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Uncertainty and ambiguity in gas transfer coefficients

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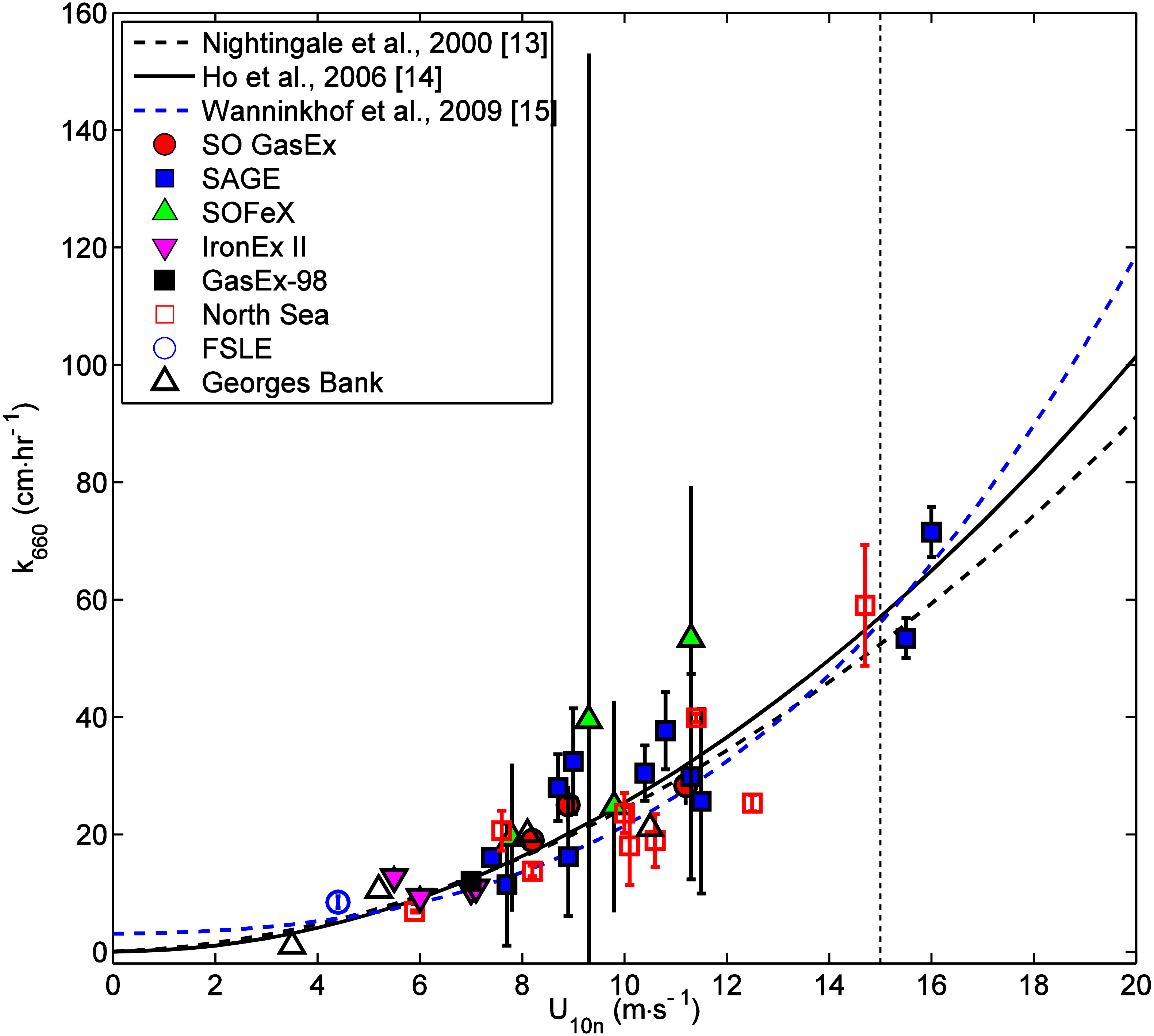
Overview

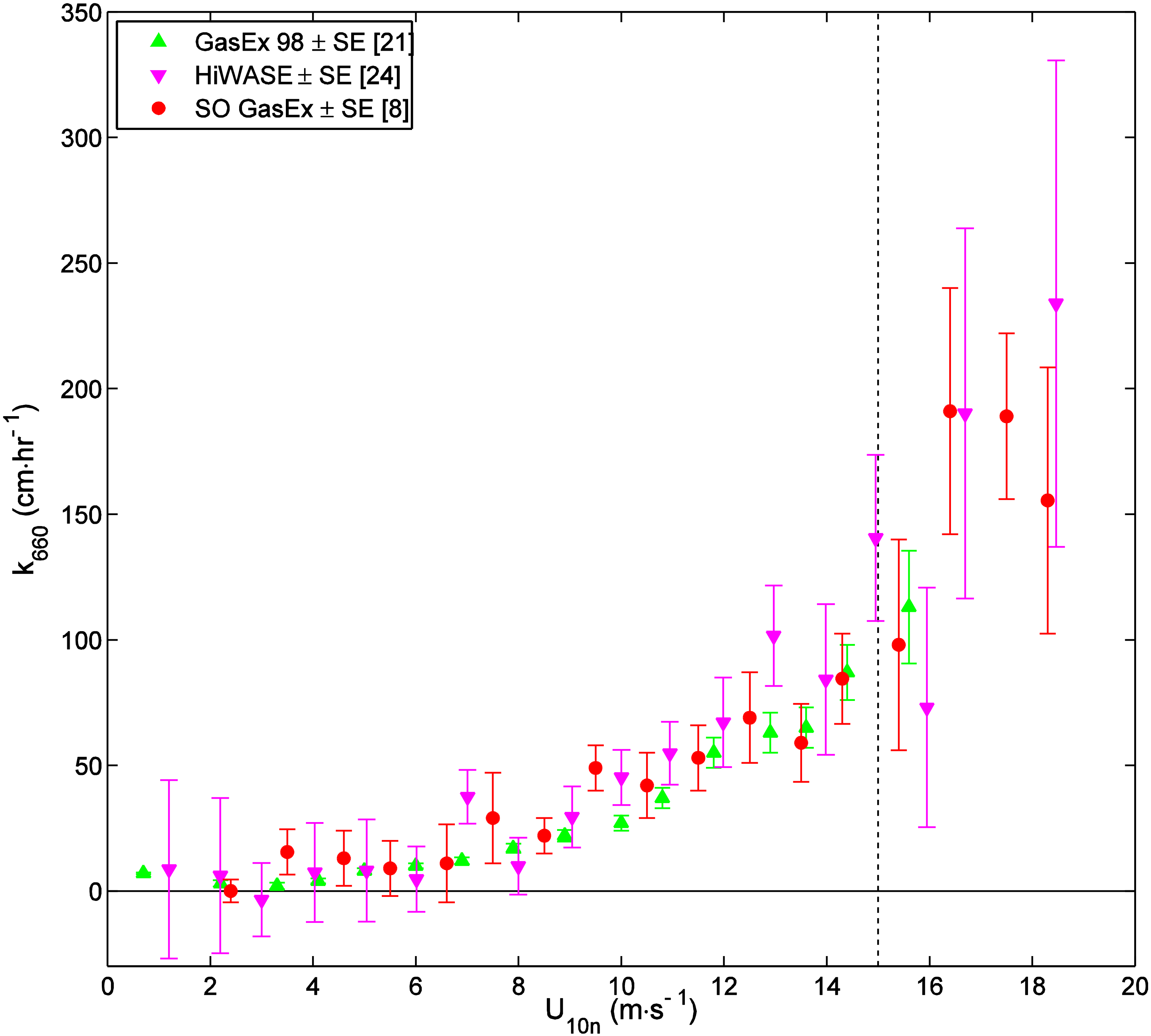
- Review of field measurements of k
  - Breadth of techniques
  - Classification by gas etc.
  - What do isotopic analyses tell us?
- What can make sense of all/most of the results?
  - Differences between gases
  - Other mechanisms
  - Is temperature a key?
  - Hybrid models revisited

Methods

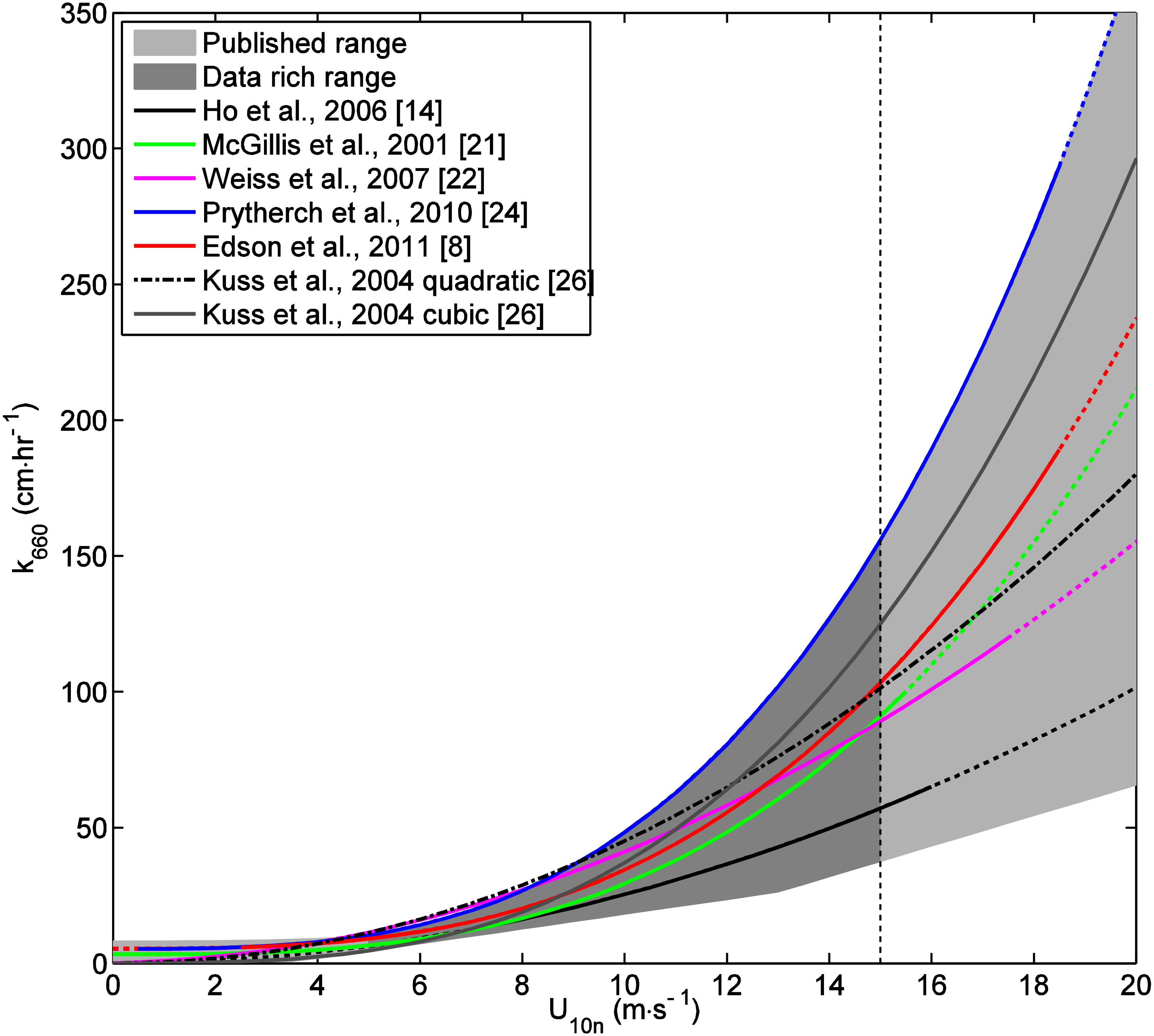
a) Chamber or dome measurements of CO_2 flux
b) Micrometeorological measurements of CO_2 flux
c) Budgets of dissolved inorganic carbon (DIC)
d) Modelling of oceanic DIC
e) Carbon isotope methods
f) Oxygen and nitrogen in the atmosphere
g) Oxygen covariance in the ocean and oxygen deficit method
h) Oxygen and nitrogen oceanic time series
i) Triple isotopes of oxygen
j) Noble gas time series
k) Radon deficit method
l) Purposeful tracers (including dual tracer method)
m) Micrometeorological measurements of dimethyl sulphide



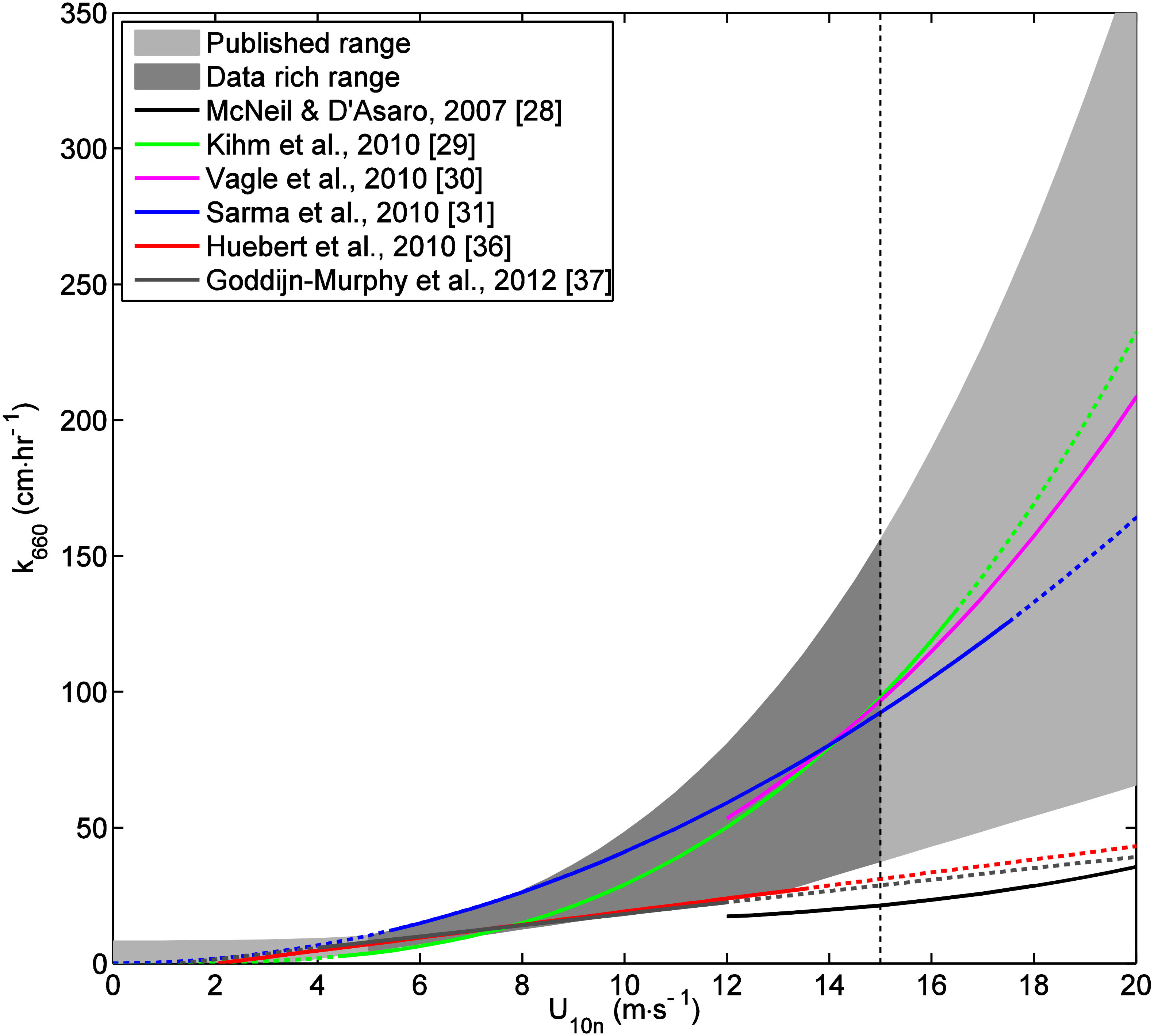
Nightingale et al., 2000 [13]
Ho et al., 2006 [14]
Wanninkhof et al., 2009 [15]
SO GasEx
SAGE
SOFeX
IronEx II
GasEx-98
North Sea
FSLE
Georges Bank
k_{660} (cm·hr^{-1})
U_{10n} (m·s^{-1})
0
20
40
60
80
100
120
140
160
0
2
4
6
8
10
12
14
16
18
20



GasEx 98 ± SE [21]
HiWASE ± SE [24]
SO GasEx ± SE [8]
k660 (cm·hr-1)
U10n (m·s-1)
0
50
100
150
200
250
300
350
0
2
4
6
8
10
12
14
16
18
20



Published range
Data rich range
Ho et al., 2006 [14]
McGillis et al., 2001 [21]
Weiss et al., 2007 [22]
Prytherch et al., 2010 [24]
Edson et al., 2011 [8]
Kuss et al., 2004 quadratic [26]
Kuss et al., 2004 cubic [26]
k_{660} (cm·hr^{-1})
U_{10n} (m·s^{-1})
0
50
100
150
200
250
300
350
0
2
4
6
8
10
12
14
16
18
20


Published range
Data rich range
McNeil & D'Asaro, 2007 [28]
Kihm et al., 2010 [29]
Vagle et al., 2010 [30]
Sarma et al., 2010 [31]
Huebert et al., 2010 [36]
Goddijn-Murphy et al., 2012 [37]
k_{660} (cm·hr^{-1})
U_{10n} (m·s^{-1})
0
50
100
150
200
250
300
350
0
2
4
6
8
10
12
14
16
18
20

Isotopic Studies

- Naegler et al., 2006
- Sweeney et al., 2007

- Krakauer et al. 2006

$$k_W = \langle k \rangle \left(\frac{u^n}{\langle u^n \rangle} \right) (Sc/660)^{-0.5}$$

Latitudinal variation in k and U

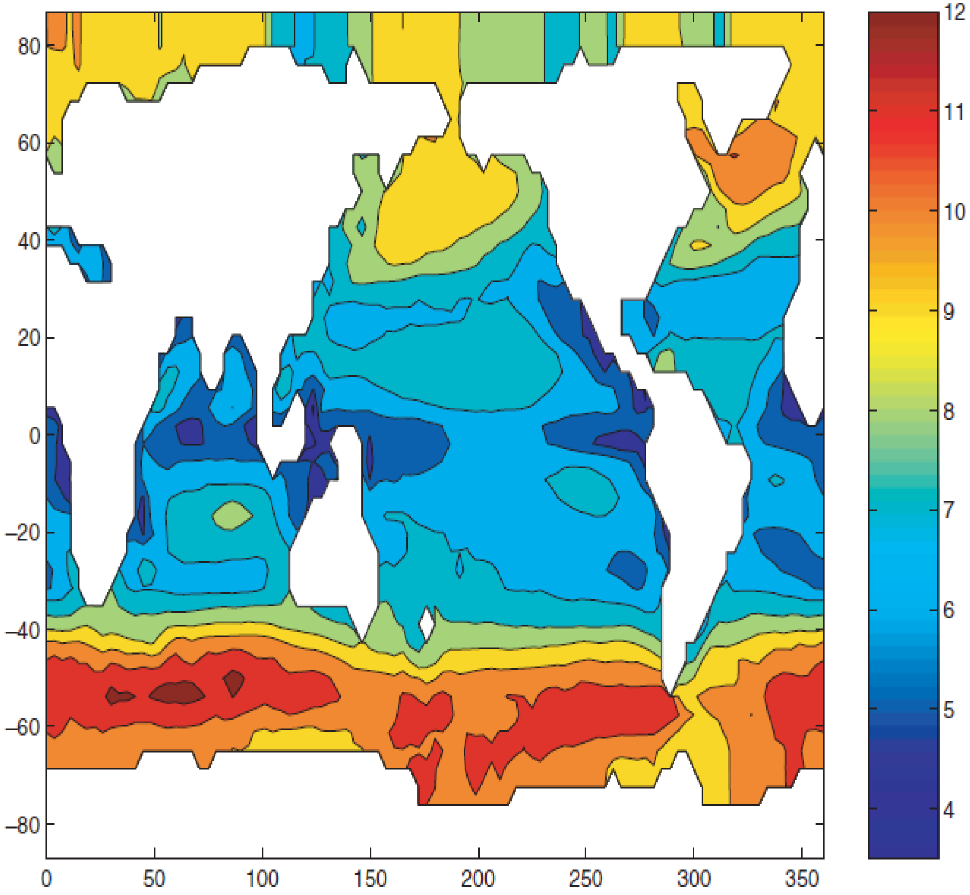


Fig. 1. Annual mean root-mean-square wind speed (m s^{-1}) over the ocean, at 10 m height, from the monthly climatology of Boutin and Etcheto (1997) and Orr et al. (2001), derived from satellite (SSM/I) data. We used the monthly climatology to explore the consequences of different dependences of the air–sea gas transfer velocity on wind speed on ocean ^{14}C uptake. The root-mean-square wind speed varies from 5 to 6 m s^{-1} near the equator to around 11 m s^{-1} over the Southern Ocean.

Data Density

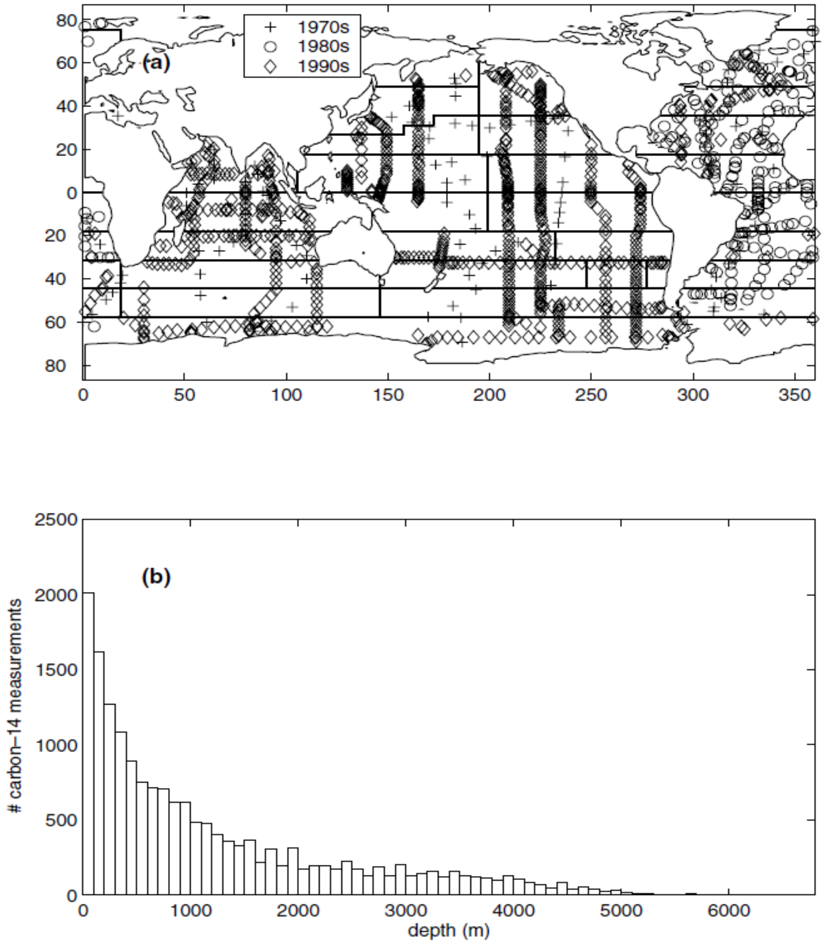


Fig. 3. Distribution of the ocean ^{14}C measurements used in this analysis (Key et al., 2004). (a) Location of measurements, grouped by decade. The 1970s measurements were made as part of GEOSECS, the 1990s measurements mostly as part of WOCE. The thick lines are the boundaries between the 30 ocean regions we use as basis regions for transport pulse functions. (b) Depth distribution of measurements (100 m bins).

Problems in the Southern Ocean

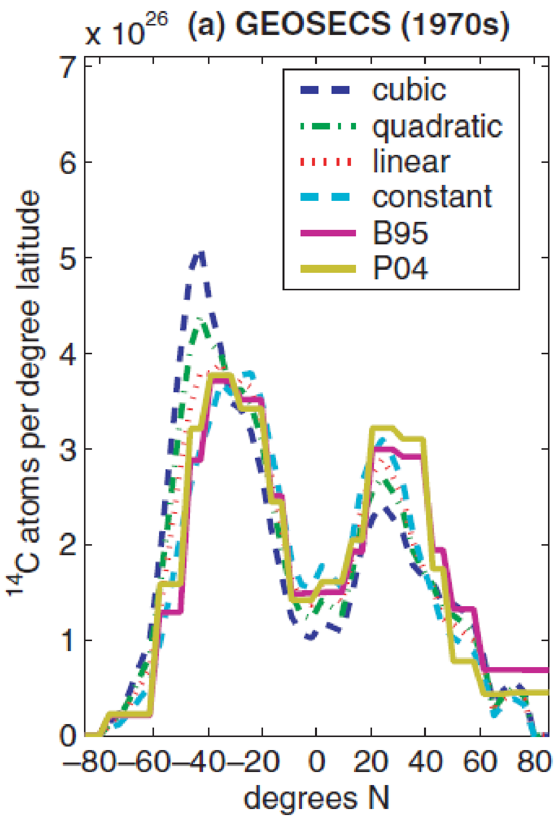


Fig. 6. Modelled latitudinal distribution of bomb ^{14}C in the ocean, for a global mean gas transfer velocity $\langle k \rangle$ of 20.6 cm/hr and a dependence on wind speed ranging from cubic to none ($n = 3$, 2, 1 or 0). A lower dependence on wind speed leads to relatively less uptake at the mid-latitudes and more near the equator. In panel (a), the 1975.0 modelled distribution is compared with extrapolations from GEOSECS observations in 10° bands by Broecker et al. (1995) and by Peacock (2004) (mean of her CFC- and anthropogenic CO_2-based extrapolation approaches). In panel (b), the 1994.5 modelled distribution is compared to the GLODAP gridded distribution based on WOCE observations (Key et al., 2004); the modelled distribution is summed only over the grid cells for which the gridded distribution is available, excluding, for example, the Arctic Ocean.

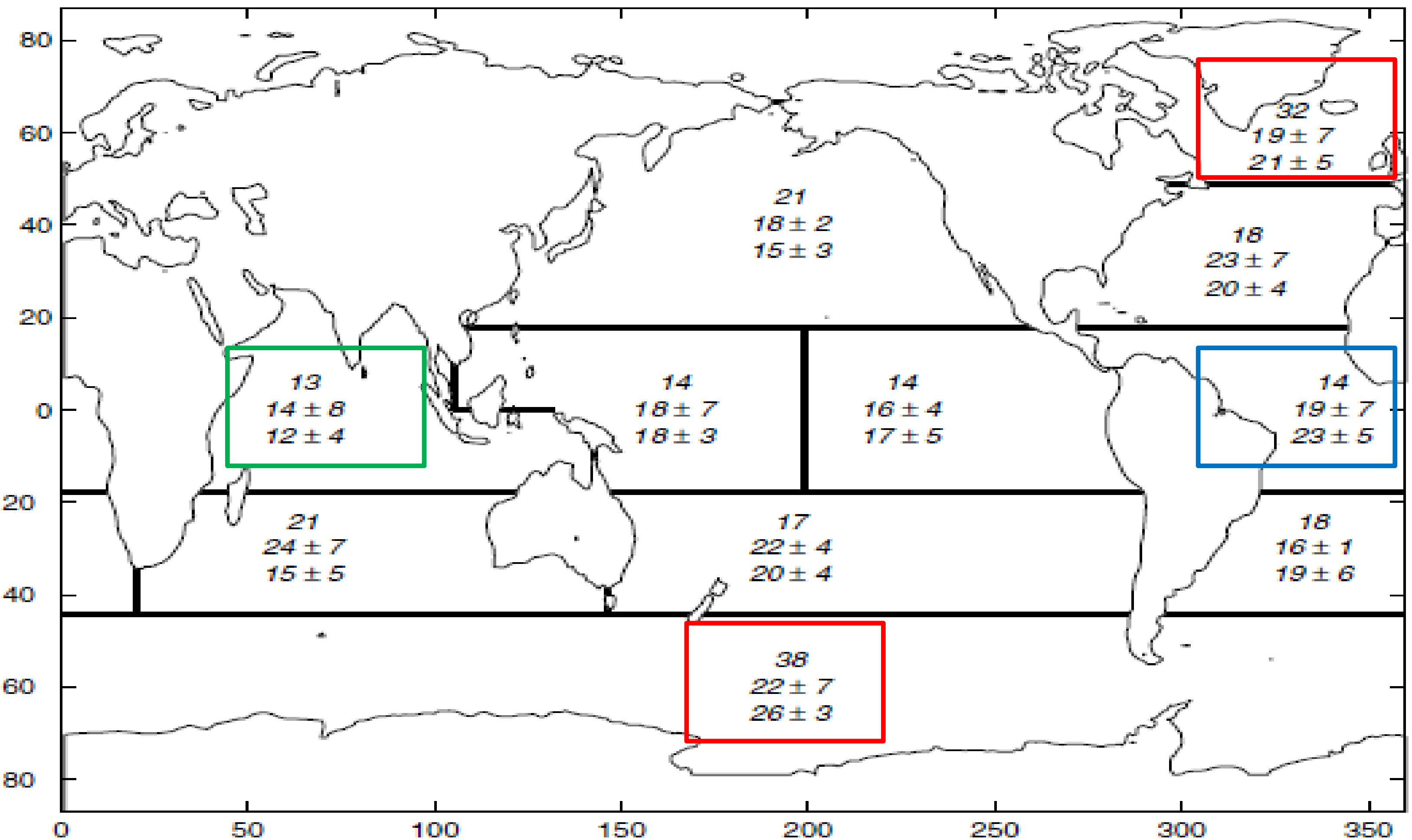
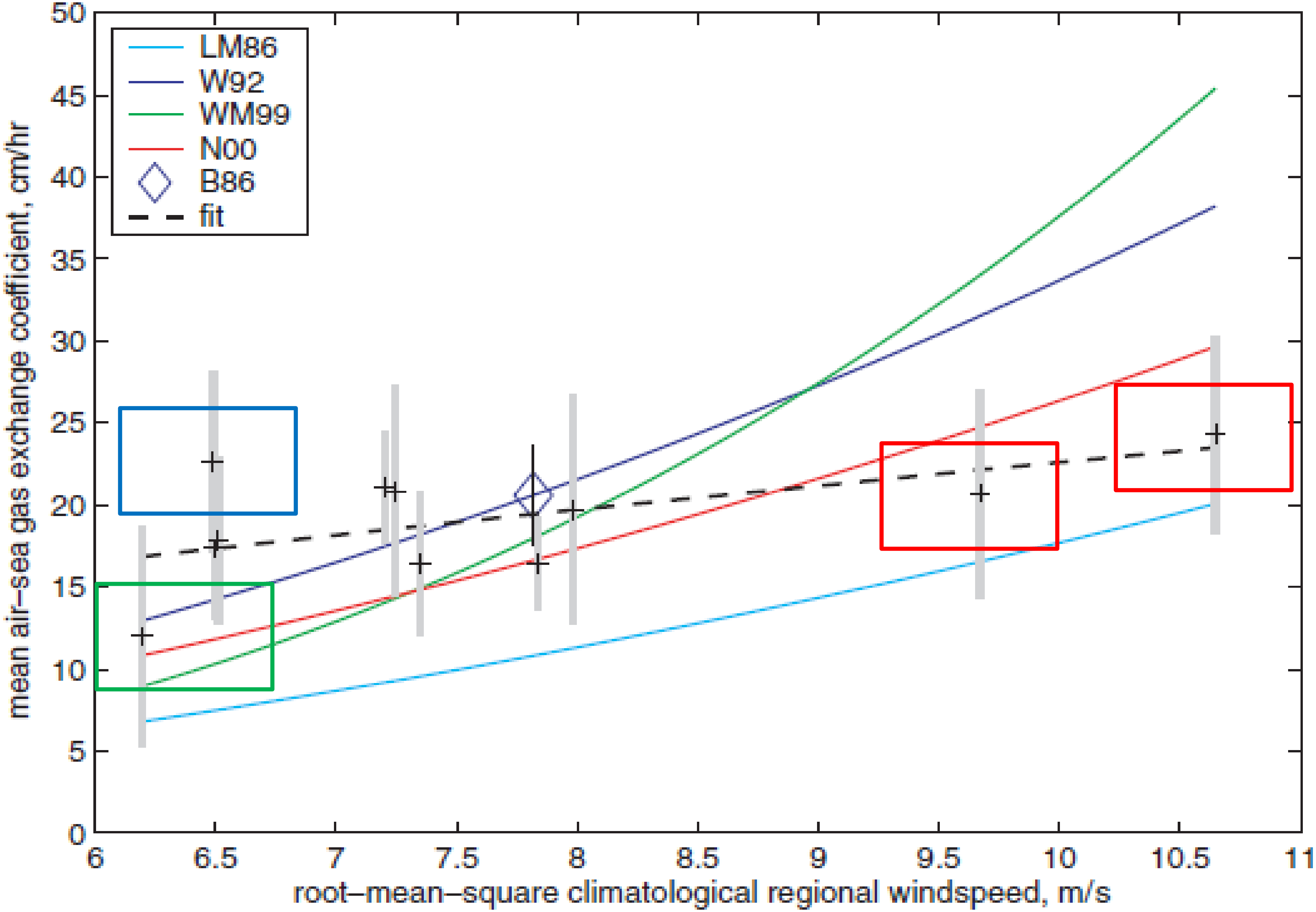


Fig. 8. Mean air–sea gas transfer velocities over 11 regions (cm/hr), derived using the quadratic relationship with wind speed of Wanninkhof (1992) and Dutay et al. (2002) (top row in each region) and estimated by optimizing the fit to the 1970s (second row) or the 1980s–1990s (third row) ocean bomb ^{14}C observations. In the second and third rows, we show the mean and the standard deviation of



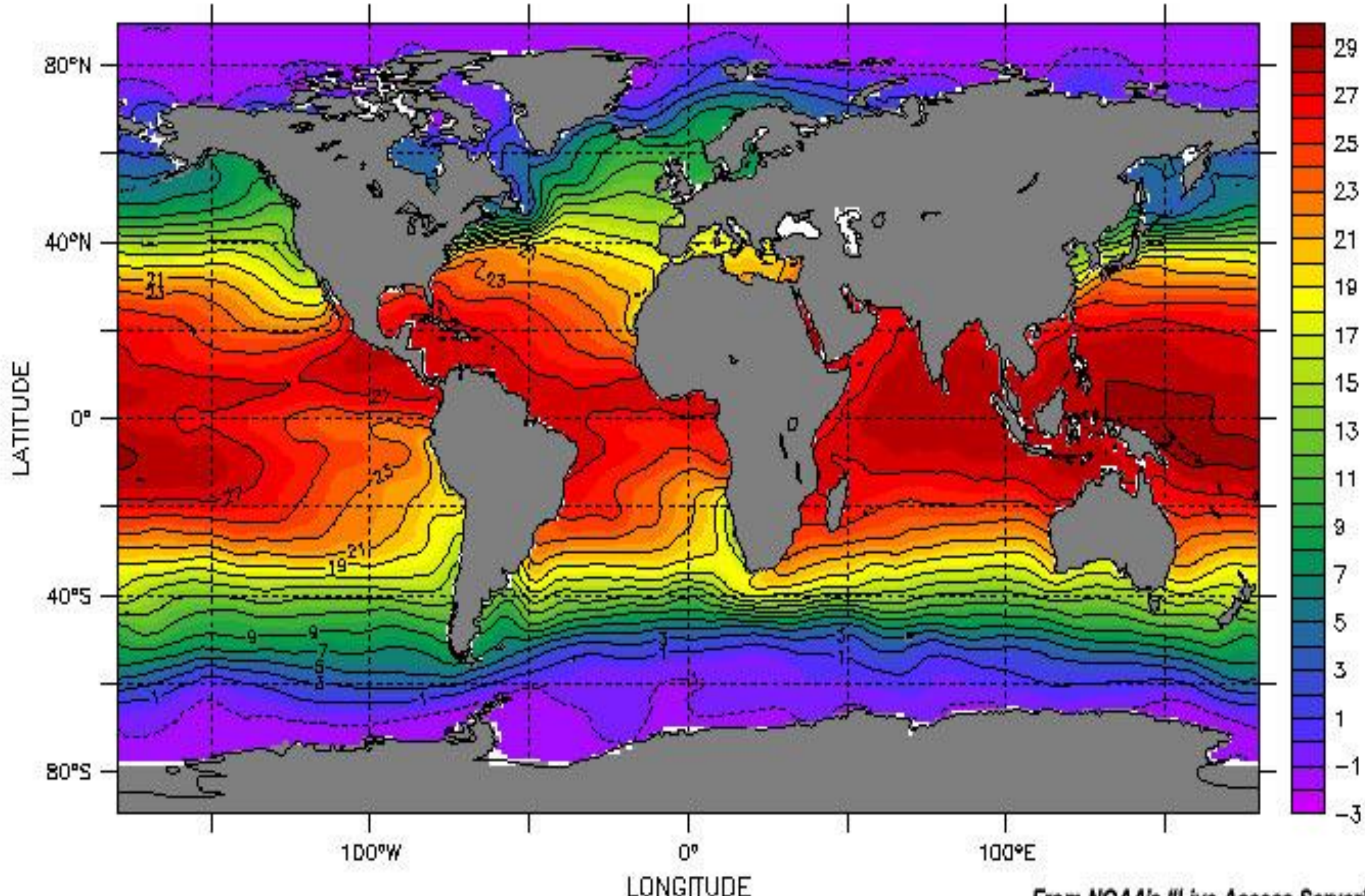
LM86
W92
WM99
N00
B86
fit
mean air–sea gas exchange coefficient, cm/hr
root–mean–square climatological regional windspeed, m/s
0
5
10
15
20
25
30
35
40
45
50
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11

Constraint	Implied $\langle k \rangle$ (cm/hr)	Implied n
Ocean bomb ^{14}C measurements		
Ocean total amount (WOCE)	14–27	
Globally optimum fit of $\langle k \rangle$, n to measurements	20 ± 3	0.5 ± 0.4
Fit of regional gas transfer velocities	19 ± 1	0.6 ± 0.7
Other ^{14}C and ^{13}C measurements[a]		
Atmospheric $\Delta^{14}C$: 1990s decline rate	20 ± 4	0.6 (0–2.0)
Atmospheric $\Delta^{14}C$: 1990s latitudinal gradient	28 ± 13	1.5 (0–2.9)
Pre-industrial ocean ^{14}C uptake	22 ± 4	
Pre-industrial atmospheric $\Delta^{14}C$ latitudinal gradient	26 ± 10	1.3 (0–2.7)
Air–sea ^{13}C isotope flux, 1990s	23 ± 5	0 (0–1.1)
Air–sea ^{13}C isotope flux, pre-industrial		1.2 (0.3–1.9)

An Imposed Temperature Dependence

$$k_w = \langle k \rangle \left(\frac{u^n}{\langle u^n \rangle} \right) (Sc/660)^{-0.5}$$

Average Sea Surface Temperature (°C)



From NOAA's "Live Access Server" Levitus 1982 Annual Climatology

Why the variation in Sc-normalised transfer velocity?

1) Different gases, $Sc^{-1/2}$ doesn't work
   Some evidence of k less for more soluble gas, but unconvincing
2) Water Temperature
   Solubility
   Viscosity
   Convection
   Hydration/Dehydration
3) Water Temperature and Sea State (Reynolds number argument)

$$k_w = \max [k_{minimum} , Sc^{-1/2} a U_* + b(Sc, solubility, viscosity) Re_w]$$

Pessimists are rarely disappointed