as they provide a quite complete coverage of the world ocean in space and time. Yet these measurements integrate the wind speed over areas having a diameter ranging from 25 to 100 km. Moreover, a satellite has a global coverage only after a few days and samples a given place every few days (usually 3 days). This paper is aimed at justifying the use of satellite wind-speed measurements for the determination of the carbon dioxide exchange coefficient at the air-sea interface and at deriving the errors induced by the intrinsic characteristics of satellite wind speed measurements, irrespective of the errors due to the wind speed retrieval from satellite raw data.

2. Method

Liss and Merlivat (1986) related the CO_2 transfer velocity at 20°C (Schmidt number 600) to the wind speed, through the non-linear set of relations:

$$\begin{aligned} k &= 0.17U & U &\leqslant 3.6 \\ k &= 2.85U - 9.65 & 3.6 < U &\leqslant 13 \\ k &= 5.9U - 49.3 & U &> 13, \end{aligned} \tag{1}$$

where the transfer velocity, k, is in cm h^{-1} and the wind speed at 10 m height, U, is in m s^{-1}. Since this relation is non-linear, any treatment of the wind speed before computing the transfer velocity should keep its distribution function in order to allow the correct determination of the transfer velocity.

Besides the instrumental errors in the wind-speed retrieval, any satellite instrument integrates in space over a diameter ranging from 25 to 100 km and samples in time, measuring during a few tens of seconds every few days (usually 3 days) depending on the satellite orbit. Thus, the use of any satellite measurement infers an intrinsic error which value depends on the wind speed variability both in space and time.

The proper determination of the error due to space integration requires the knowledge of the wind speed everywhere inside the integrated area. Since such information is not available, we used time series of in-situ measurements and assumed the equivalence between space (Δr) and time (Δt) variations using the Taylor hypothesis, $\Delta r = \langle U \rangle \, \Delta t$, where $\langle U \rangle$ is the averaged wind speed. Masmoudi and Weill (1988) recently showed that over land, this hypothesis is reasonable for spatial scales less than 38 km. Champagne-Philippe (1989) concluded, from measurements made on the Atlantic east coast of France (4°W–47°N) during very unstable conditions, that the Taylor hypothesis cannot be extended to the mesoscale range in such disturbed regimes but seems to be valid only in stable cases. Even though it is a very rough approximation, it is the only way to estimate this error; moreover we are only looking for orders of magnitude.

As far as the sampling error is concerned, we used the same time series of in-situ measurements and undersampled them in the way a spacecraft having a classical orbit would have done, to simulate satellite measurements and deduce the inferred error. In addition, the satellites used for remote sensing of the ocean are usually sun-synchronous, that is they fly over a given place always at the same local time: thus any diurnal or semi-diurnal variation having a fixed phase would be unproperly sampled. We looked at this point too.

3. Data

We used in-situ wind speed data measured with anemometers on-board a mooring, on rocks or on small islands. The characteristics and location of the measurements are given in Table 1. The measurements in the Gulf of Guinea and at Saint Peter and Saint Paul Rocks, made on board a mooring and a very small rock respectively, are of good quality. The Amsterdam Island data were

Table 1. *Characteristics of in-situ measurements*

Site	Coordinates	Time resolution	Period	Comments	Origin
Gulf of Guinea Mooring	4°W 0°N	1 h or 3 h	13 February 1983 18 August 1984		C. Colin (Colin and Garzoli, 1987)
St Peter St Paul Rocks	29°W 1°N	1 h	1 January 1985 14 January 1987		S. Garzoli (Edwards et al., 1988)
Amsterdam Island (AMS)	77°E 37°S	1 mn	February 1982 March 1983	continuous over 2 to 8 days (instrumental difficulties)	A. Gaudry (Gaudry et al., 1983)
Crozet Islands	52°E 46°S	3 h			meteorological station
Kerguelen Islands	70°E 49°S	3 h		sheltered from prevailing winds	meteorological station

recorded, with a very high time resolution, on an island, in a station sheltered from some wind directions. Due to the sheltering effect and to some instrumental difficulties, the data had to be sorted out, resulting in time series lasting only 2 to 8 days. The Crozet Islands data were recorded in a station well situated on a small island, while the Kerguelen Islands station was sheltered from the prevailing winds and likely to underestimate the wind speed.

We also used SEASAT scatterometer data from 7 July to 9 October 1978, to apply our results to real satellite data. We used a data set reduced by F. Wentz using the methods described in Wentz et al. (1984; 1986), resulting in measurements averaged over 100 km.

4. Results

4.1. Space and time integration

In order to determine the error made by averaging the wind speed before computing the transfer velocity, we either computed k directly from initial in-situ measurements, U_i, and averaged later, obtaining $\langle k(U_i) \rangle$, or averaged U_i over a time duration T, obtaining a reduced series U_a, from which we computed $\langle k(U_a) \rangle$ averaged over the whole series.

Then, we computed the algebraic Δk and the relative $\Delta k/k$ error on k as a function of T:

$$\Delta k = \langle k(U_i) \rangle - \langle k(U_a) \rangle, \qquad \frac{\Delta k}{k} = \frac{\Delta k}{\langle k(U_i) \rangle}. \quad (2)$$

When this is done for several durations T, it gives the error on k as a function of T. These results can be used to evaluate either the error made when using wind fields averaged over several days, or the error due to satellite spatial integration via the Taylor hypothesis (average over several hours). We did this study in the Gulf of Guinea, Saint Peter and Saint Paul Rocks, Amsterdam and Kerguelen Islands.

For each site the study was performed on several time series, 4 or 5 depending on the site. The duration of the original data set, U_i, is 32 days except in Amsterdam Island where it is 4 days. The maximum errors found in a given place for a given integration duration is shown on Table 2; the

Table 2. *Integration error*

Site	U integration duration (h)	Associated space integration (km)	$\langle U \rangle$ (m s^{-1})	$\langle k \rangle$ (cm h^{-1})	$\langle k \rangle$ maximum relative error (%)	$\langle k \rangle$ maximum error (cm h^{-1})
Gulf of Guinea	3	40	4.0	2.2	6	0.1
	6	80	4.0	2.2	13	0.3
	48 (2 days)	–	3.7	1.6	36	0.6
	192 (8 days)	–	3.7	1.6	51	0.8
	768 (32 days)	–	3.7	1.6	62	1.0
St Peter St Paul Rocks	3	40	3.5	1.8	4	0.1
	6	80	3.5	1.8	7	0.1
	48 (2 days)	–	3.5	1.8	27	0.5
	192 (8 days)	–	3.5	1.8	48	0.9
	768 (32 days)	–	3.5	1.8	69	1.2
Amsterdam Island	1	30	8.2	12.8	3	0.4
	2	60	8.2	12.8	4	0.5
	4	120	8.2	12.8	4	0.5
Kerguelen Island	48 (2 days)	–	10.4	23.8	12	2.9
	192 (8 days)	–	10.4	23.8	16	3.8
	768 (32 days)	–	10.4	23.8	16	3.8

indicated error does not necessarily correspond to the same serie, depending on the duration, T. The error range can be large since the seasonal variation moves the average wind speed with respect to the discontinuities of relation (1). This is true for the first discontinuity in the Gulf of Guinea and at Saint Peter and Saint Paul Rocks, and for the second one at Amsterdam Island and at Kerguelen Islands.

The error resulting from the size of the spaceborn instrument's field of view, found for 1 to 6 hours integration depending on the average wind speed and on the size of the integration area, is in any case less than 0.5 cm h^{-1}. This test could not be performed in Kerguelen Islands where the data are already averaged over 3 hours. On another hand, the use of wind fields averaged over several days or one month, results in much higher errors and should be banished. One should notice that the error resulting from averaging is always an underestimate, due to the nature of relations (1).

4.2. *Wind speed distribution*

In order to determine whether it is valid to replace the observed monthly distribution by a model distribution, as was done for instance by Erickson and Duce (1987) we compared it to three model distributions: a normal distribution of the wind speed, a Rayleigh distribution and a normal distribution of each component (Papoulis, 1985). The parameters of these models were determined from the average, the standard deviation and the correlation coefficient between the components of the wind speed. The errors were computed in the same way as above

$$\Delta k = \langle k(U_i) \rangle - \langle k(U_t) \rangle, \qquad \frac{\Delta k}{k} = \frac{\Delta k}{\langle k(U_i) \rangle}, \quad (3)$$

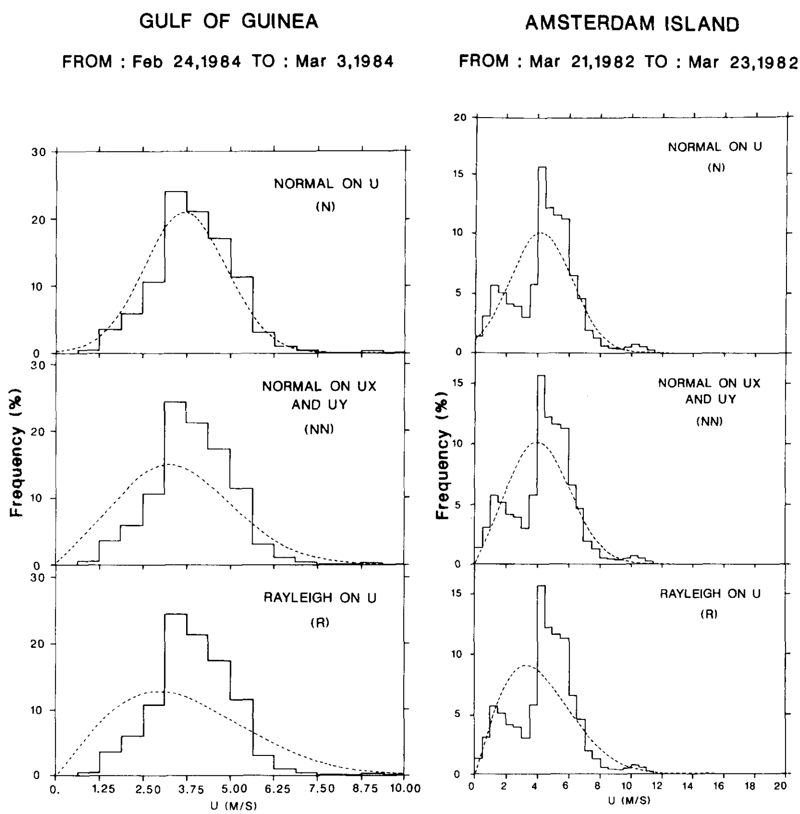

Fig. 1. Histogram of the wind speed in the Gulf of Guinea and at Amsterdam Island. Three different model distributions are superimposed.

where U_t is the wind speed from the model distribution.

The quality of the fit depends on the site. Fig. 1 shows the real distribution and the fitted model distributions in Gulf of Guinea and in Amsterdam Island respectively. At Amsterdam Island, periods 2 days long were used, while data series of one month duration were used elsewhere. At Amsterdam Island, 11 such periods, unevenly distributed during the year, were analyzed.

The errors computed from relations (3) are summarized in Table 3 where the error averaged over 1 year (or 11 periods) and the maximum monthly (or 2 days) error are both indicated. The errors resulting from a Rayleigh distribution are the highest because, in this type of distribution, while the average wind speed is kept, the standard deviation is not. The results from a normal distribution, either on the wind speed or on its components, are comparable, with a slight tendency for the first one to be better. Since it is much easier to fit a normal distribution on the wind speed than on its components (the knowledge of the correlations between components is not required), it is the one which should be used. In addition the inferred error is less than 0.3 cm h^{-1} in all the cases we studied and its sign varies with the site. More generally, any distribution which respects both the average wind speed and its standard deviation seems suitable to simulate the wind speed variability for the problem we are interested in. This is the case of the model distribution used by Heimann and Monfray (1989).

4.3. *Sampling*

The orbits commonly used for remote sensing satellites are sun-synchronous, at an altitude of about 800 km. The time necessary for the satellite to come back exactly over the same trajectory with respect to the Earth, is called a cycle. A 3-day cycle is usual and we chose to simulate such an orbit. The satellite passes again over some points (crossing points) 12 hours later (one daytime measurement, one nightime measurement) so that it makes two samples, 12 hours apart, every 3 days. When the width over which the instrument measures (swath) is large or double, it can view the same point on 2 successive days, thus making 4 measurements, 12 hours apart, every three days. We simulated these various cases by sampling in this way the time series recorded in the Gulf of Guinea, at Saint Peter and Saint Paul Rocks and

Table 3. *Errors due to model distributions*

Site	Distribution type	$\langle k \rangle$ global average (cm h^{-1})	$\langle k \rangle$ relative error average (%)	$\langle k \rangle$ relative error maximum (%)	$\langle k \rangle$ error average (cm h^{-1})	$\langle k \rangle$ error maximum (cm h^{-1})
Gulf of Guinea	Normal on U	3.3	−1.4	−5.4	−0.1	−0.1
	Normal on U_x and U_y	3.3	−3.8	−20.5	−0.1	−0.3
	Rayleigh on U	3.3	−15.8	−51.0	−0.4	−0.8
St Peter St Paul Rocks	Normal on U	4.4	1.7	5.1	0.1	0.2
	Normal on U_x and U_y	4.4	1.0	−11.0	0.1	0.3
	Rayleigh on U	4.4	−13.6	−39.0	−0.6	−1.1
Amsterdam Island	Normal on U	9.6	−1.3	−2.6	−0.1	−0.3
	Normal on U_x and U_y	9.6	−0.9	3.9	−0.1	−0.3
	Rayleigh on U	9.6	−7.8	−31.0	−0.6	−2.1
Kerguelen Island	Normal on U	20.1	−0.2	−1.1	−0.1	−0.2
	Normal on U_x and U_y	20.1	−0.6	−4.3	−0.1	−0.8
	Rayleigh on U	20.1	−1.1	−7.1	−0.2	−2.4

Kerguelen Islands, obtaining undersampled series of U_{si}. If, in addition, we want to simulate the space integration of the spaceborne instruments, we sample 3 hours averages. The errors resulting from this undersampling are then calculated by

$$\Delta k = \langle k(U_i) \rangle - \langle k(U_{si}) \rangle, \quad \frac{\Delta k}{k} = \frac{\Delta k}{\langle k(U_i) \rangle}. \tag{4}$$

An example of the results in Saint Peter and Saint Paul Rocks and Kerguelen Islands is shown on Fig. 2. The statistical error

$$E_{stat} = \frac{\sigma}{\sqrt{N}}, \tag{5}$$

inside which 70% of the measurements are expected to be for a normal distribution having a standard deviation σ and a number N of measurements (Bendat and Piersol, 1986) is

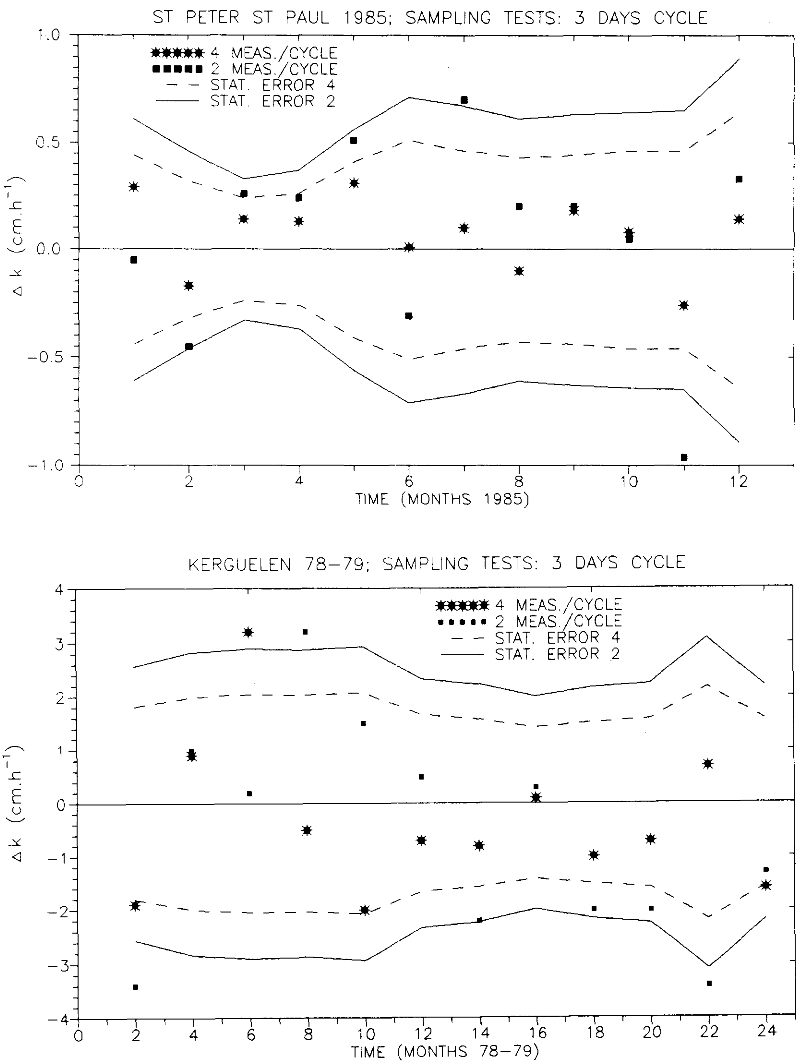

Fig. 2. Errors induced by simulated satellite undersampling in two sites. The statistical error for a normal distribution $\sigma/\sqrt{N}$ is shown for comparison.

shown for comparison. The results are summarized in Table 4: for each site and sampling sequence, we reported the yearly average and the maximum value of the monthly algebraic, Δk, relative, $\Delta k/k$, and absolute, $|\Delta k|$, k errors. The statistical error is indicated too. For all the tests we performed, the errors were inside this statistical error, even though the distribution of the transfer velocity is usually not normal. It is worthwhile pointing out that over one year, monthly errors compensate each other so that the algebraic error average is always less than 0.5 cm h^{-1}.

4.4. Sun-synchronous orbit

The easiest way to estimate the possible aliasing of diurnal or semi-diurnal variations by a sun-synchronous satellite, is to simulate the satellite sampling in the way described above with various phases in local time and check whether the variations are inside the statistical error. In other words we started the sampling sequence at 9 h; 12 h and 15 h. Since a diurnal variation is expected in coastal regions but that we are interested in what happens in the free ocean only, this test was only performed at Saint Peter and Saint Paul Rocks (more than 1000 km off the american coasts). The results are shown in Table 4. In all cases no variation larger than the statistical error is visible.

4.5. Satellite versus in-situ wind speed

Even though the validation of the retrieval algorithm of satellite wind speed is beyond the scope of this paper, it is of interest to compare the retrieved SEASAT scatterometer wind speeds to the in-situ measurements we used in this study.

When we had simultaneous data, we colocated the measurements (distance less than 200 km and time less than 1 h 30 min) and computed the average $\langle U_s \rangle$ for the satellite measurements and $\langle U_i \rangle$ for the in-situ measurements (using only the colocated data).

The standard deviation of the colocated data from the diagonal (perfect agreement) σ_{si} is computed too. Moreover, for every data set, we computed the average and standard deviation of the wind speed during the same period of the year, independently for the satellite and in-situ data. All the satellite data located at less than 5° longitude and 5° latitude in the equatorial regions and less than 3° longitude and 1° latitude in the Southern latitudes from an in-situ measuring site were averaged.

Table 4. *Sampling error*

Site	Number of samples per cycle	First sample time (phase)	$\langle k \rangle$ algebraic error average $\langle \Delta k \rangle$ (cm h^{-1})	$\langle k \rangle$ absolute error average $\langle \lvert\Delta k\rvert \rangle$ (cm h^{-1})	$\langle k \rangle$ maximum error Δk_{max} (cm h^{-1})	$\langle k \rangle$ statistical error $\sigma_k/\sqrt{N}$ (cm h^{-1})
St Peter St Paul Rocks	2	9:00	0.06	0.36	−0.96	0.59
	2	12:00	0.24	0.48	0.94	0.59
	2	15:00	0.10	0.43	−0.75	0.59
	2 (3 h means)	9:00	0.08	0.33	0.80	0.59
	4	9:00	0.07	0.16	0.31	0.42
	4	12:00	0.05	0.22	0.46	0.42
	4	15:00	0.00	0.26	0.52	0.42
	4 (3 h means)	9:00	0.06	0.13	0.36	0.42
Gulf of Guinea	2	9:00	0.36	0.44	1.00	0.59
	4	9:00	−0.08	0.17	−0.42	0.42
Kerguelen Island	2	9:00	0.40	2.00	3.20	2.53
	4	9:00	0.40	1.28	−3.40	1.79

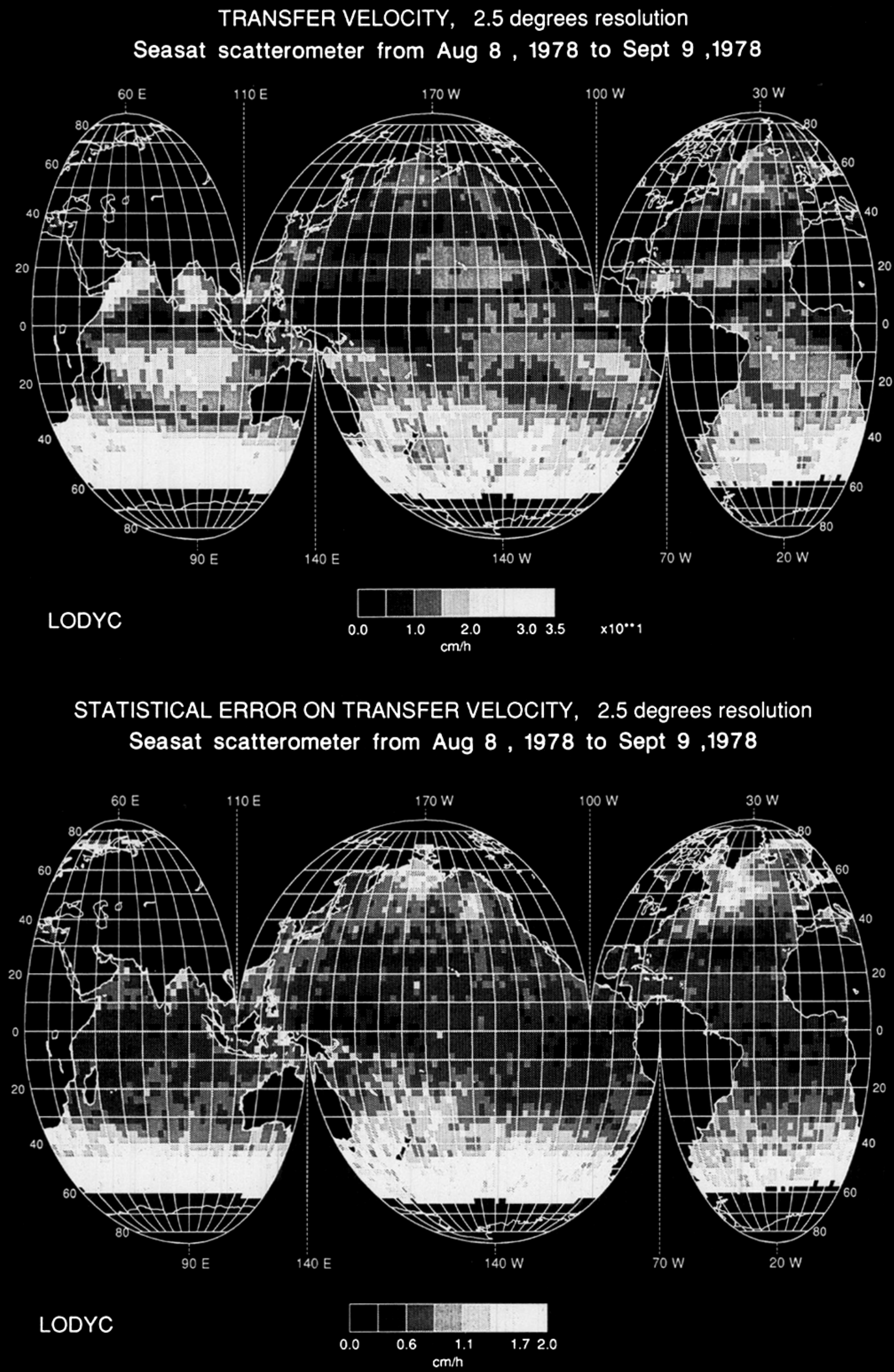

Fig. 3. Map of the transfer velocity at 20°C for the month of August 1978, at 2.5° resolution, deduced from the SEASAT scatterometer measurements, and of its statistical error.

Table 5. *Satellite versus in-situ comparison*

Site	U_s (m s^{-1})	U_i (m s^{-1})	k_s (cm h^{-1})	k_i (cm h^{-1})	σ_s (m s^{-1})	σ_i (m s^{-1})	σ_{si} (m s^{-1})
Gulf of Guinea in situ 1983	5.2	5.0	5.0	4.3	1.9	1.4	
St Peter St Paul in situ 1985	7.3	6.2	9.8	7.1	1.7	1.2	
St Peter St Paul in situ 1986	7.3	6.8	9.8	8.7	1.7	1.6	
Kerguelen island in situ 1978	12.6	11.2	28.4	24.4	4.9	5.8	
colocated	11.7	9.8					3.2
Crozet island in situ 1978	11.1	11.1	22.7	24.4	4.6	6.1	
colocated	10.5	9.4					3.0

The results are shown on Table 5, for 3 months of data, July 7 to October 9 (SEASAT lifetime). The in-situ data in Gulf of Guinea and Saint Peter Saint Paul Rocks even though they include the inter-annual variability, are close to the satellite data, even for the standard deviation, which is larger for the satellite measurements than for the in-situ ones, due to the instrument's noise. The U differences in Kerguelen (1.4 m s^{-1}) and in Crozet (0.04 m s^{-1}) are less than for the colocated data because of average smoothing. In any case, the difference is everywhere of the order or less than 1 m s^{-1}, the value usually claimed for satellite wind speed retrievals, except in Kerguelen Islands. This is probably due to the fact that the meteorological station there, is sheltered from the prevailing winds, thus underestimating the in-situ wind speed. These comparisons should be considered only as qualitative.

5. Discussion and conclusion

We studied the various intrinsic errors resulting from the use of satellite wind speeds in determining the CO_2 exchange coefficient. The space integration resulting from a 100 km footprint of the spaceborne instrument was always found to be less than 0.5 cm h^{-1}. In addition, the recent instruments have a smaller footprint, on the order of 25 km, and this error should decrease. In any case it is always an underestimate.

On another hand, the use of wind fields averaged over several days leads to a large error, unless the standard deviation of the wind speed is properly known everywhere and the wind speed variability properly simulated.

While the sun-synchronous orbit does not seem to have serious consequences, the sampling error can be large. It is comparable to the sampling error of a normal distribution and it should be kept in mind that the space and time integration used should be tuned to the expected accuracy. In order to estimate this error in a real case, we made a map of the statistical error on k using SEASAT scatterometer data during one month (August, 1978).

We first binned all the SEASAT data in $2.5° \times 2.5°$ boxes and then computed the standard deviation for each box obtaining a map of the standard deviation. Then we took one month of SEASAT data, binned them in the same way, and obtained a map of the number of measurements. We then computed the statistical error using relation (5), which is shown on Fig. 3, together with a map of k shown for comparison. The standard deviation varies between 3 and 20 cm h^{-1}, while the number of measurements per box is between 200 and 300 everywhere except in the Antarctic Ocean where it is only about 80. The statistical error is between 1 and 2 cm h^{-1} everywhere except in the Antarctic Ocean where it is more, due to both a large standard deviation and a small number of measurements. Therefore this statistical error can be large, and one should be careful when using satellite data, to properly choose the area and time of integration, in order to retain enough measurements to keep their statistical significance.

These errors are small compared to other error sources. The first one concerns the accuracy of the relation between the CO_2 transfer velocity and the wind speed. The limitations were mentioned by Etcheto and Merlivat (1988); the global CO_2 transfer velocities determined using this relation and different wind fields are between 12 and 13 cm h^{-1} (Etcheto and Merlivat, 1988; Heimann and Monfray, 1990) while this quantity is estimated to be about 20 cm h^{-1} using geochemical (^{14}C) methods (Broecker et al., 1986). However, recent experimental measurements of the transfer velocity agree with this relation, as discussed in a companion paper (Etcheto et al., 1991). The second error source is the accuracy of the satellite wind speeds, as discussed by Boutin and Etcheto (1990) which can amount to an error on the wind speed up to 3 m s^{-1}, corresponding to an error on the transfer velocity up to 10 cm h^{-1} in some areas. Also, the wind speed retrieved by the returned scatterometer signal can be influenced by the wind-fetch (Glazman et al., 1988) and if the air-sea gas transfer velocity depends in a different way on the wind-fetch, systematic errors result. The current efforts at calibrating satellite measurements should reduce the wind speed retrieval errors in the future, and make the monitoring of the exchange coefficient from satellite accessible with an accuracy better than by any other means.

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