IMPROVING OCEAN-ATMOSPHERE CARBON FLUX ESTIMATES WITH LIDAR MEASUREMENTS OF OCEAN SUBSURFACE AND OCEAN-ATMOSPHERIC INTERACTION

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ABSTRACT

Profiling lidars in space (e.g., LITE, GLASS and CALIOP) have greatly enhanced our understanding of aerosols and clouds. With minor changes to the configuration, the space-based profiling lidars can also provide unique information for improved understanding of ocean biogeochemistry and air-sea interaction. These measurements enhance the scientific payoffs of space-based lidar missions through their advanced capability in understanding physical processes and monitoring seasonal and inter-annual changes of carbon cycle, energy cycle, water cycle and their feedbacks. This study introduces the ocean profiling measurement concept and its potential scientific applications.

1. INTRODUCTION: OCEAN CARBON FLUX AND THE ROLE OF REMOTE SENSING

Over the last couple of decade, the global carbon cycle can be roughly summarized as (Fig. 1): atmospheric increase (3.2 PgC) = fossil fuel emission (6.3) + net land use emission (2.2) – oceanic uptake (2.4) – missing carbon (2.9 PgC).

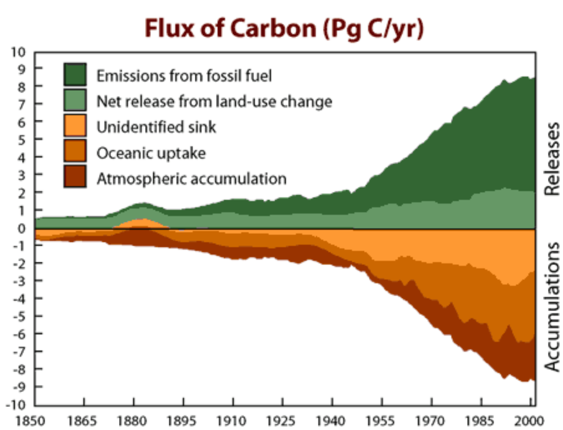

Figure 1. Flux of carbon (PgC/yr) from Woods Hole center website.

The amount of missing carbon, which is the additional carbon sink required to balance the carbon budget, is about the same as the increase of CO2 in the atmosphere every year. One of the possible causes is the uncertainties in ocean – atmospheric CO2 flux.

Ocean – atmospheric CO2 flux can be expressed as a product of gas transfer velocity (K) and partial CO2 pressure difference between air and water:

$$F_{CO2} = K\,(P_{CO2,\,Ocean} - P_{CO2,\,Atmosphere}) \ldots (1)$$

Ship measurements and modeling are used for compiling partial pressure statistics (Takahashi et al., 2002, Fig. 2). Gas transfer velocity is estimated using global satellite observations, such as sea surface wind speed and sea surface temperature (Wanninkhof, 1992).

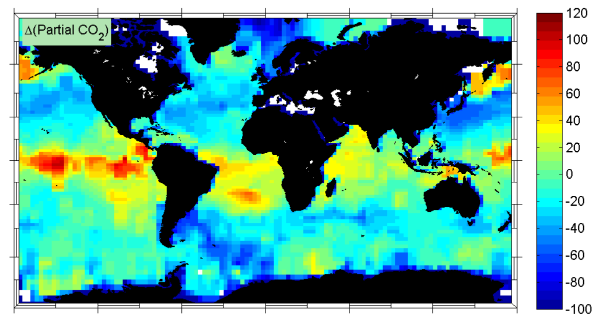

Figure 2. Δ(Partial CO_2) referenced to year 1995 compiled by Takahashi et al. (2002)..

There are huge uncertainties in ocean carbon uptake due to uncertainties in both the CO2 partial pressure and gas transfer velocity (Wallace, 1995). For example, with different wind – gas transfer velocity relation, the ocean CO2 uptake varies from 1 to 3 PgC per year (Table 1).

Table 1. Global CO_2 flux derived from different vertical turbulence velocity parameterzation schemes (Freely et al., 2001).

	Parameterization	Flux (PgC/yr)
Liss & Merlivat (1986)	0.17V (0~3.6 m/s) 2.85V-9.65 (3.6~13) 5.9V-49.3 (>13 m/s)	-1.0
Wanninkhof (W-92)	$0.39V_L^2$	-1.8
Wanninkhof & McGillis (W-99)	$1.09V_L - 0.333V_L^2 + 0.078\,V_L^3$	-3.0
Nightingale (2000)	$0.333V+0.222V^2$	-1.5
NCEP average wind	$0.39\,V_L^2$ (W-92)	-2.2
NCEP 6-hour wind	$0.31\,V^2$ (W-92)	-1.7
NCEP 6-hour wind	$0.0283V_L^3$ (WM-99)	-2.3

Global observations of air-sea gas transfer velocity and primary productivity from space can help reduce the uncertainty in global oceanic CO2 budget (Carr et al., 2002).

2. LIDAR BACKSCATTER FOR IMPROVING GAS TRANSFER VELOCITY ESTIMATE

Conventional approach of estimating gas transfer velocity at air-sea interface is through surface wind speed (e.g., Wanninkhof, 1992) and it introduces huge uncertainty in CO2 uptake (Table 1). The causes of the huge uncertainties includes,

- The nonlinear nature of the relation between gas transfer velocity and wind speed (table 1 and lower panel of Fig. 3) requires eddy scale wind speed statistics, which is not available;
- The relation between gas transfer velocity and wind speed changes with the presence of surfactants (Fig. 4).

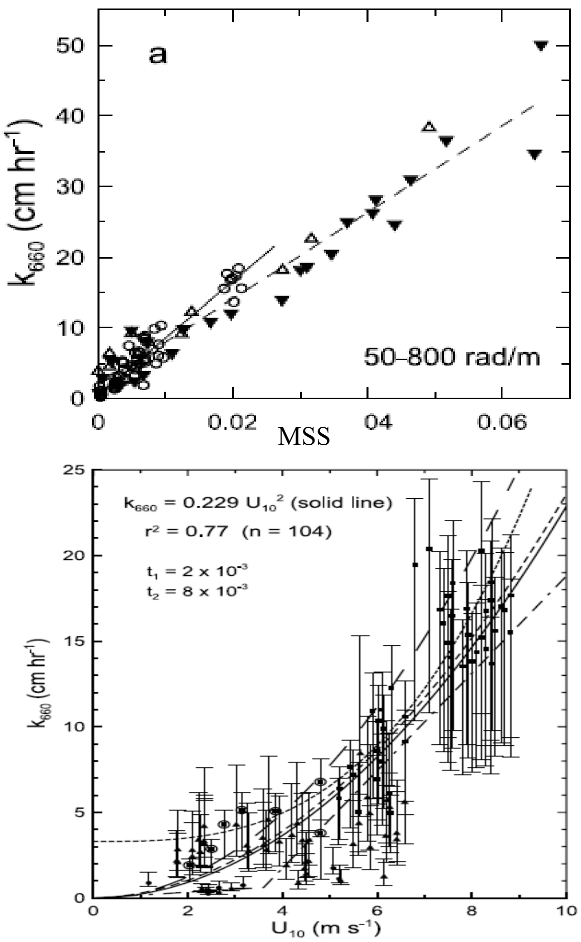

Figure 3. Vertical turbulence transfer velocity as a linear function of mean square slope (upper panel) and a nonlinear function of surface wind speed (lower speed). The figure is adopted from Frew et al. (2004).

Vertical turbulence transfer velocity at air-sea interface is linearly related to the mean square slopes of all surface waves (e.g., Jahne et al., 1987; Frew et al., 2004). Mean square slope is more directly linked to the gas transfer velocity than wind speed, and it can be accurately measured from spacebased lidars, such as CALIPSO (Hu et al., 2008).

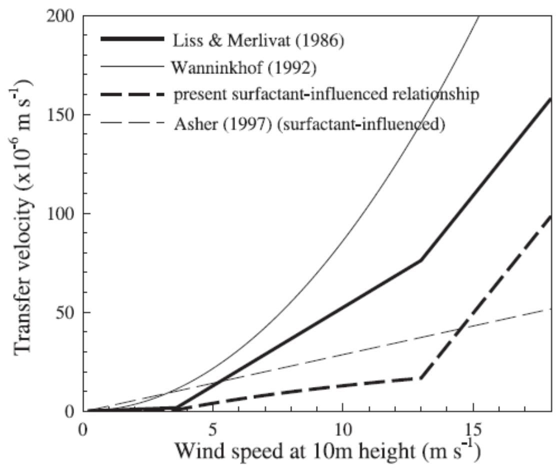

Figure 4. Vertical transfer velocity – wind speed relation depends on the presence of surfactants (Tsai & Liu, 2003).

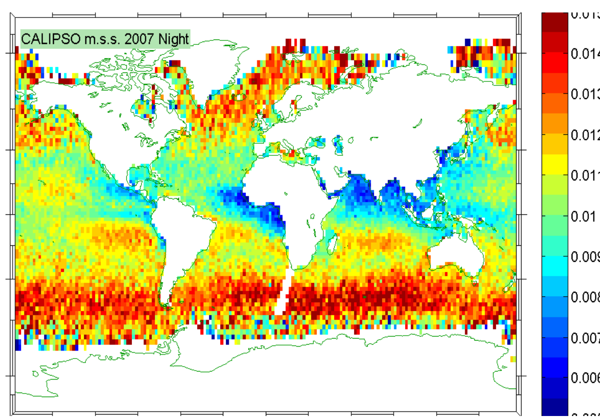

Figure 5. Mean square wave slope from CALIPSO ocean surface lidar backscatter measurement.

Lidar backscatter of ocean surface is inversely proportional to ocean surface mean square wave slope (MSS). Fig. 5 shows the global statistics of mean square slopes from CALIPSO measurements. The MSS measurements can be improved with more accurate atmospheric two-way transmittance estimate with collocated radar/lidar/microwave measurements (Josset et al., 2009) and with HSRL in space (e.g. Earthcare and ACE mission).

3. OCEAN LIDAR PROFILING FOR IMPROVEMENT OF OCEAN PRIMARY PRODUCTIVITY ESTIMATE

While oceanic PCO2 measurements are mostly performed by in situ measurements, linking that to satellite measurements of primary productivity and carbon cycle models can provide the high spatial and temporal resolution information required for reducing uncertainty of CO2 flux (Takahashi et al., 2002; Carr et al., 2002).

Ocean primary productivity is highly correlated to optical properties such as beam attenuation and backscatter coefficient (Behrenfeld and Falkowski, 1997). There is ocean subsurface signal from space-based lidars such as CALIPSO (Hu et al., 2008). CALIPSO provides column integrated ocean sub-surface backscatter (Figure 6) for the top 3 or more optical depths (which mean first a few meters in coastal waters, and up to 100m for clearest part of open-ocean with diffuse attenuation as low as 0.03 m^{-1}). It takes faster vertical sampling (1 m resolution or so) and/or Brillouin scatter from HSRL to separate backscatter from attenuation. Multiple scatter in water is a significant and cab be evaluated and corrected for with multiple field of view measurements.

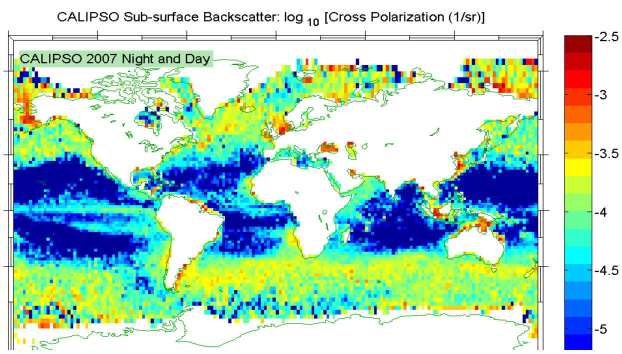

Figure 6. Column integrated ocean subsurface lidar backscatter from CALIPSO (perpendicular component, in logrithmic scale).

4. VARIABILITY AND FEEDBACKS OF ENERGY – WATER – CARBON CYCLES

Carbon cycle, energy cycle and water cycle are inter-connected. With unambiguous measurements of different atmospheric and ocean processes, space-based atmosphere – ocean profiling lidar measurements are ideal for studying interactions and feedbacks of varies physical processes of carbon/energy/water cycles. Climate predictions require good understanding of these physical processes and feedback mechanisms, as well as its impact on the global carbon budget (Cox et al., 2000).

Space-based lidar/radar atmosphere and ocean profiling measurements provide the most accurate seasonal and inter-annual variations of clouds, aerosols, and ocean processes (e.g., Fig. 7) due to its unambiguous separation of different components of the climate system and due to the superior long-term calibration stability. The long-term calibration of the profiling lidars can be assessed with various vicarious calibration targets, such as ocean surface (Josset et al., 2009) and water clouds (Hu et al., 2007).

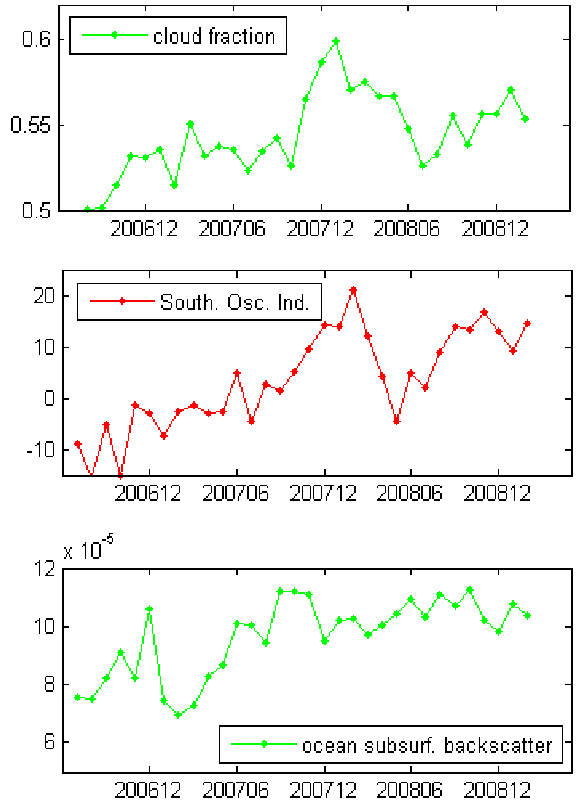

Figure 7. Southern Oscillation Index (middle) and CALIPSO climate records of monthly, ocean subsurface lidar backscatter (lower), cloud fraction (upper).

5. SUMMARY

The ocean surface and sub-surface measurements from space-based profiling lidars have the potential to reduce uncertainty in ocean carbon flux estimates by providing unique information for improving the understanding of air-sea interaction and ocean primary productivity.

The most important modifications to current space-based lidars for atmospheric profiling needed to perform ocean profiling are fast vertical range sampling, Brillouin scatter from HSRL, and multiple field of view. Highly accurate measurements of aerosol, clouds, air-sea interaction and ocean biogeochemistry can be made with the atmosphere and ocean profiling lidar.

These measurements can help understanding the physical processes important to carbon cycle and can be a complimentary to other satellite missions for CO2 measurements.

The purpose of this presentation is to introduce the concept to the broad ILRC community, to invite discussions/debates and to seek collaborations among researchers in community.

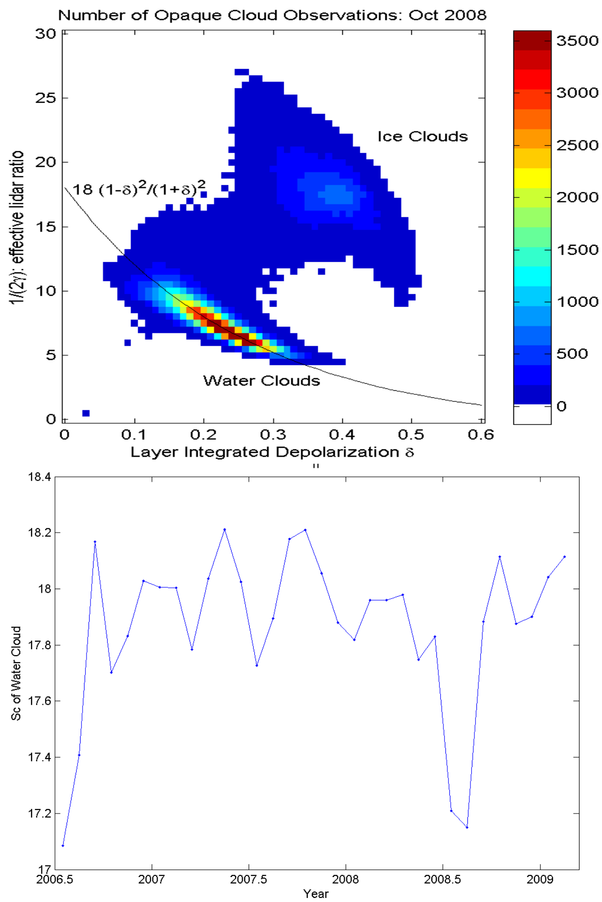

Figure 8. Upper panel: effective lidar ratio of thick water clouds from CALIPSO measurements. Real lidar ratio can be derived when δ=0. The black line is from radiative transfer theory (Hu, 2007). Lower panel: CALIPSO water cloud lidar ratio for each month during 2 and half years.

REFERENCES

[1] Behrenfeld, M.J., and P.G. Falkowski (1997): A consumer's guide to phytoplankton primary productivity model. *Limnol. Oceanogr., 42*(7), 1479–1491.

[2] Carr, M., C. McClain, and J. Moore, 2002: The role of remote sensing in an ocean CO2 observing plan. A Large-scale CO2 Observing Plan (Appendix F). 185-192.

[3] Cox, P., R. Betts, C. Hones, S. Spall and I., Totterdell, 2000: Accelleration of global warming due to carbon-cycle feedbacks in a coupled climate model, Nature, 408, 184-187.

[4] Feely, R.A., C.L. Sabine, T. Takahashi, and R. Wanninkhof, 2001: Uptake and Storage of Carbon Dioxide in the Ocean: The Global CO2 Survey, Oceanography, **14**/4, 18-32.

[5] Frew, N. M., et al. (2004), Air-sea gas transfer: Its dependence on wind stress, small-scale roughness, and surface films, J. Geophys. Res., 109, C08S17, doi:10.1029/2003JC002131.

[6] Jahne, B., K. O. Munnich, R. Bosinger, A. Dutzi, W. Huber, and P. Libner (1987), On the parameters influencing air-water gas exchange, J. Geophys. Res., 92, 1937– 1949.

[7] Josset, D., J. Pelon, Y. Hu, and H. Maring, 2009: Determination of aerosol optical properties using ocean surface reflectance, SPIE Newsroom, DOI: 10.1117/2.1200903.1574.

[8] Josset, D., Pelon, J., Hu, Y., 2009: Multi-Instrument Calibration Method Based on a Multiwavelength Ocean Surface Model, Geoscience and Remote Sensing Letters, 10.1109/LGRS.2009.2030906

[9] Hu, Y., et al., 2008: "Value-Added CALIPSO Ocean, Land and Meteorology Product", *24rd International Laser Radar Conference (ILRC 24)*, Boulder (USA), 23-27 June 2008.

[10] Hu, Y., et al., 2007, "The depolarization - attenuated backscatter relation: CALIPSO lidar measurements vs. theory," Opt. Express **15**, 5327-5332. doi:10.1364/OE.15.005327.

[11] Hu, Y. et al., 2008, Sea surface wind speed estimation from space-based lidar measurements, ACP, 8, 3593-3601.

[12] Hu, Y, M. Vaughan, Z. Liu, K. Powell, and S. Rodier, 2007: "Retrieving Optical Depths and Lidar Ratios for Transparent Layers Above Opaque Water Clouds From CALIPSO Lidar Measurements", Geoscience and Remote Sensing Letters, 4, 523–526.

[13] Hair, J. W., C. et al., 2008: Airborne High Spectral Resolution Lidar for Profiling Aerosol Optical Properties, *Appl. Opt.* **47**, 6734-6752; doi:10.1364/AO.47.006734

[14] Takahashi, T., et al. (2002). Global sea-air CO2 flux based on climatological surface ocean pCO2, and seasonal biological and temperature effects, Deep-Sea Res. II, 49, 1601-1622.

[15] Tans, P. P., I. Y. Fung, and T. Takahashi (1990), Observational constraints on the global atmospheric CO2 budget, Science, 247, 1431-1438.

[16] Tsai, W., and K.-K. Liu (2003), An assessment of the effect of sea surface surfactant on global atmosphere-ocean CO_2 flux, *J. Geophys. Res.*, 108(C4), 3127, doi:10.1029/2000JC000740.

[17] Wallace, 1995: Monitoring global ocean carbon inventories, OOSDP Background Report, Ocean Observing System Development Panel.

[18] Wanninkhof, 1992: Relationship between wind speed and gas exchange over ocean, JGR, 7373-7382.