PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

World-Scale Monthly Mapping of the CO$_{2}$ Ocean--Atmosphere Gas-Transfer Coefficient

Fabienne Thomas, C. Perigaud, L. Merlivat and J.-F. Minster

Phil. Trans. R. Soc. Lond. A 1988 **325**, 71-83
doi: 10.1098/rsta.1988.0043

Phil. Trans. R. Soc. Lond. A **325**, 71–83 (1988) [71]
Printed in Great Britain

World-scale monthly mapping of the CO_2 ocean–atmosphere gas-transfer coefficient

By Fabienne Thomas[1], C. Perigaud[1], L. Merlivat[2] and J.-F. Minster[1]
[1] *UM39 at CNES/GRGS* 18 *avenue Edouard-Belin*, 31055 *Toulouse Cedex, France*
[2] *LODYC, Université Pierre et Marie Curie*, 75230 *Paris Cedex* 05, *France*

Monthly maps of the ocean–atmosphere CO_2 gas-transfer coefficient are derived from meteorological winds for 1982. The seasonal variations are of the order of a factor 2, mostly in the Northern Hemisphere. A strong meridional pattern is observed: the exchange coefficient is larger at high latitudes than in tropical areas. However, the zonal variations within a latitudinal band (generally a westward enhancement) can be as large as the meridional ones. The representativity of the winds is a major concern: interannual variations of the order of 30% are documented by an analysis of four years of the monthly transfer coefficient derived from meteorological winds in the Atlantic ocean. In the future, these maps will be obtainable on a routine basis from satellite data. As an example, a map derived for August 1978 from *Seasat* altimeter winds is compared with the present ones.

0. Introduction

Gas exchange between the ocean and the atmosphere is one of the controlling processes of the CO_2 geochemical cycle. The net flux of gas at this interface can be expressed as

$$F = ks\,\Delta p_{CO_2}, \tag{1}$$

where k is a gas-transfer velocity, s is the solubility of CO_2 in seawater and Δp_{CO_2} is the difference between the CO_2 partial pressure in the surface-ocean water and in the air. The product ks will be called the gas-transfer coefficient. An increasing number of studies provide estimates of Δp_{CO_2} and its variation with season and geography. This requires sampling and analysis of sea water. On the other hand, k and s depend on wind, sea-surface temperature and salinity and can *a priori* be estimated by remote sensing and from climatological data.

The present note analyses the geographical and seasonal variations of k and ks as determined from a meteorological data set for wind speed. Some of the uncertainties in these determinations will be discussed. One important difficulty is the representativity of wind data. This will be illustrated by an analysis of four years of monthly maps of the transfer velocity in the Atlantic ocean, by comparison with the climatological maps of Erickson & Duce (1987) and by comparison with a map deduced for August 1978 from *Seasat* altimeter wind speed measurements.

1. World-scale monthly maps for the gas-transfer velocity

Liss & Merlivat (1986) and Broecker *et al.* (1986) discuss thoroughly the data and models that established the relation between the gas-transfer velocity, wind speed and sea-surface temperature. Here we use the relations proposed by Liss & Merlivat (1986) (see figure 1). The

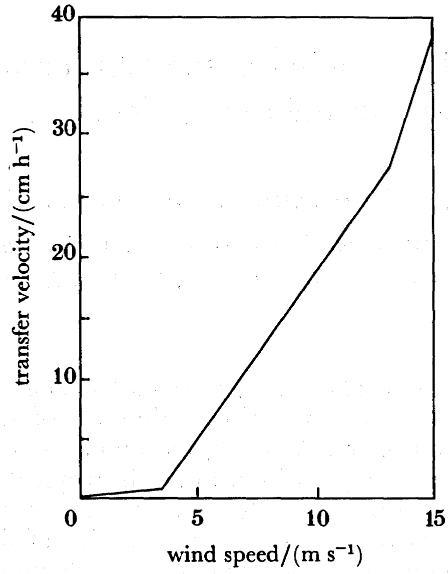

FIGURE 1. Relation between the CO_2 gas-transfer velocity (normalized to a Schmidt number of 600) and the wind speed at 10 m above the sea surface. Adapted from Liss & Merlivat (1986). See text for the corresponding equations.

relation between k and the wind speed is given for three different wind régimes, where the physical processes that control the gas exchange are different: exchange across a smooth surface at low wind speed, across a rough surface at intermediate wind speed, and bubble effects at high wind speed. These relations are

$$\left.\begin{aligned} V \leqslant 3.6\ \text{m s}^{-1}, &\quad k = 0.17\,V(Sc(\theta)/Sc(20))^{-\frac{2}{3}};\\ 3.6\ \text{m s}^{-1} < V \leqslant 13\ \text{m s}^{-1}, &\quad k = (2.85V - 9.65)\,(Sc(\theta)/Sc(20))^{-\frac{1}{2}};\\ V > 13\ \text{m s}^{-1}, &\quad k = (5.9\,V - 49.3)\,(Sc(\theta)/Sc(20))^{-\frac{1}{2}};\end{aligned}\right\} \tag{2}$$

where V is the wind speed (in metres per second) at 10 m above the sea surface, k is the transfer velocity (in centimetres per hour), Sc is the Schmidt number ($Sc = v/D$, where v is the kinematic viscosity of seawater and D is the molecular diffusivity of CO_2 in seawater). θ is the sea-surface temperature and 20 is a reference temperature of 20 °C ($Sc(20) = 595$ for CO_2).

In a preliminary study, we derived monthly maps of the gas-transfer velocity (Thomas *et al.* 1986) from the climatological winds of Hellerman & Rosenstein (1983) and from the sea-surface temperatures and salinities of Levitus (1982). To do this we used the relations between s and temperature and salinity of Weiss (1974) and between Sc and temperature of Jahne (1980). By comparison with other estimates, it has become clear that this approach under-estimates k.

Erickson & Duce (1987) recently provided climatological maps of the gas-transfer velocity normalized to a Schmidt number of 600, derived from the *NOAA* 5° × 5° monthly means of measured wind speeds. To overcome difficulties related to the wind-averaging process and to the undersampling of wind measurements in some areas, they introduced an artificial monthly frequency distribution as described in Erickson *et al.* (1986).

To assess the accuracy and representativity of such maps, we derive here monthly values of k and ks from meteorological winds. Such winds are provided as outputs of world-scale

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

meteorological models. The model assimilation is a very efficient cleaning and interpolating process for measured data. In addition, a number of other types of data constrain the models, and thus their various outputs. Finally models generally provide wind fields at intervals of 6 h, so that the estimation of monthly averages should be quite reliable. On the other hand, as winds at the air–sea interface are required, the accuracy depends on the reliability of the meteorological boundary layer parametrization in the models.

The winds that we have used are outputs of the European Meteorological Centre (European Centre for Medium-Range Weather Forecasts; ECMWF). They are 6 h, 1.875° resolution, 10 m height winds. The year 1982 was selected, and k and ks were estimated each 6 h on the grid of the meteorological model and monthly averaged. Figure 2 shows isocontours for k (in units of centimetres per hour) for February, May, August and November. Figure 3 provides numerical values for ks averaged on 7.5° × 7.5° squares for the same months, expressed in units of 10^{-2} mol m^{-2} a^{-1} µatm^{-1}. Figure 3 is mainly provided so that the reader can extract numerical values usable in estimates of CO_2 fluxes from p_{CO_2} measurements. As in Erickson & Duce (1987), our values are not corrected for temperature and salinity; that is, k is normalized to a Schmidt number of 600. Note that the dependence of k on temperature and salinity is small compared to that on wind, so that k could be adjusted by using climatological values of these parameters. As for ks, its dependence on temperature is small (less than 10% for a temperature change of 20 K for winds larger than 3.6 m s^{-1}), so that our values can be used directly for estimating the CO_2-exchange fluxes.

2. Validation

To validate these maps and assess their representativity, we made the four following tests.

The first test is a comparison with the maps of Erickson & Duce (1987). This could only be made qualitatively (i.e. by eye from the isolines). The values agree reasonably well, that is within 30%. This is true even in the tropics where the ECMWF winds are frequently said to be too low (A. Ratier, H. Charnock, personal communications).

The second test is a comparison with gas-transfer velocities derived from wind and sea-surface temperature data provided by a meteorological buoy near 47° N, 17° W (station Romeo off Brittany). Of course, as these data have been assimilated into the model, the comparison for the particular period should be rather good. For this comparison we derived first the monthly mean values of k for the model grid square that contains the buoy, for the years 1981–1984 (heavy line in figure 4). Note that in this data set, the temporal resolution was 12 h. This provides a four-year average of monthly mean values of k. Figure 5 then compares this 'reference' to the values derived from 30 months of three-hourly buoy data during the years 1975–1977. In this figure, the lower diagram shows the monthly mean wind and sea-surface temperature values and their monthly root mean squares (r.m.s.). The upper diagram compares the normalized monthly values for k with the reference curve: the difference is less than 30%, winter 1976 values being consistently lower than those of winter 1977 (this may be related to the 1976 El Niño event and the well-remembered drought in Europe that year). This suggests that, at least at this location, the model winds are reasonably correct.

The heavy broken curve in the upper diagram of figure 5 shows the effect of temperature at this location (that is of the dependence of the Schmidt number on temperature in (2)). The

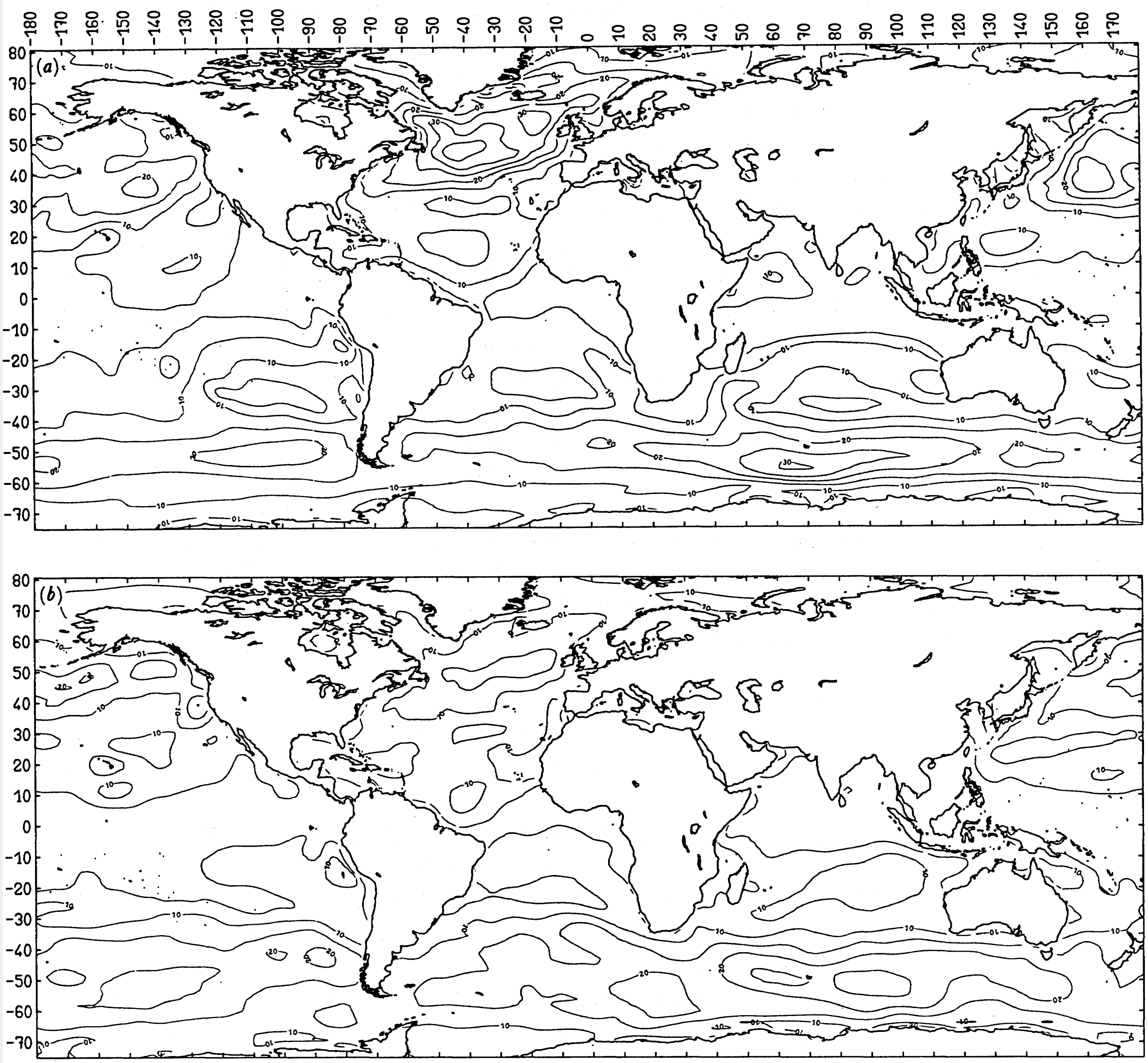

FIGURE 2 (*a*, *b*). For description see opposite.

value of k is decreased by 20% in winter, when the temperature is lower (around 12 °C). Finally the light broken curve illustrates the effects of averaging: wind and temperature are monthly averaged first, before calculating k (contrary to what is done for figures 2–4). Although the wind speed varies by 40% on the average (lower diagram) and its values frequently overlap the 13 m s^{-1} break in the curve of figure 1 (and thus nonlinearity effects are significant), the monthly value of k is generally less than 10% below the heavy broken curve. This would suggest that for estimating monthly mean values for k, monthly averages of wind and temperature are sufficient, provided the sampling gives a good statistical description of the real situation in the area considered.

A third test concerned the effects of sampling frequency on monthly averages of k by using

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

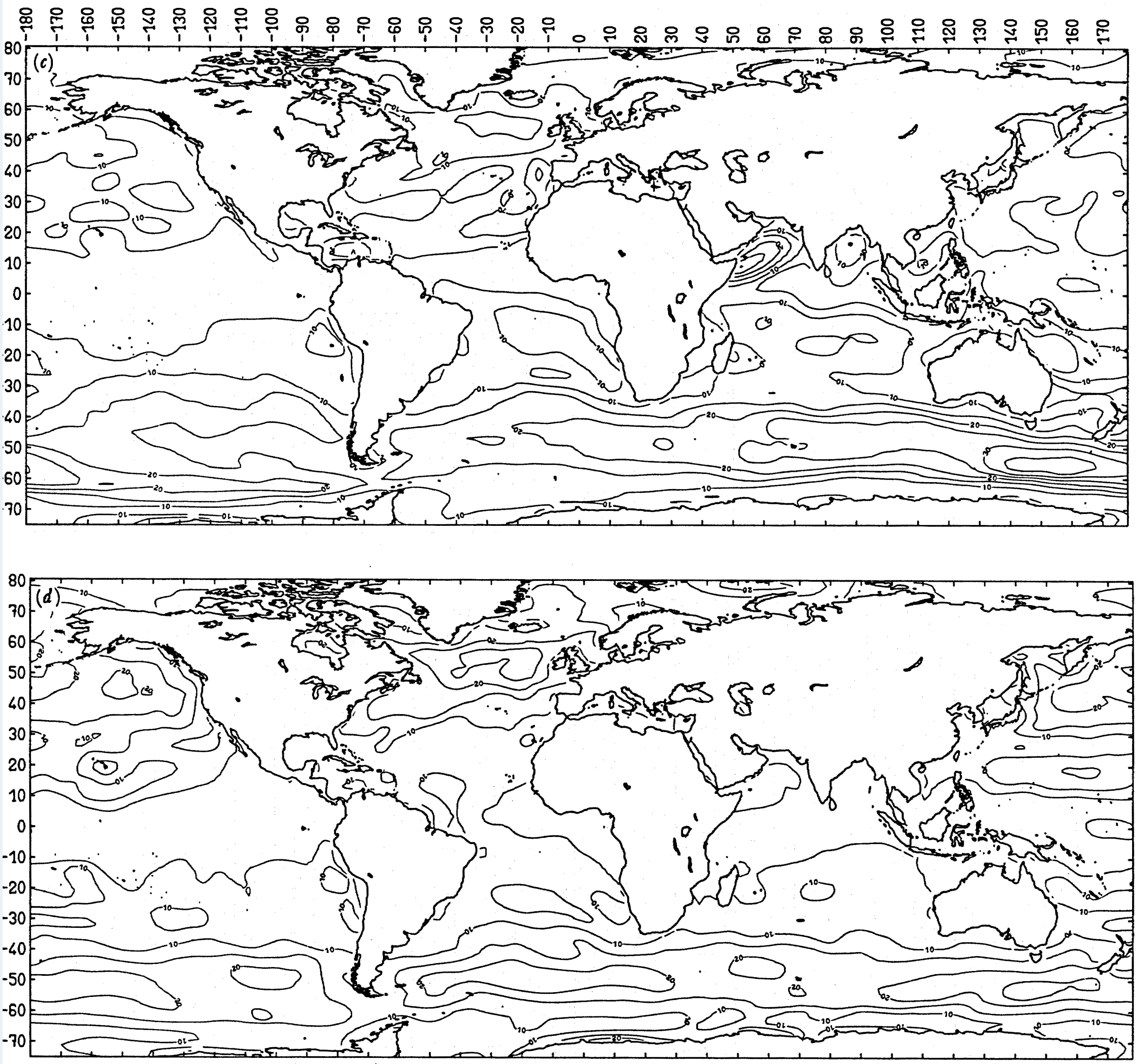

FIGURE 2. Maps of the monthly mean, temperature-normalized, CO_2 gas-transfer velocity deduced from winds of the European Centre for Medium-Range Weather Forecast for year 1982. (*a*) February; (*b*) May; (*c*) August; (*d*) November. Units of gas-transfer velocity are centimetres per hour.

a three-day sampling of the ECMWF wind data for the four years 1981–1984. The broken line on figure 4 shows the result of this calculation. The difference between these values and the preceding ones (heavy line on figure 4) is no more than 20%.

The fourth test evaluates the representativity of the year 1982. This is already indicated in figures 4 and 5, which show interannual variations of up to 30% near 47° N, 17° W. It is further documented by mapping the relative variations of monthly mean values for k deduced from the four years of ECMWF winds (years 1981–1984), over the tropical and North Atlantic Ocean (figure 6). These interannual variations can be in excess of 100%, but in well-defined

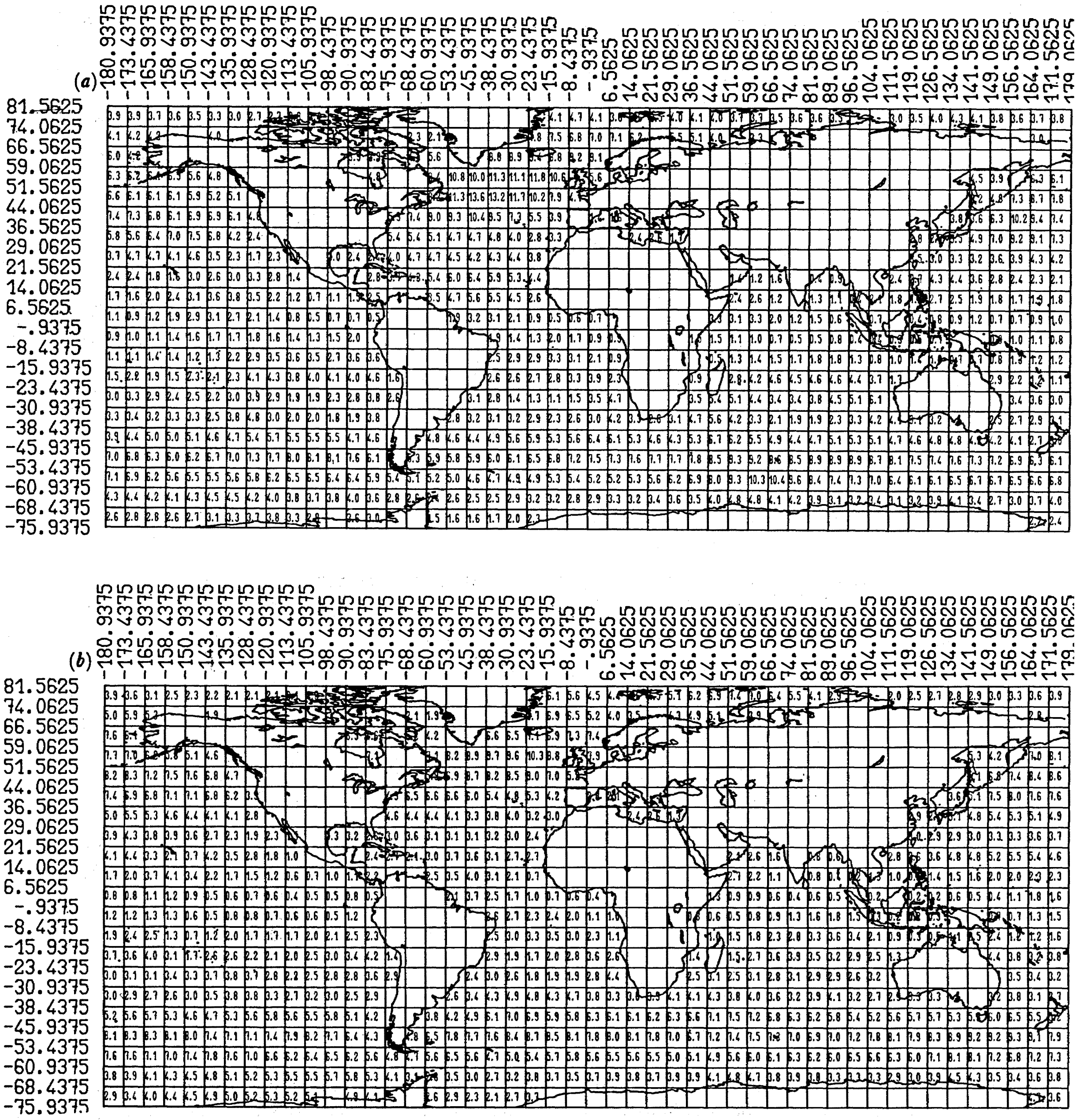

FIGURE 3 (*a*, *b*). For description see opposite.

areas only: in the trade winds at all seasons, and in the westerlies in summer and winter. At other locations, the change is less than 60%. Thus, values from the maps derived from climatological data (Erickson & Duce 1987) and from our maps can differ by a factor 2 for any particular year, because of interannual variability of the wind. However, we suspect that these interannual variations are mainly caused by the varying latitudinal boundary between the trade winds and the westerlies, as shown by the empirical orthogonal function analysis of these ECMWF winds over the North Atlantic Ocean of MacWeigh *et al.* (1988). Most of the large-scale features in figures 2 and 3 should therefore be generally valid.

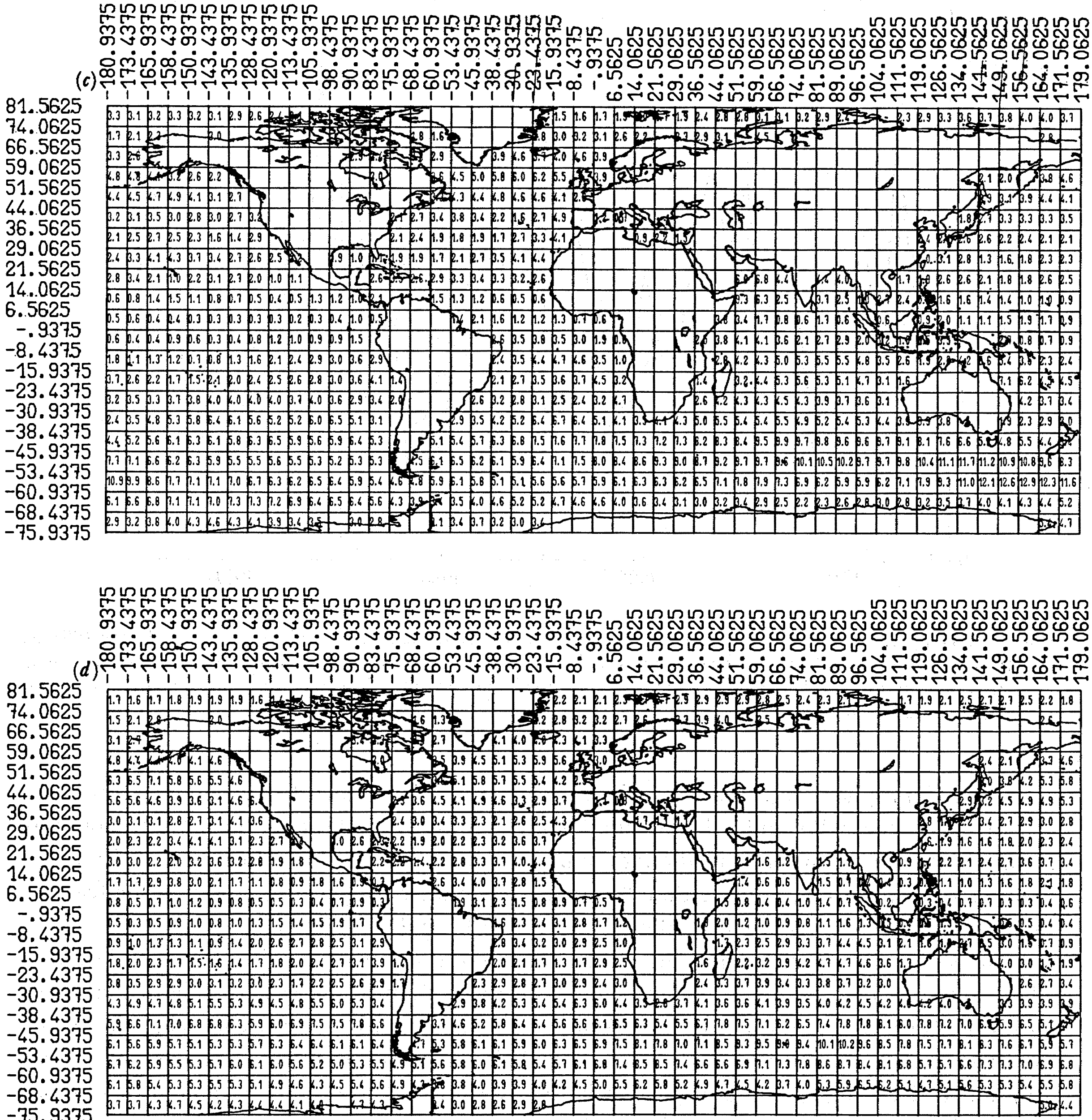

FIGURE 3. Values of the monthly mean CO_2 gas-transfer coefficient (*ks*) (in units of 10^{-2} mol m^{-2} a^{-1} μatm^{-1}), derived from figure 2 by multiplying *k* by a constant value for CO_2 solubility at 20 °C (33.37 mol m^{-3} atm^{-1}) and by averaging over 7.5° × 7.5° squares. (*a*) February; (*b*) May; (*c*) August; (*d*) November.

3. Analysis of the results

The *k* and *ks* vary from small values ($k < 10$ cm h^{-1} and $ks < 0.05$ mol m^{-2} a^{-1} μatm^{-1}) over most of the ocean, to values in excess of 35 cm h^{-1} and 0.1 mol m^{-2} a^{-1} μatm^{-1} in the Somali area or at high latitudes in winter time. The temperature effect would decrease the actual winter values of *k* by a factor 2 but the effect on *ks* would be less than 10%.

The most obvious feature in figures 2 and 3 is the seasonal change (by a factor 2) in the

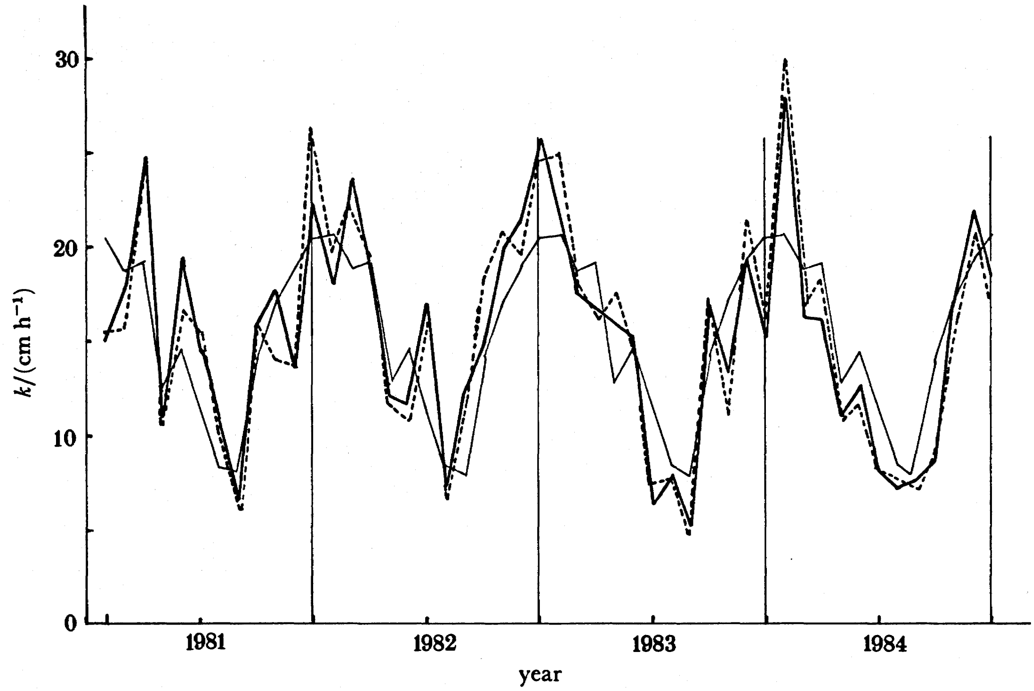

FIGURE 4. Temperature-normalized monthly mean values of k from the meteorological model winds, for 1981 to 1984, near 47° N, 17° W. The heavy solid line is for monthly means calculated with a twelve-hour sampling ($Sc = 600$) and the broken line is for monthly means calculated with a three-day sampling. The light solid line is the average of the four years.

Northern Hemisphere. The seasonal effect in the Antarctic is much less pronounced, transfer velocities in excess of 25 cm h^{-1} being found in all seasons. In the Tropics, the most pronounced feature is the monsoon effect in the Arabian sea, where the transfer velocity varies from less than 5 cm h^{-1} in spring, to more than 30 cm h^{-1} in summer. In general, however, the transfer velocity in the tropics is much smaller than at high latitudes (figure 7).

Figures 2 and 3 also show that there is as much variability with longitude as with latitude. The transfer velocity tends to be larger in the western than in the eastern side of the ocean basins. For example, k in the trade-winds domain in the Atlantic generally increases westward by a factor of 2–5 in all seasons but summer. This was also found in the analysis of ocean–atmosphere CO_2 fluxes in the tropical Atlantic by Andrié *et al.* (1986) (although their zonal westward increase of the gas-transfer coefficient also occurred in the summer).

4. Discussion and conclusion

The world-scale yearly mean is 10 cm h^{-1} or 0.029 mol m^{-2} a^{-1} μatm^{-1}. This is smaller than the global piston velocity deduced from ^{14}C decay model that is of the order of 15–20 cm h^{-1} (see for example, Broecker *et al.* 1986). One could use this to assess the value of our estimates. Uncertainties can be attributed to the wind data set or to the choice of the wind dependence of k (equation (2)).

However, two factors indicate that this is not necessarily the case. First, one should remember

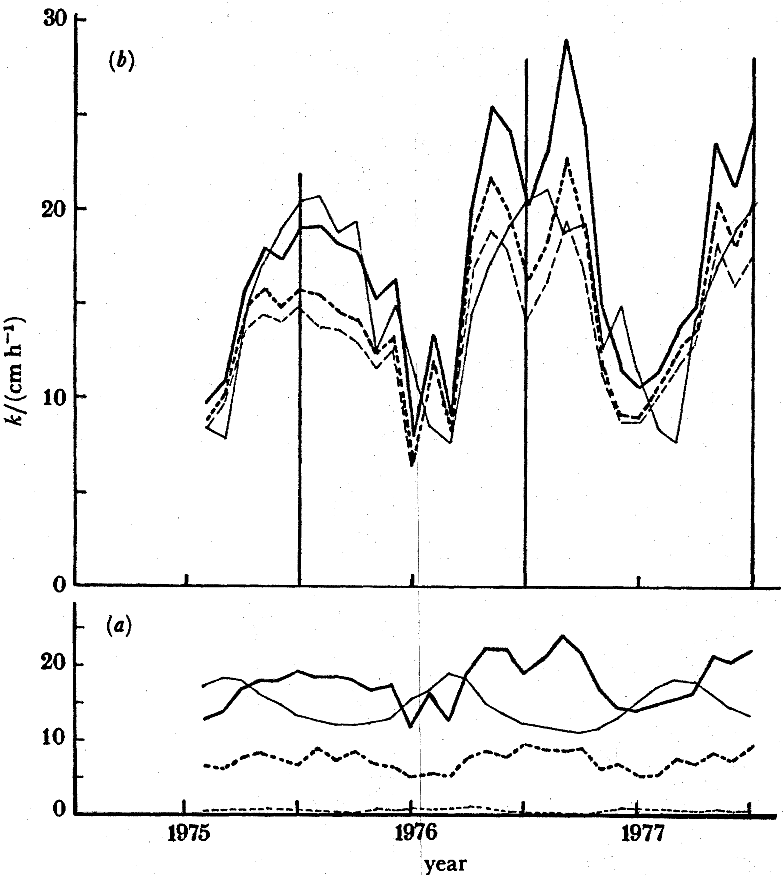

FIGURE 5. (a) Monthly mean wind and sea-surface temperature and their monthly r.m.s. values at meteorological buoy Romeo for years 1975–1977 (30 months). Heavy line, wind velocity (knots); light line, temperature (°C); heavy broken line, wind r.m.s.; light broken line, temperature r.m.s. (b) Heavy line, temperature normalized, monthly mean CO_2 gas-transfer velocity derived from the buoy data by using equations (2); light line, four-years average from figure 5 (reference); heavy broken line, same as heavy line but corrected for temperature variations; light broken line, monthly transfer velocities deduced from the monthly averaged wind and temperature values by using equations (2).

that the ^{14}C method mostly describes CO_2 invasion at high latitudes and subsequent radioactive decay in the deep ocean. Thus the effective value for k would be much higher than the world average. For example, the yearly mean in the Southern Ocean is of the order of 17 cm h^{-1} and 0.05 mol m^{-2} a^{-1} μatm^{-1}, close to the ^{14}C value.

Second, the observations of strong seasonal and zonal variations of the gas-transfer coefficient suggest that world-scale averages should be made with great care. An example of the effects of averaging in estimating the CO_2 gas flux is given here, by using the data of the North Pacific seasonal programme (Takahashi *et al.* 1986): figure 8 compares the zonal changes of ks from figure 3 with that for Δp_{CO_2} from Takahashi *et al.* In winter, the intensity of degassing due to Δp_{CO_2} strongly decreases from west to east. This is enhanced by 20% by a change of ks. In summer, Δp_{CO_2} is much smaller and of the opposite sign (pumping by the ocean). But the actual exchange is very small, because ks is a factor 2 smaller than in winter.

For estimating the net yearly gas flux to the ocean in this area, one has to average zonally,

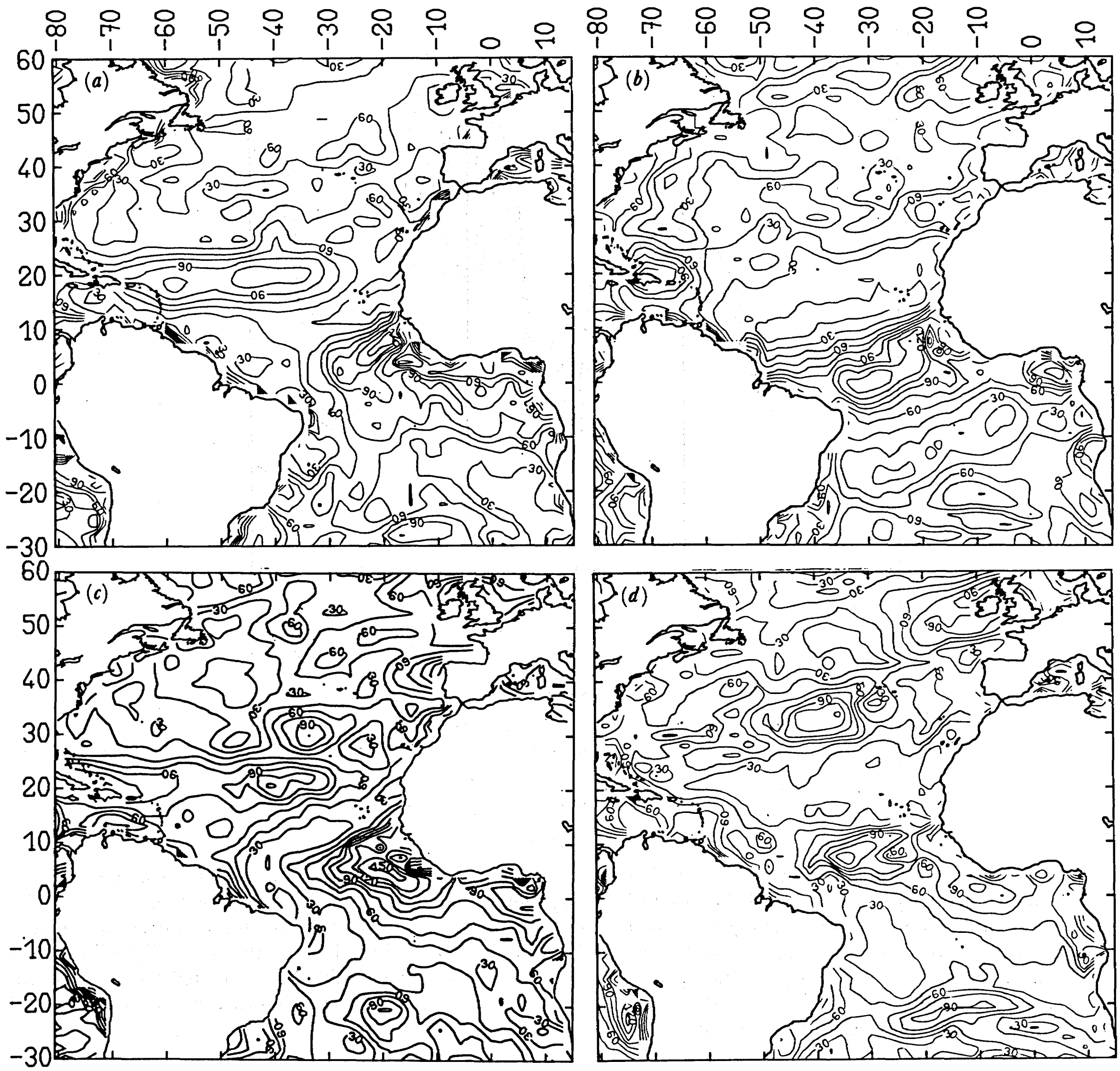

FIGURE 6. Relative variations (percentage, of the temperature-normalized, monthly mean values for the gas-transfer velocity deduced from the ECMWF winds for years 1981–1984. Isococontours each 15%. (*a*) February; (*b*) May; (*c*) August; (*d*) November.

weighting by the surface involved as in Takahashi *et al.* (1986), and seasonally. Denoting the zonal average by an overbar and the seasonal average by an underbar, one gets

$$\overline{\underline{ks}}\;\overline{\underline{\Delta p_{CO_2}}} = 0.81\ \mathrm{mol\ m^{-2}\ a^{-1}},$$

$$\underline{\overline{ks}\;\overline{\Delta p_{CO_2}}} = 1.01\ \mathrm{mol\ m^{-2}\ a^{-1}},$$

$$\overline{\underline{ks}\;\underline{\Delta p_{CO_2}}} = 3.54\ \mathrm{mol\ m^{-2}\ a^{-1}},$$

$$\underline{\overline{ks\,\Delta p_{CO_2}}} = 4.72\ \mathrm{mol\ m^{-2}\ a^{-1}}.$$

In the first case, the averages are made on the two terms separately, before making the product. In the last case, the product was made first, then averaged. The result is a factor of 6 larger than in the first case! Of course, the most critical factor is seasonality, as indicated by comparing the second and the third cases. Working with zonal averages of the seasonal values underestimates the flux by 30%.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

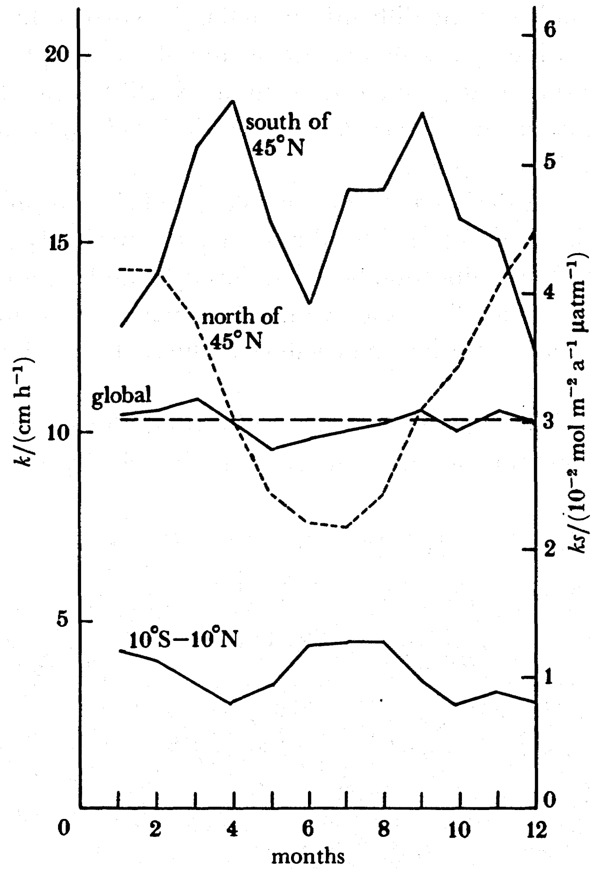

FIGURE 7. Zonal averages of the monthly mean value of the temperature-normalized CO_2 gas-transfer velocity and of the CO_2 gas-transfer coefficient, for high- and low-latitude bands. 'Global' stands for the world-scale averages.

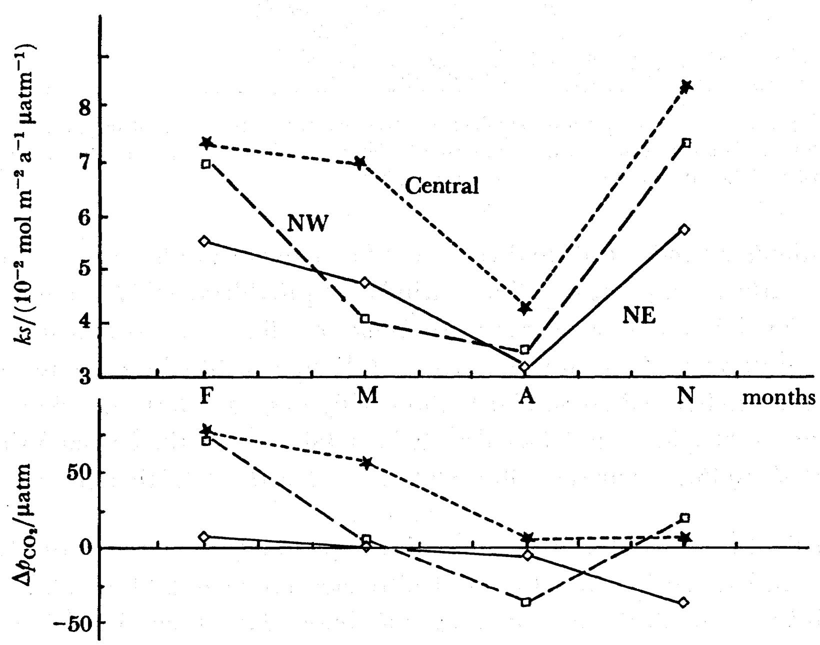

FIGURE 8. Seasonal variations of Δp_{CO_2} (lower diagram) and the gas-transfer coefficient (upper diagram) in the Central, North West (NW) and North East (NE) Pacific; p_{CO_2} data from the North Pacific seasonal program (Takahashi *et al.* 1986). Gas-transfer coefficients are averaged from figure 3.

This very large effect indicates the difficulty in making a correct direct estimate of the net fluxes of CO_2 between various parts of the ocean and the atmosphere. For this, seasonal programmes of Δp_{CO_2} measurements, such as those in the North Pacific (Takahashi *et al.* 1986), in the tropical Atlantic Ocean (Smethie *et al.* 1985; Andrié *et al.* 1986) or in the South Indian Ocean (Goyet 1987) will be necessary.

At present, we believe that deriving the gas-transfer coefficient from meteorological winds with equation (2) is the best approach. Monthly means are probably appropriate in view of the typical timescale for CO_2 equilibration between the ocean and the atmosphere (of the order of one year). From the present analysis, such values are apparently accurate within 30%, and they are probably more representative than values deduced from wind measurements from ships.

In the future, estimates will be feasible from satellite wind and temperature measurements. As an example, Figure 9 provides a map of the gas-transfer velocity, deduced for August 1978

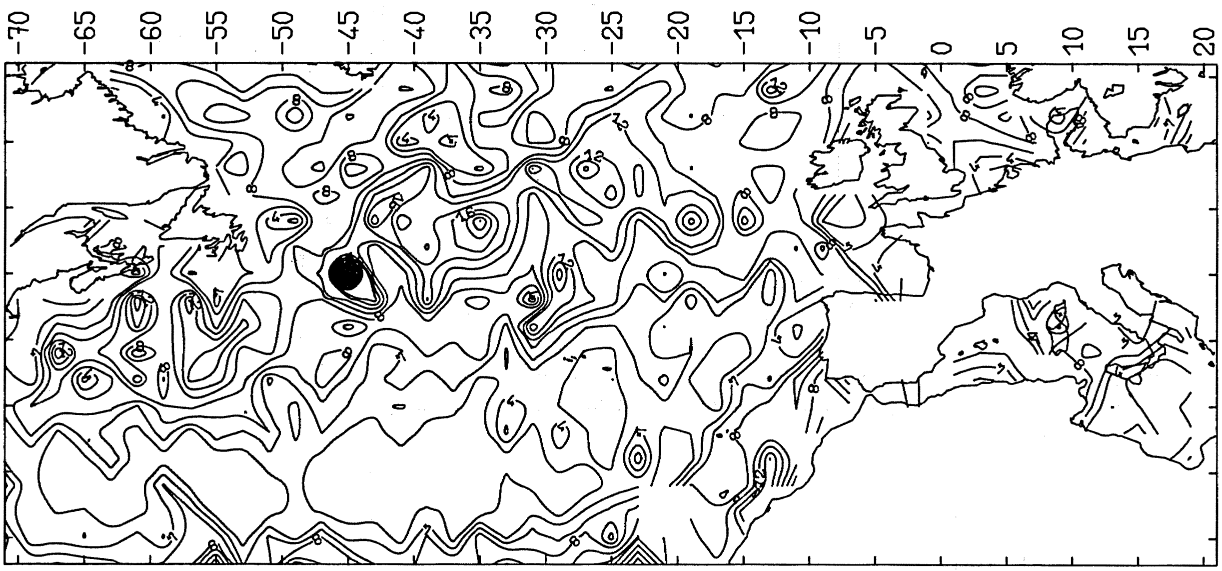

FIGURE 9. Map of the gas-transfer velocity (in units of centimetres per hour, corrected for temperature) derived for August 1987 from the *Seasat* altimeter wind data (see Chelton & Wentz 1986) and the climatological sea-surface temperature of Levitus (1982). Isoline each 2 cm h^{-1}.

from the *Seasat* altimeter wind speeds and corrected for temperature from the Levitus (1982) climatological sea-surface temperatures. These winds are provided each 7 km along the track of the satellite. The wind values, as given in the *Seasat* data files were corrected for their bias at strong wind intensities (see, for example, Chelton & Wentz (1986) for a discussion). Most of the significant features in figure 9 are similar to those of figures 2 and 3 (trade winds, westerlies, intensification near 50° N). Such maps can already be obtained from the Geosat altimeter wind speeds (Cheney *et al.* 1986). Their reliability will be the matter of further studies.

This work benefited from fruitful discussions with C. Jeandel, V. Garçon, and L. Memery, B. Barnier and A. Ratier. Technical help from C. Brossier has been most useful. M. Ollitrault from COB in Brest is thanked for providing the buoy data tape. La Direction de la Météorologie Nationale provided the ECMWF wind data files.

References

Andrié, C., Oudot, C., Genthon, C. & Merlivat, L. 1986 CO_2 fluxes in the tropical Atlantic during Focal cruises. *J. geophys. Res.* **91**, 11741–11755.

Broecker, W. S., Ledwell, J. R., Takahashi, T., Weiss, R., Merlivat, L., Memery, L., Peng, T. H., Jahne, B. & Munnich, K. O. 1986 Isotopic versus micrometeorologic CO_2 fluxes: a serious conflict. *J. geophys. Res.* **91**, 10517–10527.

Chelton, D. B. & Wentz, F. J. 1986 Further development of an improved altimeter wind algorithm. *J. geophys. Res.* **91**, 14250–14260.

Cheney, R. E., Douglas, B. C., Agreen, R., Miller, L., Milbert, D. & Porter, D. 1986 The Geosat altimeter mission: a milestone in satellite oceanography. *Trans. Am. geophys Un.* **67**, 1354–1355.

Erickson, D. J., Merill, J. T. & Duce, R. A. 1986 Seasonal estimates of global oceanic whitecap coverage. *J. geophys. Res.* **91**, 12975–12977.

Erickson, D. J. & Duce, R. A. 1987 On the global transfer velocity field of gases with a Schmidt number of 600. *Searex Newslett.* **10**, 7–10.

Goyet, C. 1987 Variations saisonnières de pCO_2 dans les eaux de surface du Sud Ouest de l'Ocean Indien. Thèse de Doctorat de l'Université Pierre et Marie Curie, Paris, France.

Hellerman, S. & Rosenstein, M. 1983 Monthly wind stress over the world ocean with error estimates. *J. phys. Oceanogr.* **13**, 1093–1104.

Jahne, B. 1980 Zur parameterisierung des gasaustausches mit hilfe von laborexperimenten. Doctoral Dissertation, University of Heidelberg. (124 pages.)

Levitus, S. 1982 Climatological atlas of the world ocean. *N.O.A.A. Professional Paper* no. 13. Rockville, Maryland. (173 pages.)

Liss, P. S. & Merlivat, L. 1986 Air–sea gas exchange rates: introduction and synthesis. In *The role of air sea gas exchange in geochemical cycling* (ed. P. Buat-Menard). N.A.T.O. A.S.I. series, vol. 185, pp. 113–128.

MacWeigh, J. P., Barnier, B. & Le Provost, C. 1988 Spectral and E.O.F. analysis of four years of E.C.M.W.F. wind stress curl over the North Atlantic ocean. *J. geophys. Res.* (In the press.)

Smethie, W. M., Takahashi, T., Chipman, D. W. & Ledwell, J. R. 1985 Gas exchange and CO_2 fluxes in the tropical Atlantic ocean determined from ^{222}Rn and pCO_2 measurements. *J. geophys. Res.* **90**, 7005–7012.

Takahashi, T., Goddard, J., Sutherland, S., Chipman, D. W. & Breeze, C. C. 1986 Seasonal and geographic variability of carbon dioxide sink/source in the oceanic areas: observations in the North and equatorial Pacific ocean, 1984–1986 and global summary. *Final report to CO_2 research division*, Office of Energy Research U.S.A., Department of Energy. (52 pages.)

Thomas, F., Foubert, J. M., Perigaud, C., Merlivat, L. & Minster, J.-F. 1986 Mapping the CO_2 ocean-atmosphere gas transfer coefficient from climatological wind and sea surface temperature data. *Trans. Am. geophys. Un.* **67**, 1041.

Weiss, R. F. 1974 Carbon dioxide in water and sea water: the solubility of a non ideal gas. *Marine Chem.* **2**, 203–215.