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Model-validated parametrization for air-sea gas transfer in the north Indian Ocean

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Abstract. Mixed-layer CFC-11 saturations measured in the northwestern Indian Ocean during the 1995 World Ocean Circulation Experiment (WOCE) along I7N are compared to those from a numerical model using three alternative parametrizations for the air-sea flux of CFC-11. The *Wanninkhof* [1992] gas flux parametrization for climatological winds gives gas saturations which agree best with those observed. The observed and model mixed-layers are in equilibrium with the contemporary atmosphere to within 1% (the experimental error) in the summer of 1995, excluding cold coastal upwelled waters. When the model is used to extend the space and time scales of the observations in the Arabian Sea, widespread supersaturations of 5% due to weak winds and warming are predicted in the spring and fall, and undersaturations of 5% due to mixing in the winter. The model validation of CFC-11 transfer parametrization and investigation of temporal and spatial variability in saturation are applicable to the physically-forced saturation variations of carbon dioxide and other gases of interest.

1. Introduction

The Indian Ocean is notable for its large annual variability, particularly in the northwest where monsoonal reversals in wind direction drive reversing boundary currents and seasonal upwelling. Variability observed in CFC concentrations provides an analog for the variations due to physical forcings (i.e. excluding biological and chemical) in other gases. In this work temperature and CFC-11 observations from WOCE I7N, a north-south section that reaches from 20°S into the Arabian Sea collected in July-August 1995, are compared to results from a circulation model.

The exercise follows the suggestion of *Haine and Richards* [1995] that, with a physically realistic seasonal ocean model, CFC saturations should be predictable. The reduced-gravity circulation model used is most recently described in *Jensen* [1991], but with the addition of a mixed-layer formulation [*Ji and Luther, J. Geophys.*

Res., submitted]. It has been shown to reproduce seasonal eddies and ephemeral circulation features seen in other observations (e.g., satellite images of SST). The model has four layers and spans the Indian Ocean to 30°S with a horizontal resolution of 1/12° (output is archived¹ at 1/3° resolution).

Model and observed mixed-layer temperatures show a close agreement at the offshore stations (Plate 1 and Fig. 1a). Nearshore locations are influenced by eddy activity and associated cold upwelled waters. Cold water filaments extending from the Omani coast appear to have been sampled at stations 795–810. Upwelled waters appear during the strong winds of the summer southwest monsoon and disappear by fall.

Along the section model mixed-layer depths (MLDs) are similar to those observed (Fig. 1b), although they are on average 9 m deeper (st.dev. 22 m). While the southernmost stations (720–760) have shallower MLDs than the corresponding locations in the model, temperature profiles there show a second main thermocline at 140 m.

2. CFC Air-Sea Flux

Departures from saturation equilibrium occur when temperature changes and entrainment occur more rapidly than the air-sea gas flux can restore equilibrium. The equilibration time scale is equal to the MLD, H , divided by the gas-exchange velocity, k , (also temperature dependent via the Schmidt number (Sc)).

Mixed-layer gas concentration, c , may be calculated from

$$\frac{dc}{dt} = (k(c^* - c) + \Lambda w_e(c_t - c))/H, \quad (1)$$

where c^* is the equilibrium concentration, a function of atmospheric CFC-11 concentration, temperature, and salinity [*Warner and Weiss*, 1985]. Following the notation of *Haine and Richards* [1995], the second set of terms describe dilution due to entrainment of thermocline waters of concentration c_t . Observations taken

¹Output from both the thermodynamical model and a dynamical model run in near-real time are available via the Internet: anonymous ftp to kelvin.marine.usf.edu/pub/ndncon; web-site at <http://ompl.marine.usf.edu>.

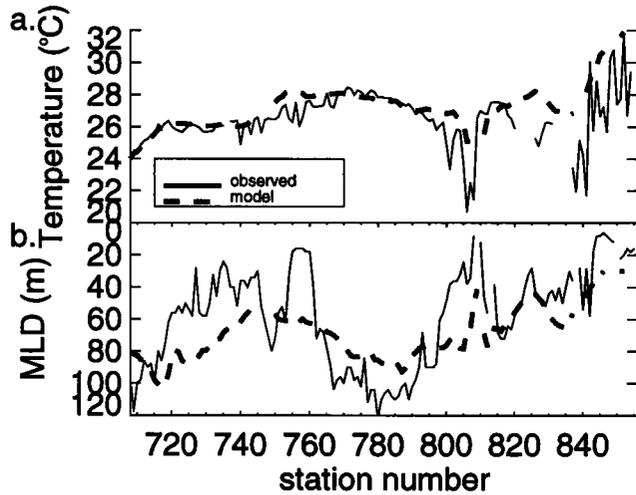


Figure 1. a. Model and observed mixed-layer temperatures along the I7N section. Agreement is close except at the northern stations near the coast influenced by cold upwelling waters. b. Mixed-layer depths from the model (dashed) and CTD temperature profiles (solid) along the I7N section.

from I7N between 50–100 m show thermocline waters to be at 85% saturation (st. dev. 10%). This is equivalent to c_t equal to 0.95 of the mixed-layer concentration, so here the second term in (1) is replaced with $-0.05\Lambda w_e c$. The entrainment velocity is w_e , and Λ is a step-wise function equal to one when w_e is positive and zero when w_e is negative (detrainment is occurring). Horizontal advection is ignored in the gas flux parametrization. Numerical integration of Eq. 1 at every $1/3^\circ \times 1/3^\circ$ gives time-varying mixed-layer CFC-

11 concentrations. Levitus salinity and reconstructed and observed values for northern hemisphere (NH) atmospheric CFC-11 concentrations are used [S. Walker, R. Weiss, and P. Salameh, pers. comm., 1997]. Measurements from the southern hemisphere (SH) GAGE site [Cunnold et al., 1994] show that the standard deviation of the monthly measurements about the annual mean was less than 0.3% for 1993–1995, suggesting that the use of the smoothed annual Walker et al. values is sufficiently accurate for this exercise. The tables show a north to south gradient in atmospheric CFC-11 concentrations of 2% in 1995.

Archived fields for H , T , and w_e obtained with climatological (monthly-mean) forcing of the thermodynamical circulation model are used.

3. Gas-exchange parametrizations

Three alternative wind-speed based parametrizations of k were investigated. In each case COADS (Comprehensive Ocean Atmosphere Data Set) monthly-mean climatological winds are used. These are the same wind fields used to drive the circulation model, except that the winds are reduced by 10% to convert them from 20-meter to 10-meter height equivalents (D. Legler, pers. comm.). Wanninkhof's [1992] Eq. 1 for climatological winds is used to generate k -W1 and his Eq. 3 for constant winds gives k -W3. Like k -W1, k -W3 varies with wind speed squared, but with a lower constant factor of 0.31 (compared to 0.39). It is not clear which parametrization is more appropriate when monthly winds are available, perhaps something in between the two. The Liss and Merlivat [1986] parametrization, which fits three linear relationships to wind speed to reproduce the known increase of k with wind speed, is used to generate k -LM. Conversion from the reference values for CO_2 to CFC-11 values at observed temperatures is made using $k \propto \text{Sc}^{1/2}$.

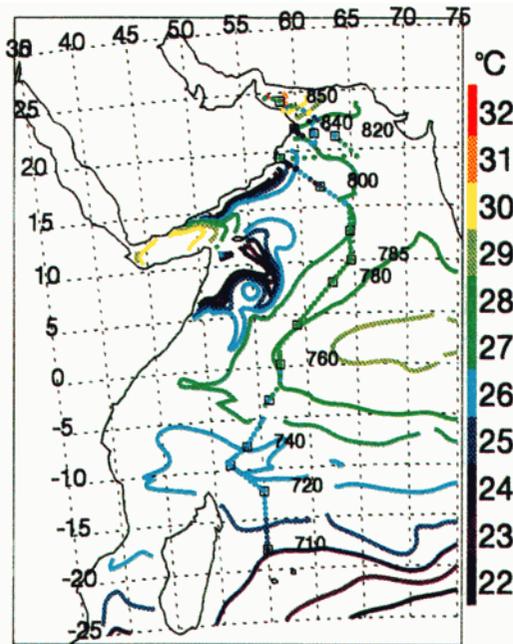


Plate 1. WOCE I7N station locations and mixed-layer temperatures superimposed on contours of model mixed-layer temperatures.

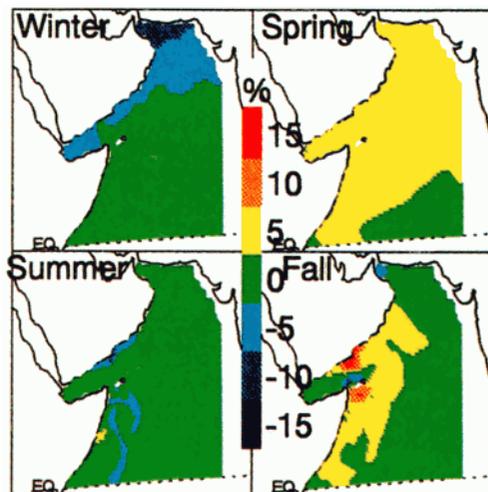


Plate 2. Modeled CFC-11 supersaturations relative to 265.76 ppt (reference NH value for mid-1995) at four seasonal snapshots during 1995.

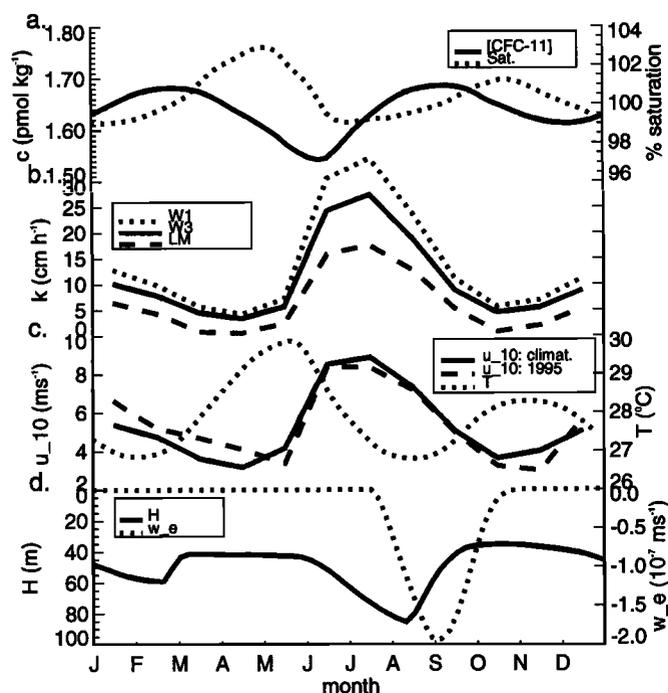


Figure 2. Annual cycle of modeled CFC-11 gas concentrations (a.) and related parameters at the location corresponding to WOCE I7N station 785 (10°N, 64°40'E). Saturations (dashed) follow a seasonal cycle that is dominated by mixed-layer temperature. b. Gas exchange velocity, k , according to three parametrizations, as defined in the text. c. Wind speed (1995 and climatological) and model mixed-layer temperature. d. Model MLD and entrainment velocity.

4. Mixed-layer CFC-11 calculations

Model behaviour is now investigated at a location corresponding to WOCE station 785, which is offshore (Plate 1), and shows good temperature agreement with the observations (Fig. 1). The calculated annual cycle of CFC-11 concentrations is shown in Fig. 2a. Saturations range between 99–104%.

The annual cycle of parameters controlling these gas concentrations are next examined. Exchange velocities are highest during the high winds of the summer monsoon (15–32 cm h⁻¹) and lowest during the inter-monsoon periods (0–3 cm h⁻¹) (Fig. 2b). Mixed-layer

equilibration times are correspondingly fastest during the summer (typically 10–20 days).

The COADS winds for 1995 closely match the annual cycle of climatological winds (Fig. 2c). Unfortunately wind data from the I7N ship were not yet available for comparison. The annual range of model mixed-layer temperatures is from 27°C to 30°C. Temperatures are highest during the inter-monsoon periods of spring and fall. The MLD also doubles from 40 m during most of the year to near 80 m during the summer monsoon (Fig. 2d). The entrainment velocity is a model-derived quantity that is partly determined by the mixed-layer physics, but also is adjusted to maintain the MLD at a minimum of 30 m. The w_e values for the entire I7N section span a wide range from $-7e^{-6}$ m s⁻¹ to $4e^{-4}$ m s⁻¹ and are shown for station 785 location in Fig. 2d. However, in sensitivity tests the dilution effect of entrainment of thermocline waters was negligible, even when the entrained waters were given zero CFC-11 concentrations.

The measured atmospheric CFC-11 concentrations during the WOCE cruise averaged 261.44 ppt. This is comparable to Walker *et al.*'s mean SH value of 260.77 ppt and suggests that during the summer's strong southwest winds, a SH air concentration is an appropriate reference value for the entire region. Consequently the observed concentrations are referenced to 261.44 ppt. Excluding the strongly undersaturated ($\leq 90\%$) filament waters, the average saturation level of the NH I7N stations is 102.0% (Fig. 3). The average saturation of all the I7N stations, again excluding filament waters, is 101.0%.

The modeled saturations are also illustrated relative to 261.44 ppt, i.e., are scaled up compared to the reference air values used to drive the gas flux (265.76 ppt in mid-1995). This scaling is more appropriate for the NH comparison, but is applied to the whole section. The modeled saturation values are always highest using k -W1 and lowest using k -LM, with k -W3 in between. In the NH the average saturation levels are 100.07% for k -LM, 100.52% for k -W3 and 100.79% for k -W1. Haine and Richards [1995] also found the choice of gas-exchange parametrization to introduce relatively small changes in calculated saturations, with seasonality in

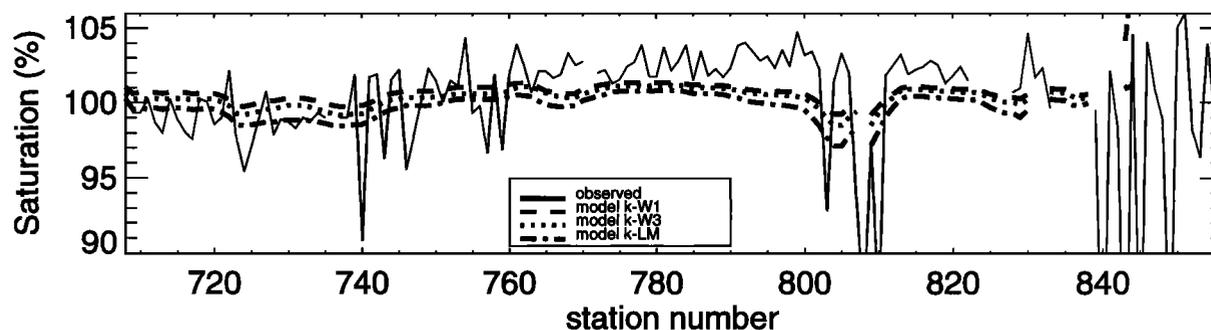


Figure 3. CFC-11 saturations along I7N compared to modeled values. Saturations are referenced to the measured air concentration of 261.44 ppt. and are calculated using each of the three k parametrizations, as described in the text. Breaks occur in the model curves where stations are in less than 200 m of water.

MLD contributing larger uncertainties. At the location corresponding to station 785 the model MLD of 90 m is 20 m shallower than the observed value, while the reverse is generally true, i.e., observed values are deeper (section 1). In sensitivity tests, the effect of adding 20 m to model MLDs everywhere reduced the average percent saturation for the section by 0.5%. A bias of 20 m in MLD produces comparable changes in gas saturations as choosing the k -W3 parametrization versus the k -W1.

The observed gas saturations agree more closely with the modeled values using the higher k values from *Wanninkhof's* Eq. 1 for climatological winds. However, the modeled values are on average 1% less saturated than the observed data. Bubbles injected by breaking waves can support supersaturations [*Farmer et al.*, 1993]. However, in order to model the bubble contribution more detailed wind information is required so that a bubble-flux enhancement may be applied for the fraction of time that winds are strong enough to cause significant wave-breaking. Differences between 1995 and the mean climatology represented in the model may be responsible for other discrepancies. Advection and mixing of coastal waters, particularly where it occurs as narrow filaments, is likely to show annual variability which will not be captured in the model.

Using the k -W1 exchange velocities, region-wide CFC-11 departures from saturation are modeled and illustrated in Plate 2. Saturations are calculated relative to the reference NH air concentrations used to force the model. The waters are generally close to saturation equilibrium in the summer, except for undersaturations (of order 5–10%) in the cold coastal waters. In the winter the northern Arabian Sea waters appear undersaturated by 5–10%, due to cooling. In the spring and fall widespread supersaturations of order 5–10% and more are predicted. Due to the weaker winds in the intermonsoon periods, a combination of warming and slower equilibration rates result in supersaturations appearing in these seasons. In data collected during repeat cruises to the I7N region *Rhein et al.* [1997] note that while surface waters were saturated or supersaturated with CFC-12 in April, by June and the beginning of the summer monsoon, there were mean undersaturations of 10% and values as low as 70% in the cold coastal waters.

5. Conclusions

A limitation in the use of gases from the CFC family of tracers, and those also affected by biology (e.g. carbon dioxide and oxygen), is related to gas transfer parametrization [*Dixon et al.*, 1996] and temporal and spatial variability in the degree of equilibration of surface waters with the atmosphere.

Model experiments show better agreement with observed CFC-11 saturations for the WOCE I7N transect in the Indian Ocean using the *Wanninkhof* [1992] gas-exchange velocity parametrization than that of *Liss and Merlivat* [1986]. In particular, *Wanninkhof's* equation for climatological winds gives the best fit of the three when monthly-mean winds are used. However, uncer-

tainty in MLD of order 20 m introduces uncertainty in saturation estimates comparable to that introduced by the choice of gas flux parametrization. Based on a qualitative comparison of the annual cycles of parameters at the location of WOCE I7N station 785, it is clear that wind speed is the most important factor controlling k .

The model results show that there are large spatial and seasonal variations in surface gas saturations. Model and observed results show CFC-11 is close to saturation (within 1%) in the northwestern Indian Ocean in summer, with large undersaturations in the cold upwelled waters. The model results further predict large seasonal changes, with widespread supersaturations of 5–10% predicted for the spring and fall due to weaker winds and warming. Further model comparisons with observational data spanning larger space and time scales are needed.

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