4. pCO$_2$s estimation and associated error

We estimated monthly pCO$_2$s in a 1° × 1° grid from 1985 through 2009 by using the grid data described in Section 2 and the empirical equations introduced in Section 3. Data for Chl-*a* by remote sensing have been available only since 1998. For pCO$_2$s estimates before 1998 we used the climatological Chl-*a*, which is the average of monthly remote sensing data sets from 1998 through 2009.

We generated time series of monthly pCO$_2$s and pCO$_2$a averaged in the five regions since 1985 (Fig. 5). The estimates for 25 years agree with observations very well in the five regions. For example, our method adequately reproduced the drastic decrease in pCO$_2$s in the equatorial region during 1997/1998 El Niño. The method also estimates pCO$_2$s in subarctic regions where large seasonal variations in pCO$_2$s occur because of biological consumption and vertical mixing.

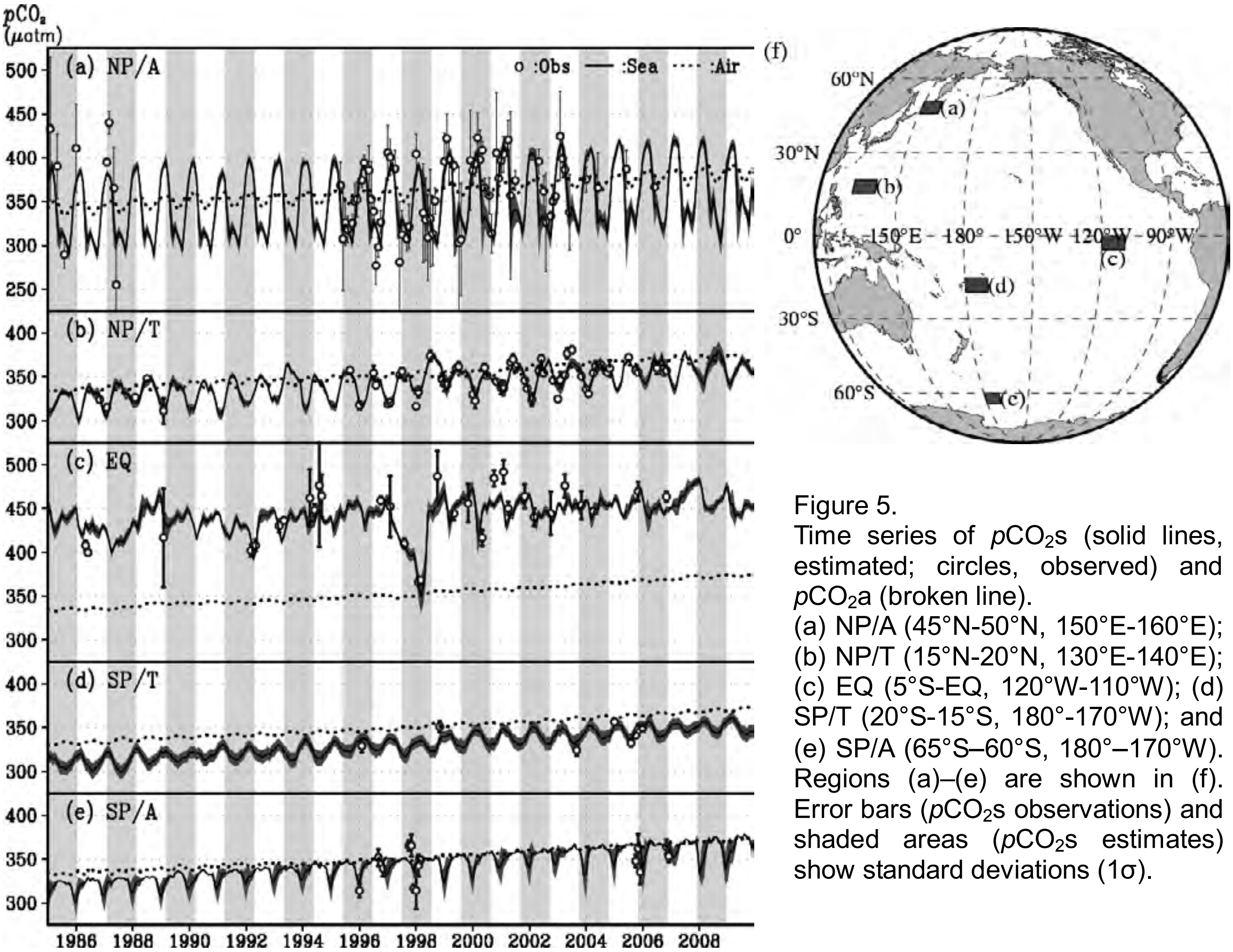

Figure 5.
Time series of pCO$_2$s (solid lines, estimated; circles, observed) and pCO$_2$a (broken line).
(a) NP/A (45°N-50°N, 150°E-160°E); (b) NP/T (15°N-20°N, 130°E-140°E); (c) EQ (5°S-EQ, 120°W-110°W); (d) SP/T (20°S-15°S, 180°-170°W); and (e) SP/A (65°S–60°S, 180°–170°W). Regions (a)–(e) are shown in (f). Error bars (pCO$_2$s observations) and shaded areas (pCO$_2$s estimates) show standard deviations (1σ).

We determined the annual mean bias and RMSE between pCO$_2$s estimates and observations in each region over 25 years. For error estimation in 2007 and 2008, we also used the latest LDEO Database V2008 (Takahashi et al., 2009a). The mean biases in all regions are small, ranging from −10 to +10 μatm (Fig. 6). The RMSE in the subarctic regions and the equatorial region (approximately 30 μatm) is relatively larger than that in the subtropical regions (about 20 μatm).

We used monthly mean SST, SSS and Chl-*a* data to estimate monthly pCO$_2$s fields. These data sets represent a different time-scale than observational data, which are instantaneous values. This difference in time-scale causes some error in $p\mathrm{CO_2}$s estimation.

The differences between estimates and observations in the subtropical and warm-pool regions are smaller than those in the equatorial upwelling region and subarctic regions. This is because the estimation errors in subtropical and equatorial warm-pool regions, where $p\mathrm{CO_2}$s varies mainly because of the thermodynamic effect, are based almost entirely on SST data errors.

In the equatorial region, the boundaries between the upwelling region, the low salinity region and the warm-pool region are determined by monthly SSS data, but these boundaries actually shift over shorter time scales. This time lag in region division increases the estimation error in the equatorial region.

In the subpolar regions, monthly Chl-*a* fields are used for $p\mathrm{CO_2}$s estimation. $p\mathrm{CO_2}$s is very sensitive to Chl-*a* levels, which vary widely over short time intervals. Furthermore, climatological Chl-*a* was used for $p\mathrm{CO_2}$s estimates before 1998. These factors increase RMSEs in the subpolar regions.

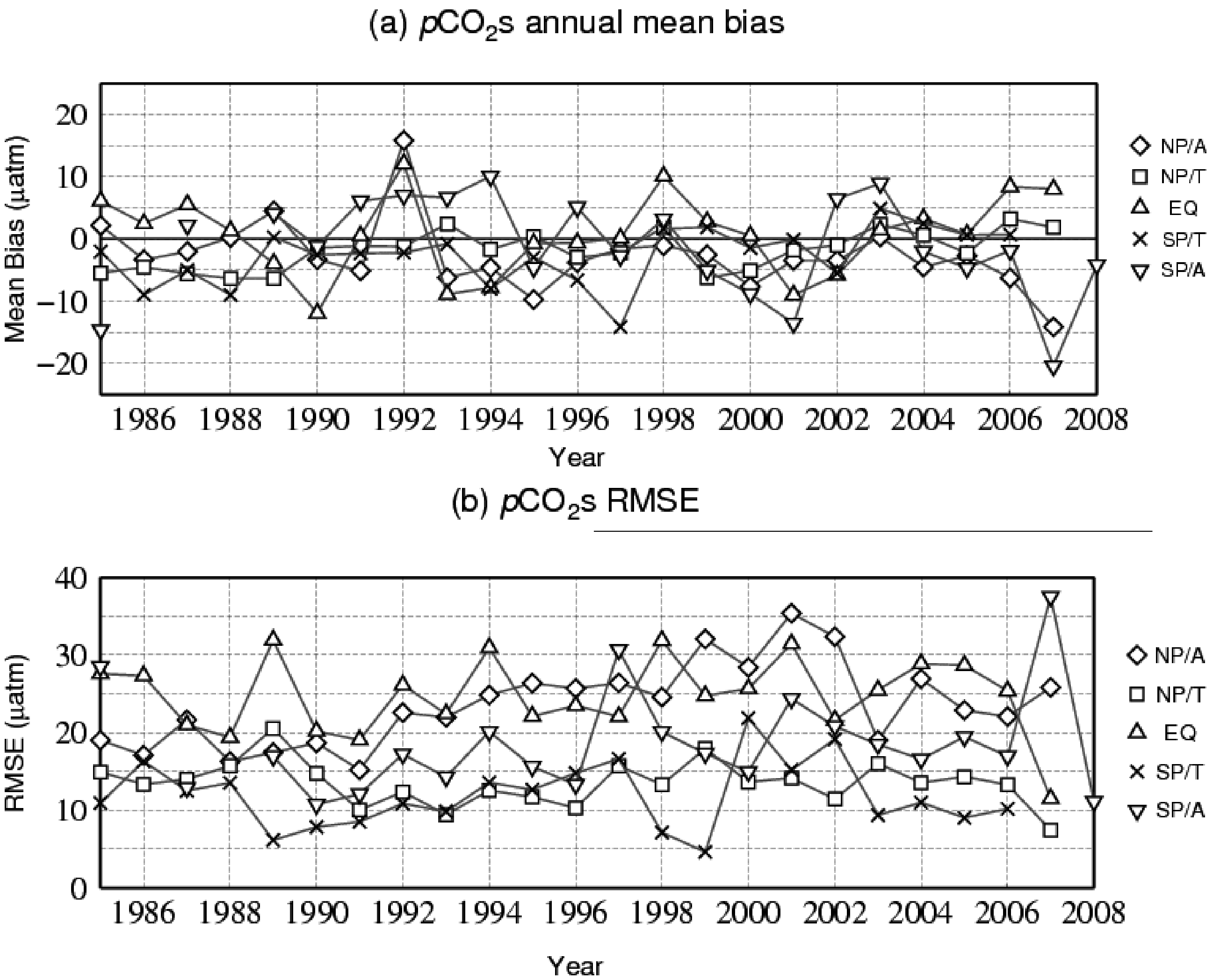

Figure 6. Annual mean biases (a) and annual RMSE (root mean square error) (b) between estimated and observed $p\mathrm{CO_2}$s in each region. Bias is defined as $\Sigma(p\mathrm{CO_2}\mathrm{s}\ [\mathrm{estimated}] - p\mathrm{CO_2}\mathrm{s}\ [\mathrm{observed}])/n$, and RMSE is defined as $\sqrt{\Sigma(p\mathrm{CO_2}\mathrm{s}\ [\mathrm{estimated}] - p\mathrm{CO_2}\mathrm{s}\ [\mathrm{observed}])^2/(n-1)}$. n is the number of data.