

**Wave slope variance measurements from CALIPSO
and applications in estimating air-sea gas exchange
and near-surface wind speed**

Yongxiang Hu
NASA Langley Research Center

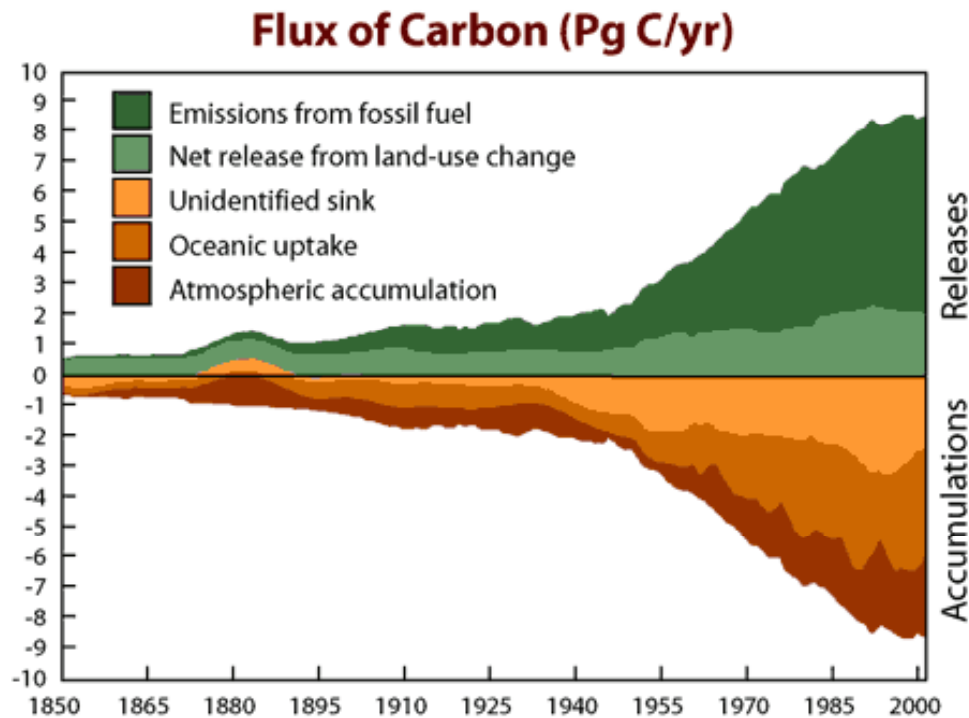
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Summary

1. Introduction of the linear relation between wave slope variance (mean square wave slope) and gas transfer velocity
2. CALIPSO lidar measures wave slope variance of all wavelengths directly, thus provide accurate gas transfer velocity
3. High resolution surface wind speed can be estimated from CALIPSO. After averaging, the wind speed agrees well with AMSR-E wind measurements but the gas transfer velocity increases by about 30%
4. Gas transfer velocity estimated from wave slope variance derived from CALIPSO is compared with the one derived from AMSR-E wind speed
5. Looking for collaboration (inter-comparison/validation, ...)

The Missing Carbon Sink

Atmospheric increase (3.2 PgC/yr) =
Emissions from fossil fuels (6.3) + Net emissions from changes in land use (2.2)
- Oceanic uptake (2.4) - **Missing carbon sink (2.9)**

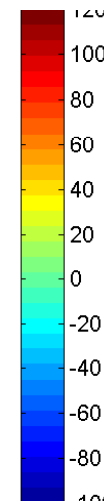
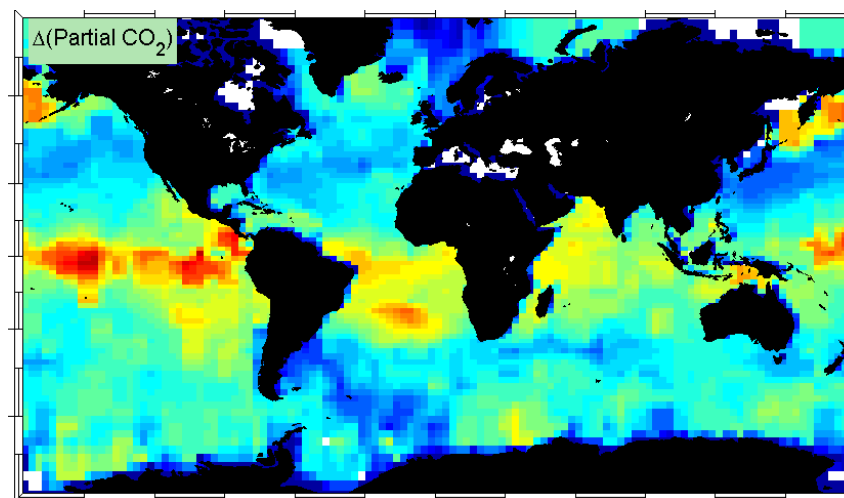
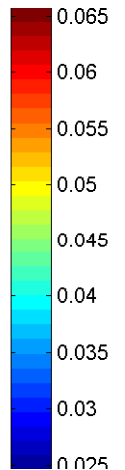
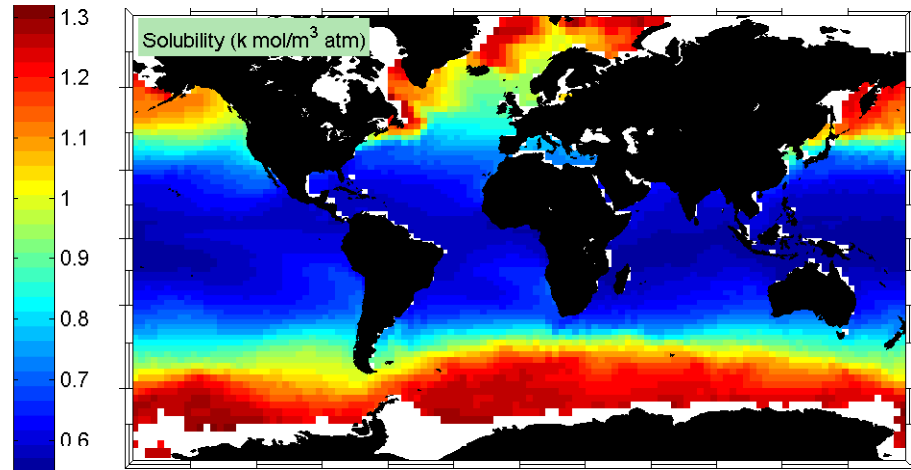
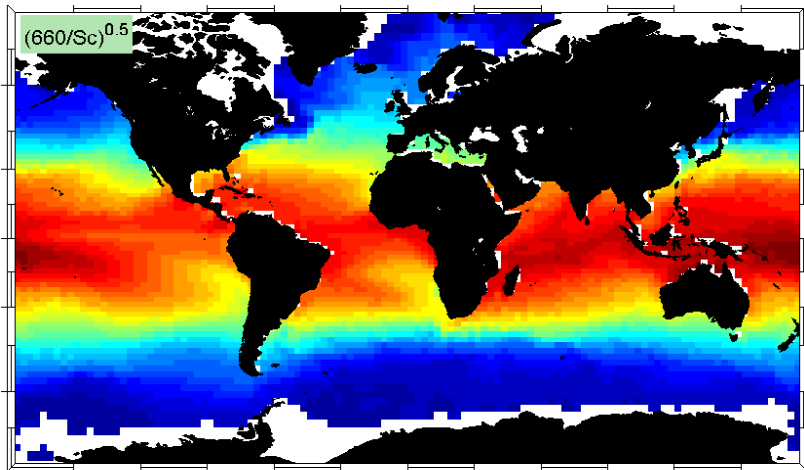


From Woods Hole Reserch Center Website

Combined with errors in partial pressure, the uncertainty of a factor of two in air-sea gas transfer velocity can lead to unacceptable error in global ocean flux of CO₂ (Wallace, 1995)

Air-sea Gas Exchange

$$\text{CO}_2 \text{ Uptake} = \text{Air-sea Gas transfer velocity } k \times (660/S_c)^n \times \text{solubility} \times \Delta(P_{\text{CO}_2})$$



Air-sea gas transfer velocity: A source of uncertainty in Ocean Carbon Uptake

CO_2 Uptake = Air-sea gas transfer velocity k x $(660/\text{Sc})^n$ x solubility x $\Delta(\text{Pco}_2)$

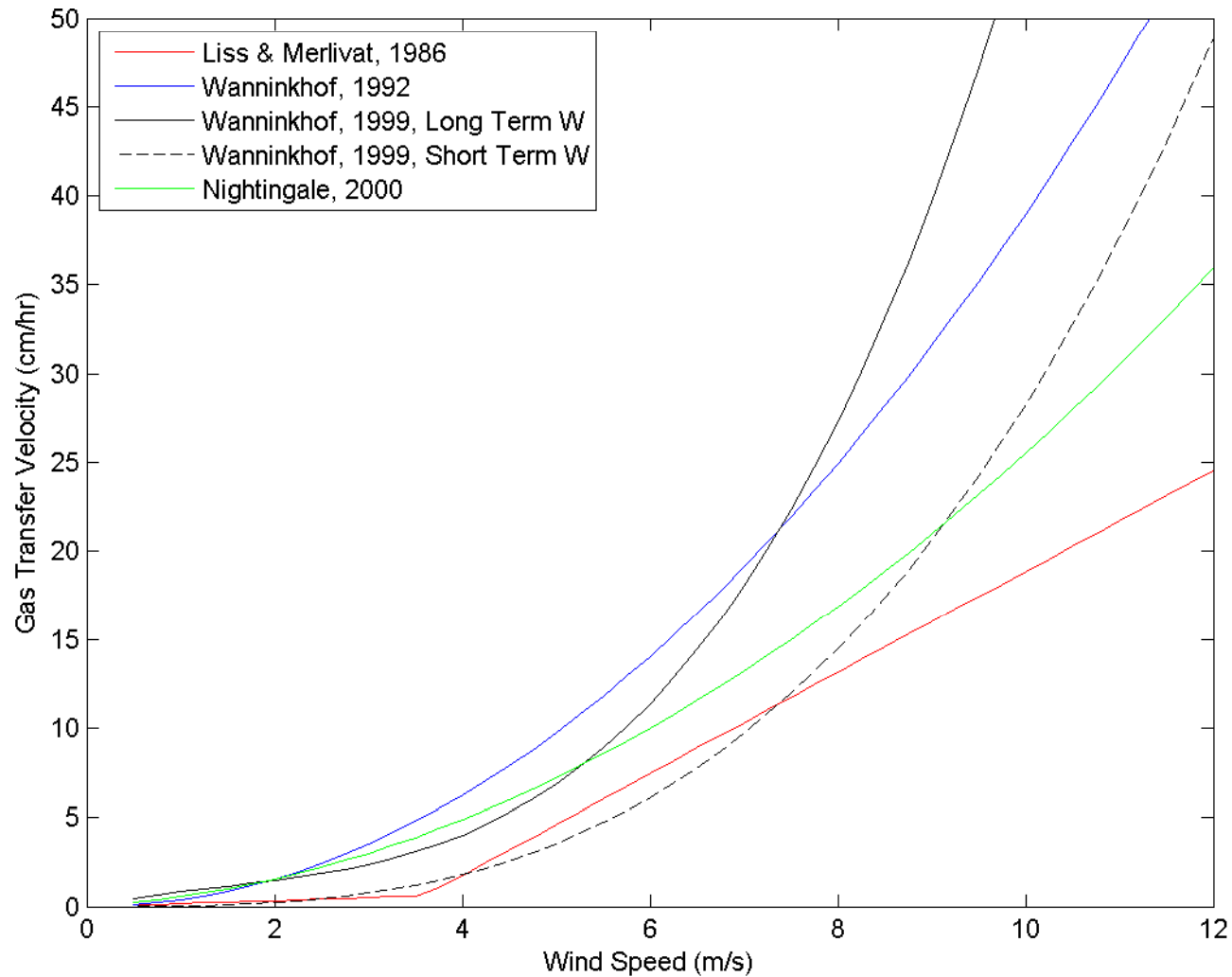
Global oceanic CO₂ uptake estimates using different gas exchange-wind speed relationships and different wind speed products^a.

Relationship	Equation	Flux (Pg C yr ⁻¹)
Liss & Merlivat [1986]	$k = 0.17 U_{10}$ ($U_{10} < 3.6 \text{ m s}^{-1}$) $k = 2.85 U_{10} - 9.65$ ($3.6 \text{ m s}^{-1} < U_{10} < 13 \text{ m s}^{-1}$) $k = 5.9 U_{10} - 49.3$ ($U_{10} > 13 \text{ m s}^{-1}$)	-1.0
Wanninkhof [1992] [W-92]	$k = 0.39 U_{10}^2$ (long term averaged winds)	-1.8
Wanninkhof & McGillis (1999) [W&M-99]	$k = 1.09 U_{10} - 0.333 U_{10}^2 + 0.078 U_{10}^3$ (long term averaged winds)	-3.0
Nightingale et al. [2000]	$k = 0.333 U_{10} + 0.222 U_{10}^2$	-1.5
NCEP-41 year average winds ^b [W-92]	$k = 0.39 U_{10}^2$ (long term averaged winds)	-2.2
NCEP 6-hour winds ^c	$k = 0.31 U_{10}^2$ (instantaneous winds) [W-92]	-1.7
NCEP 6-hours winds ^c	$k = 0.0283 U_{10}^3$ [W&M-99]	-2.3

R.A. Feely, 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.

Air-sea gas transfer – wind speed relation: a source of ocean carbon uptake uncertainty

$\text{CO}_2 \text{ Uptake} = \text{Air-sea gas transfer velocity } k \times (660/\text{Sc})^n \times \text{solubility} \times \Delta(\text{Pco}_2)$

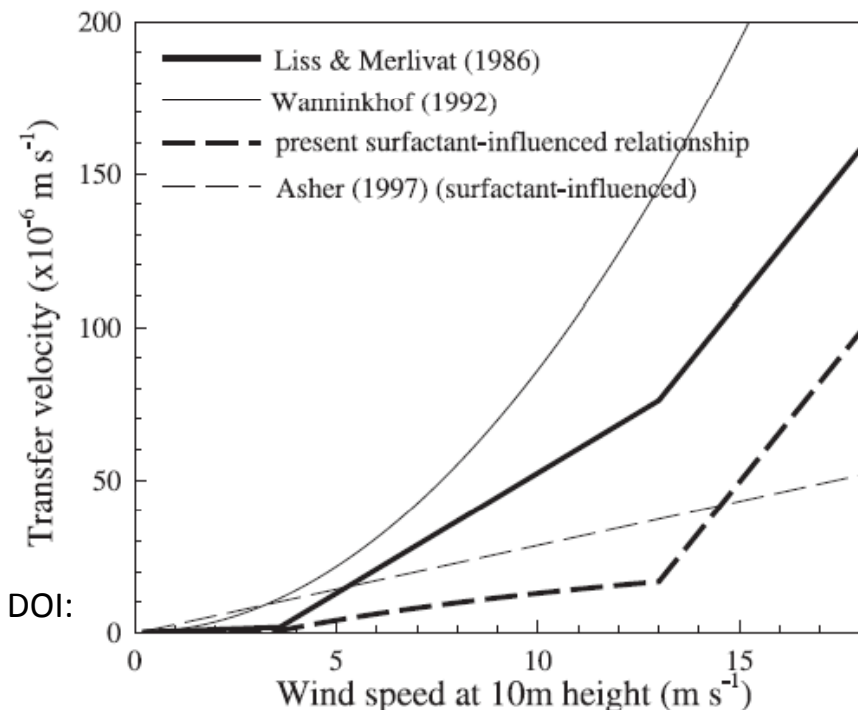


Air-sea gas transfer velocity – wind speed relation: physics behind the uncertainties

1. Nonlinear dependence of gas transfer velocity – wind speed makes it hard to us spatial/temporal averaged wind speed:

$$(W_1^2+W_2^2)/2 > [(W_1+W_2)/2]^2$$

2. For the same wind speed, gas transfer velocity reduces when surfactant (such as degraded planktons) presents.

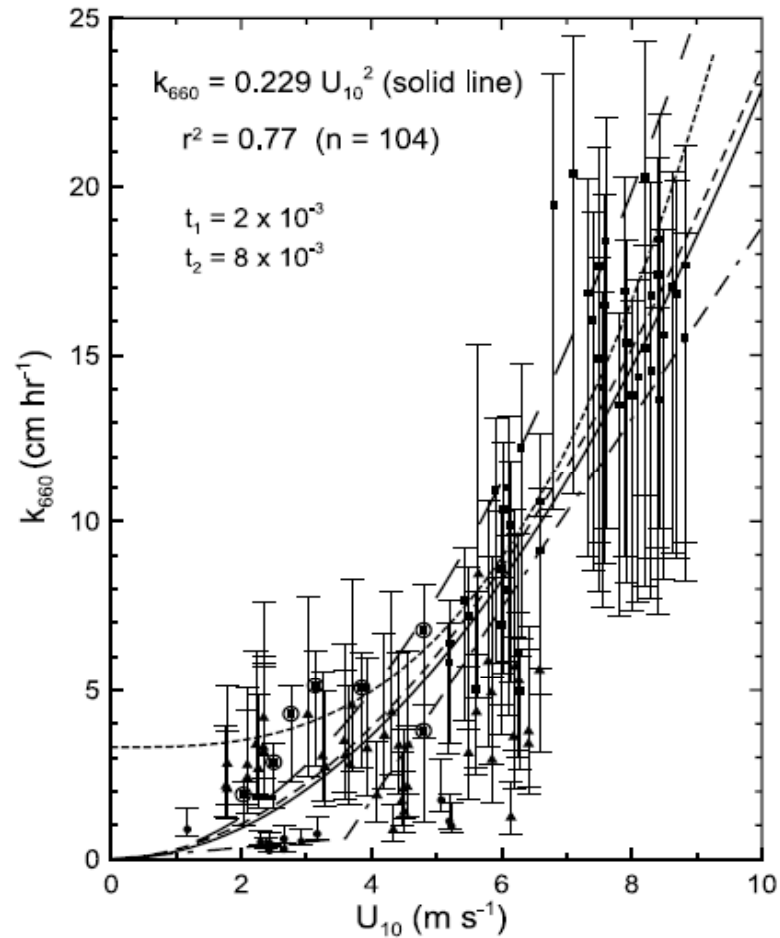
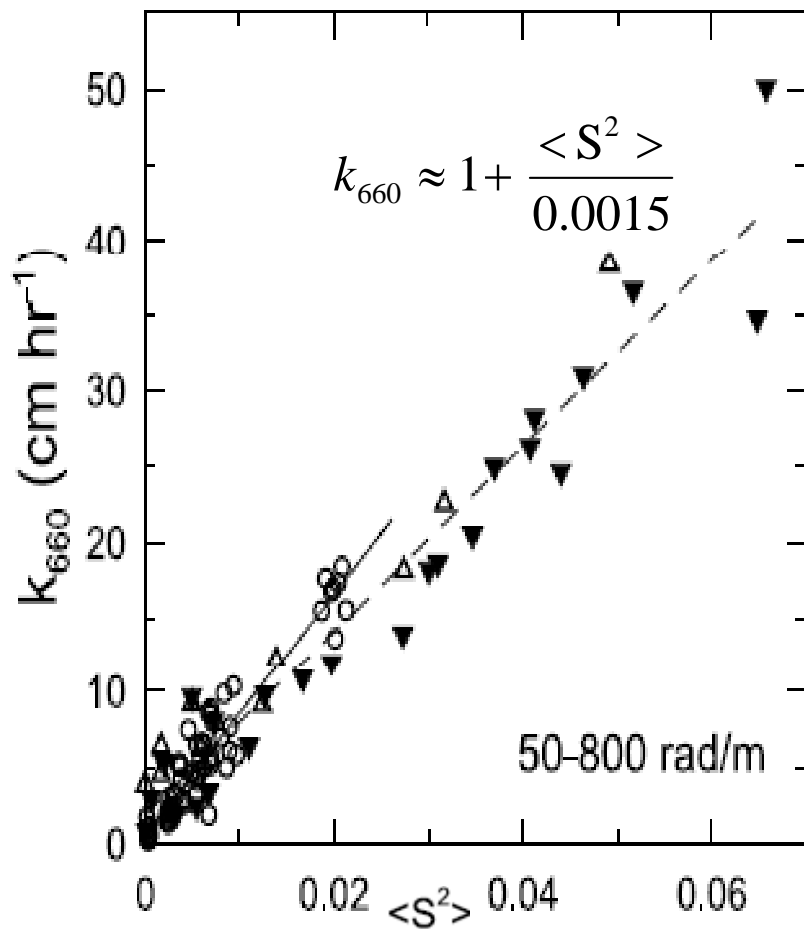


Tsai & Liu, 2003: JGR, 108, C4, DOI:
10.1029/2000JC000740.

Gas transfer velocity correlates with wave slope variance better than wind speed and wind stress

(Jahne et al 1984; Hara et al 1995; Bock et al 1999; Frew et al 2004, ...)

1. Near Linear relation between gas transfer velocity and wave slope variance

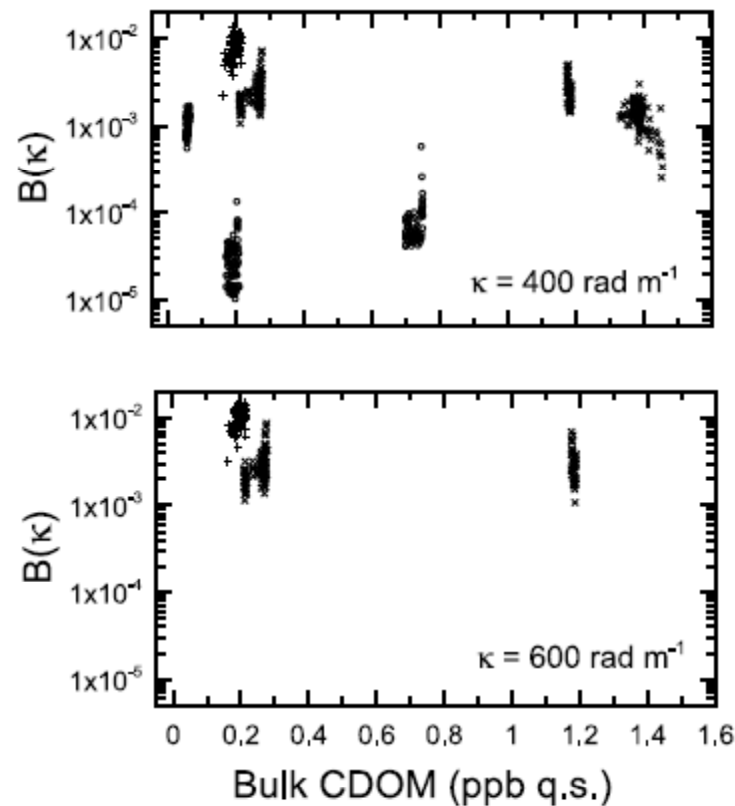


Frew et al, 2004, JGR

Gas transfer velocity correlates with wave slope variance better than wind speed and wind stress

(Jahne et al 1984; Hara et al 1995; Bock et al 1999; Zappa et al 2002, Frew et al 2004, ...)

2. Gas transfer velocity – wave slope variance relation is NOT correlated with surfactants



Frew et al, 2004, JGR

Nadir-Viewing lidar measures wave slope variance of all wavelengths

Backscatter cross section = Backscatter efficiency * cross section area

For microwave: backscatter efficiency depends on wavelength of surface wave

(λ_{radar} and $\lambda_{\text{surface wave}}$ are close, part of signal comes from diffraction)

Lidar (0.532 μm and 1.064 μm)

For lidar: backscatter efficiency is independent of wavelengths of the surface

waves ($\lambda_{\text{lidar}} \ll \lambda_{\text{surface wave}}$, signal comes from geometry optics)

Nadir viewing lidar measurement of ocean surface backscatter γ is inversely proportional to wave slope variance $\langle s^2 = s_x^2 + s_y^2 = \tan^2 \theta \rangle$:

$$\gamma_{\text{backscatter}}(\theta = 0) = \frac{\text{Reflectivity}}{2\pi \langle S^2 \rangle \cos^4 \theta} \exp\left[-\frac{\tan^2 \theta}{2 \langle S^2 \rangle}\right] = \frac{\text{Reflectivity}}{\langle S^2 \rangle}$$

Lidar on CALIPSO

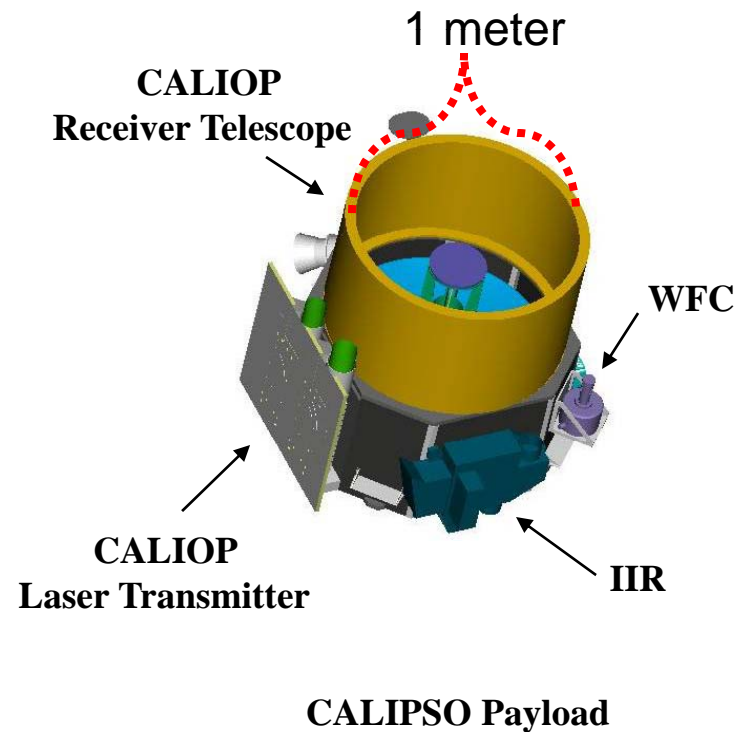
Lidar

CALIOP (Surface Laser Spot Size: 70 m)

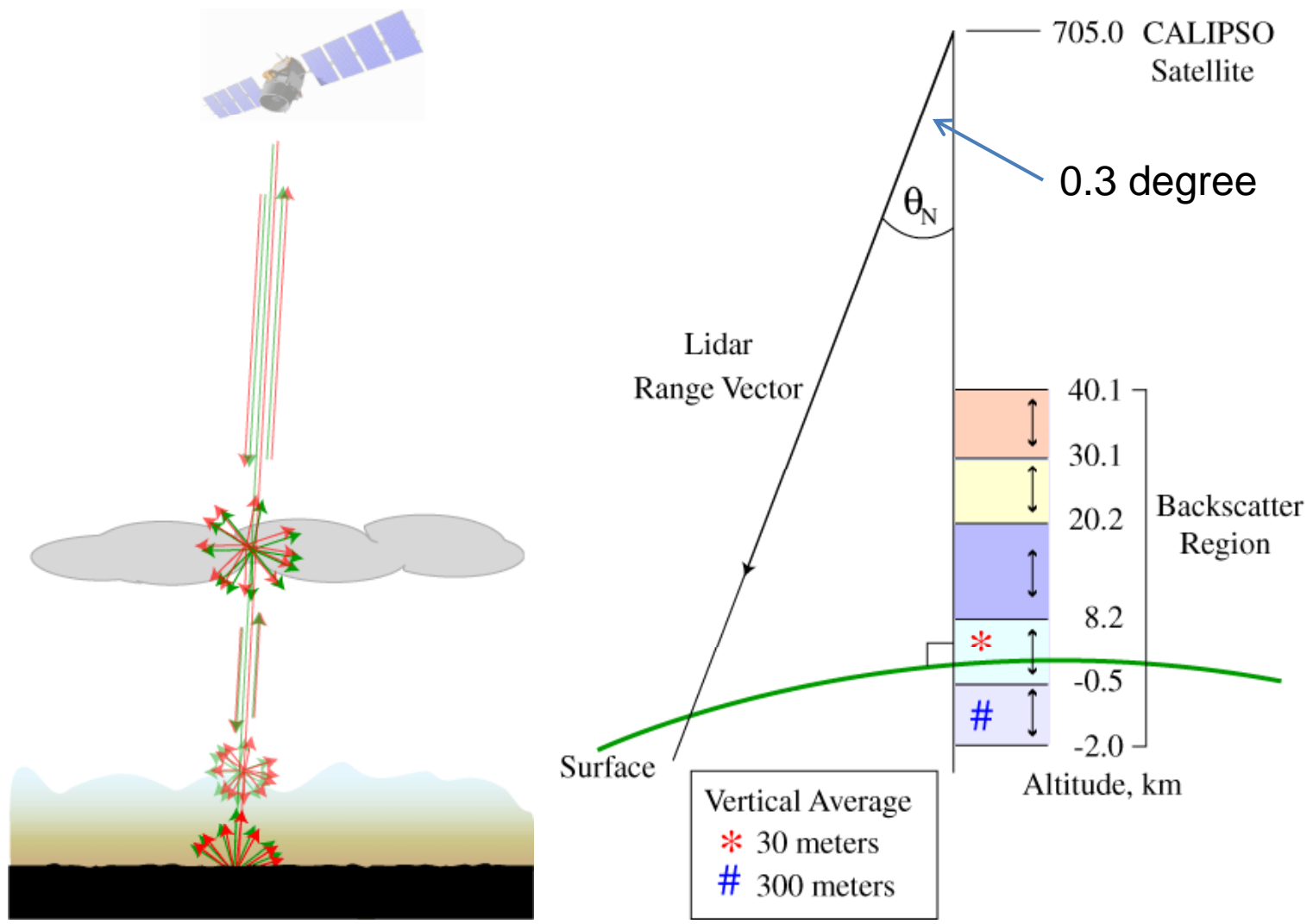
Cloud-Aerosol Lidar with Orthogonal Polarization

Vertical profiles of atmosphere

2 wavelength polarization sensitive lidar:
1064 nm, 532 nm (parallel and perpendicular)



Vertical Profiling of atmosphere, ocean surface and ocean sub-surface



Sea surface wind speed from CALIPSO: introduction

- The signal: ocean surface lidar backscatter signal from specular reflection
- The physics:
 - higher wind → rougher surface → lower backscatter
 - (nadir pointing laser;
 - 2% sea surface reflection at 1064nm wavelength;
 - higher probability of laser beam normal to sea surface at lower wind speed, thus more chance of specular return back to the lidar system)

Relation between Sea Surface Lidar Backscatter γ and Wave Slope Variance ($\langle \tan^2\theta \rangle$)

Surface Backscatter $\gamma =$
laser power * atmospheric attenuation * sea surface Fresnel reflectivity

* fraction of the wave slope surfaces captured by the lidar receiver ($\theta=0$)

$$= C * [\sec^4\theta / \langle \tan^2\theta \rangle \exp(- 0.5 \tan^2\theta / \langle \tan^2\theta \rangle)]$$

$$= C / \langle \tan^2\theta \rangle$$



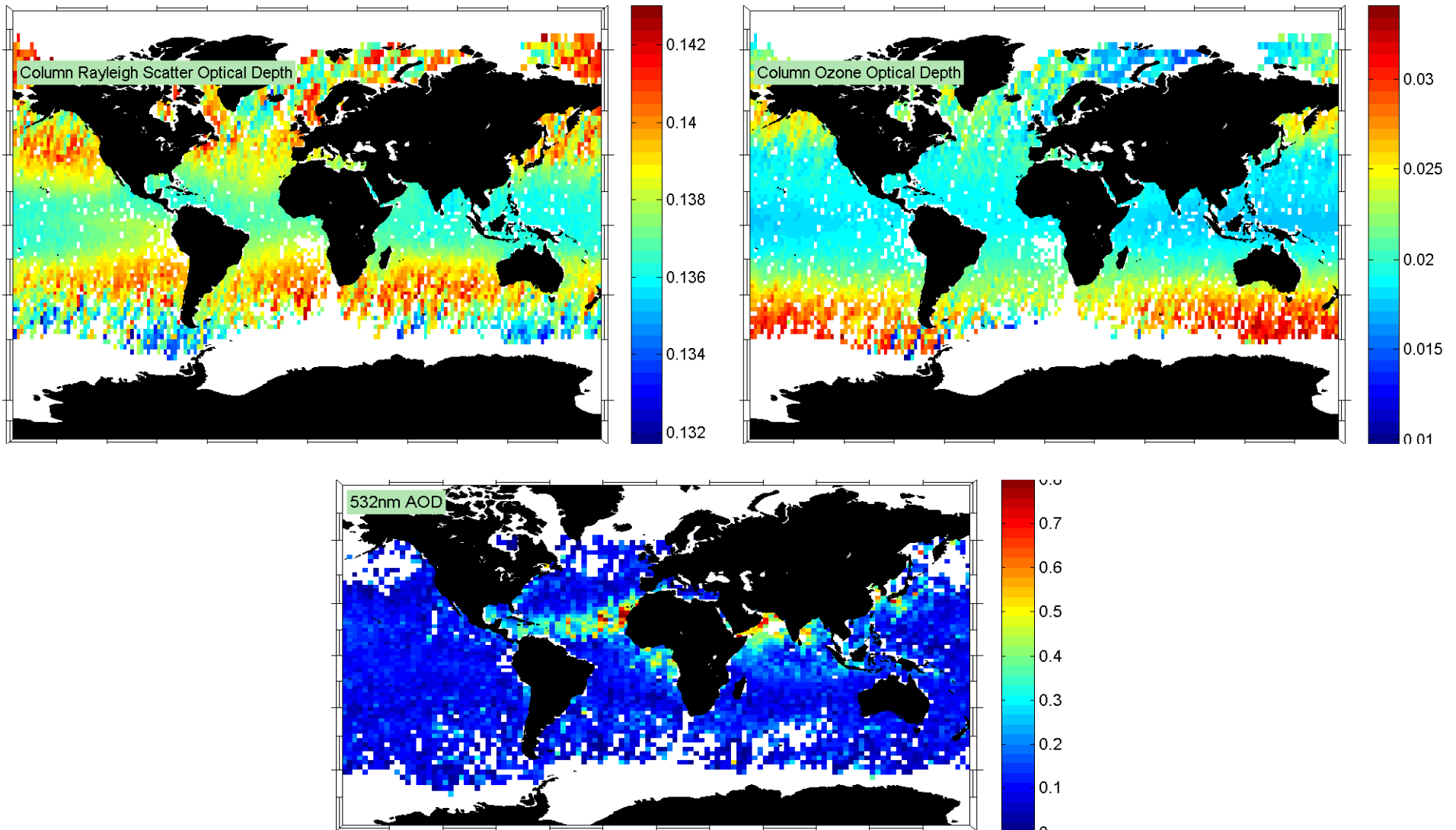
Estimating wave slope variance from CALIPSO: procedures

- Correcting for atmospheric two-way transmittance
- Correcting for backscatter from bubbles, water and particulates in water

Wave slope variance =

$$0.02 / [4\pi \text{ corrected sea surface lidar backscatter}]$$

Estimating wave slope variance from CALIPSO: correction for atmospheric attenuation (molecular scatter, absorption and aerosol/cloud scattering)

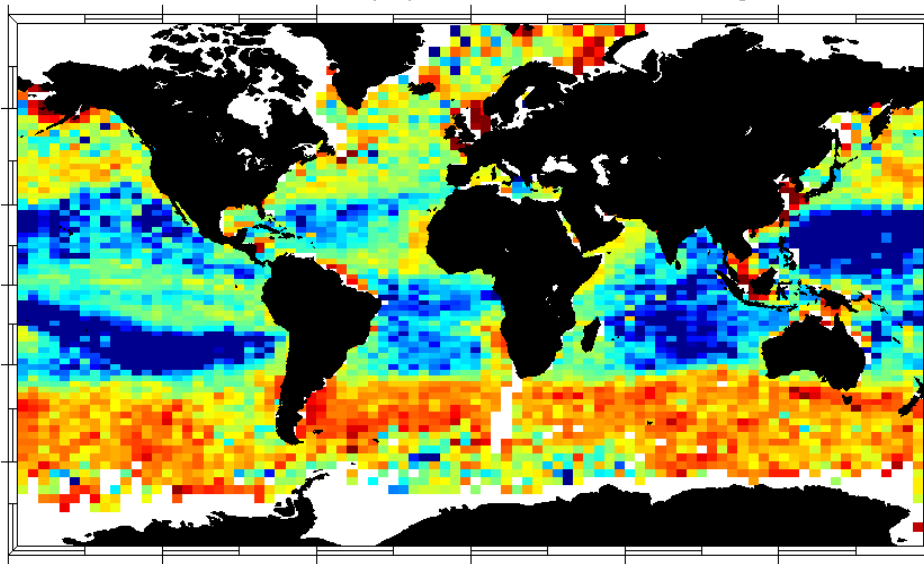


Estimating wave slope variance from CALIPSO: correction for other backscatter (in water particulates and Rayleigh, and Bubbles)

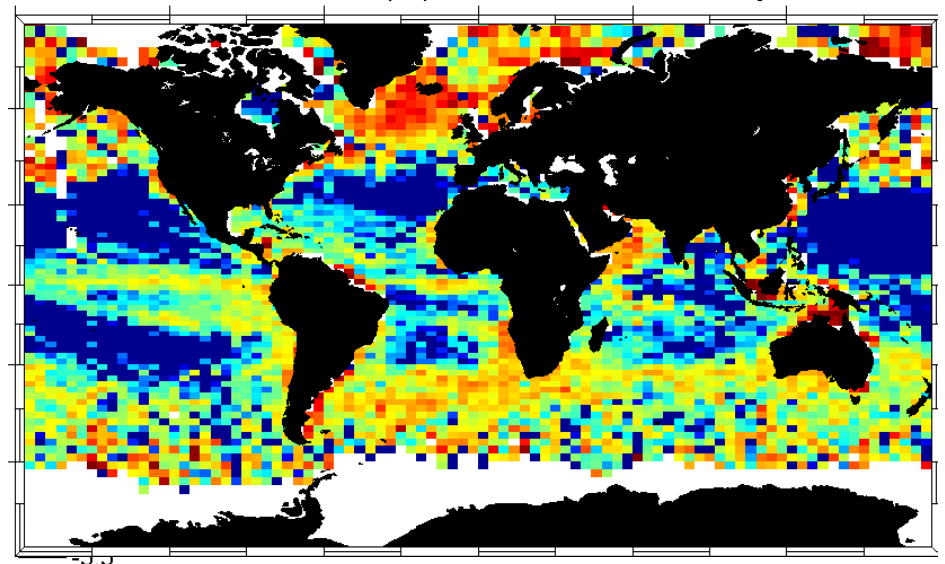
Difference between specular reflection from waves vs other
backscatter: backscatter from waves does not change state of
polarization (cross-polarization backscatter = 0)

A simple algorithm (Hu et al., 2008):
other backscatter = cross-polarization / 0.15

Ocean subsurface perpendicular backscatter: DJF Night



Ocean subsurface perpendicular backscatter: JJA Day

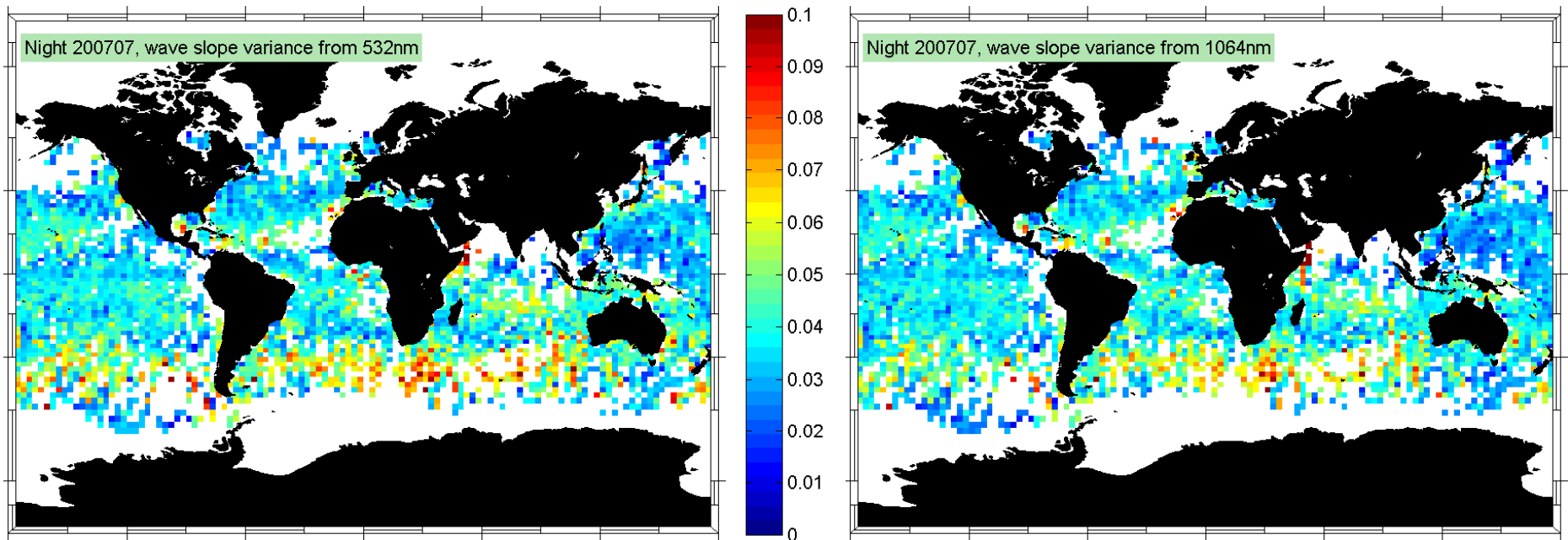


Wave Slope Variance from CALIPSO

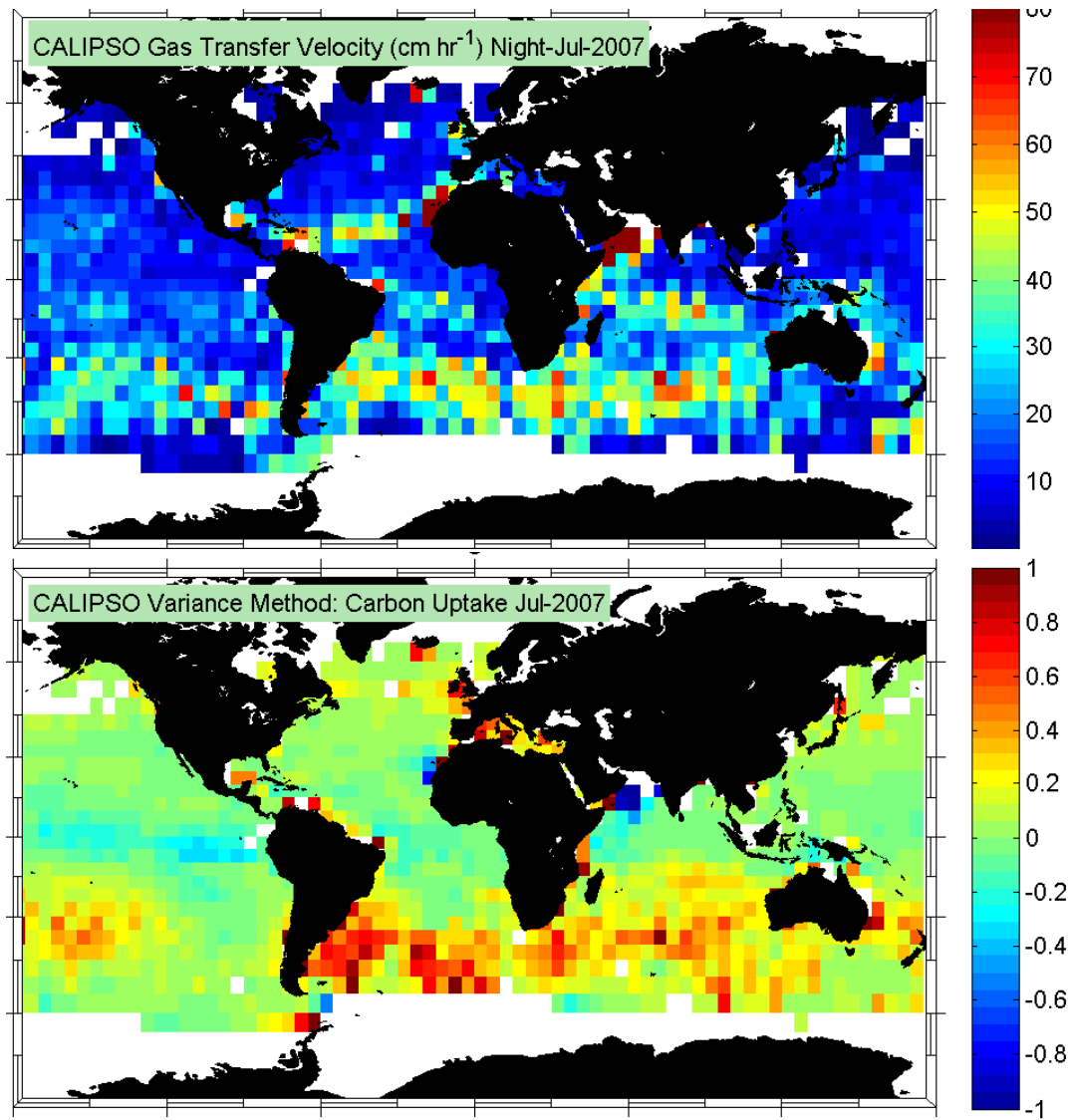
$$\text{Wave slope variance} = 0.02 / [4\pi * \text{sea surface lidar backscatter}]$$

green laser wavelength (left);

Infrared laser wavelength (right)



Gas transfer velocity and carbon uptake from CALIPSO wave slope variance measurements

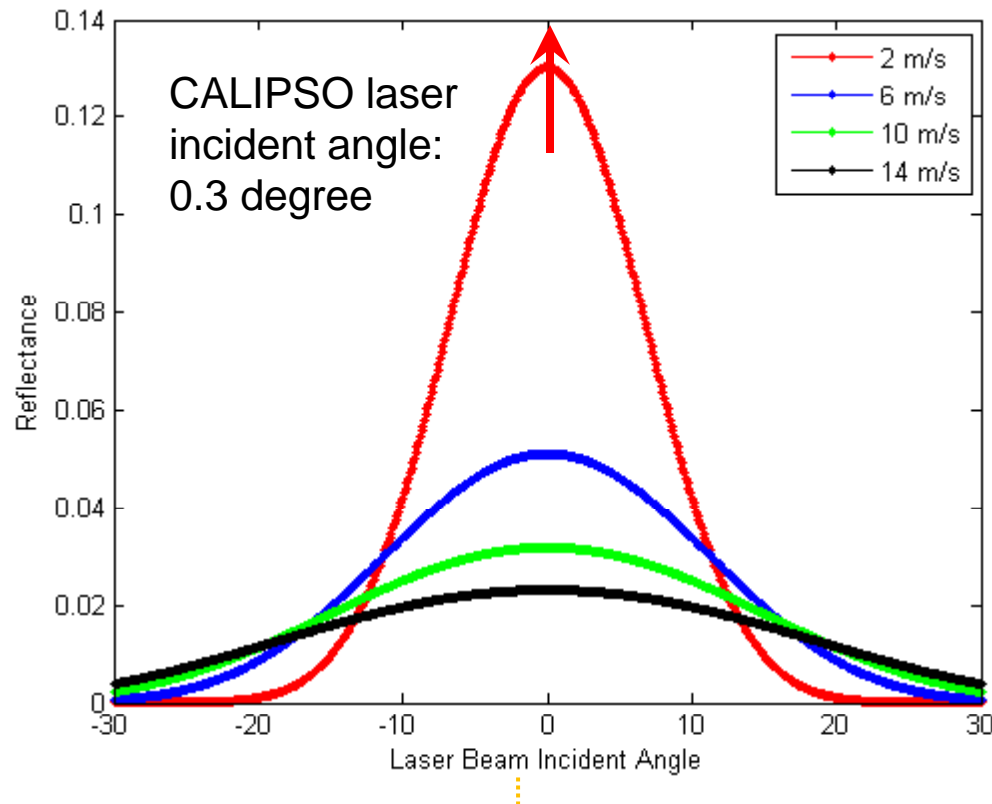


near surface wind speed from CALIPSO lidar backscatter

Sea surface lidar backscatter (after a few corrections) = $c / \langle s^2 \rangle$

Linear relation between wind speed and wave slope variance $\langle s^2 \rangle$ (Cox-Munk):

$$\text{Lidar backscatter} = c / (a + b * \text{wind})$$



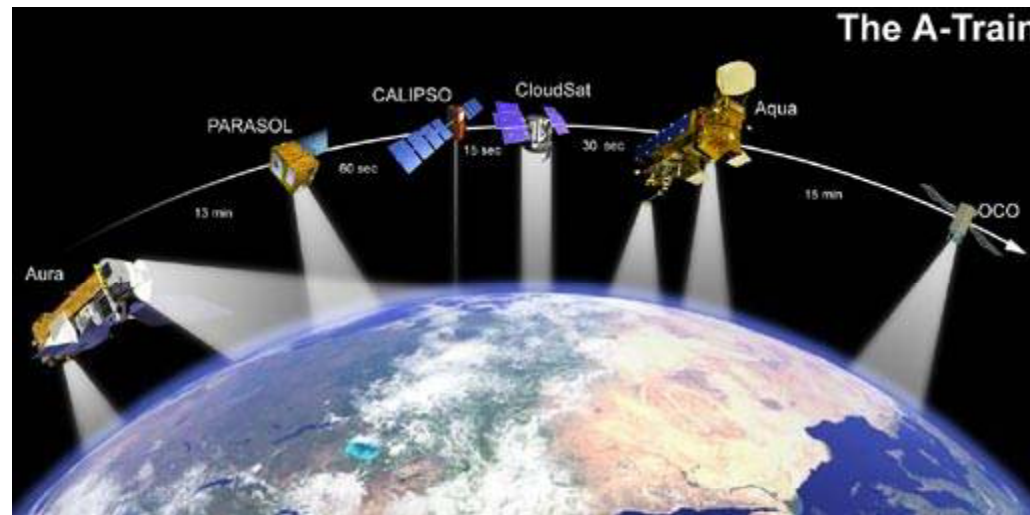
$$P(s)ds = \frac{c}{\langle s^2 \rangle} e^{-\frac{s^2}{2\langle s^2 \rangle}} ds^2$$

$$\langle s^2 \rangle = a * \text{Wind} + b;$$

Verify wave slope variance – wind speed relation Using collocated CALIPSO wave slope and AMSR-E wind measurements

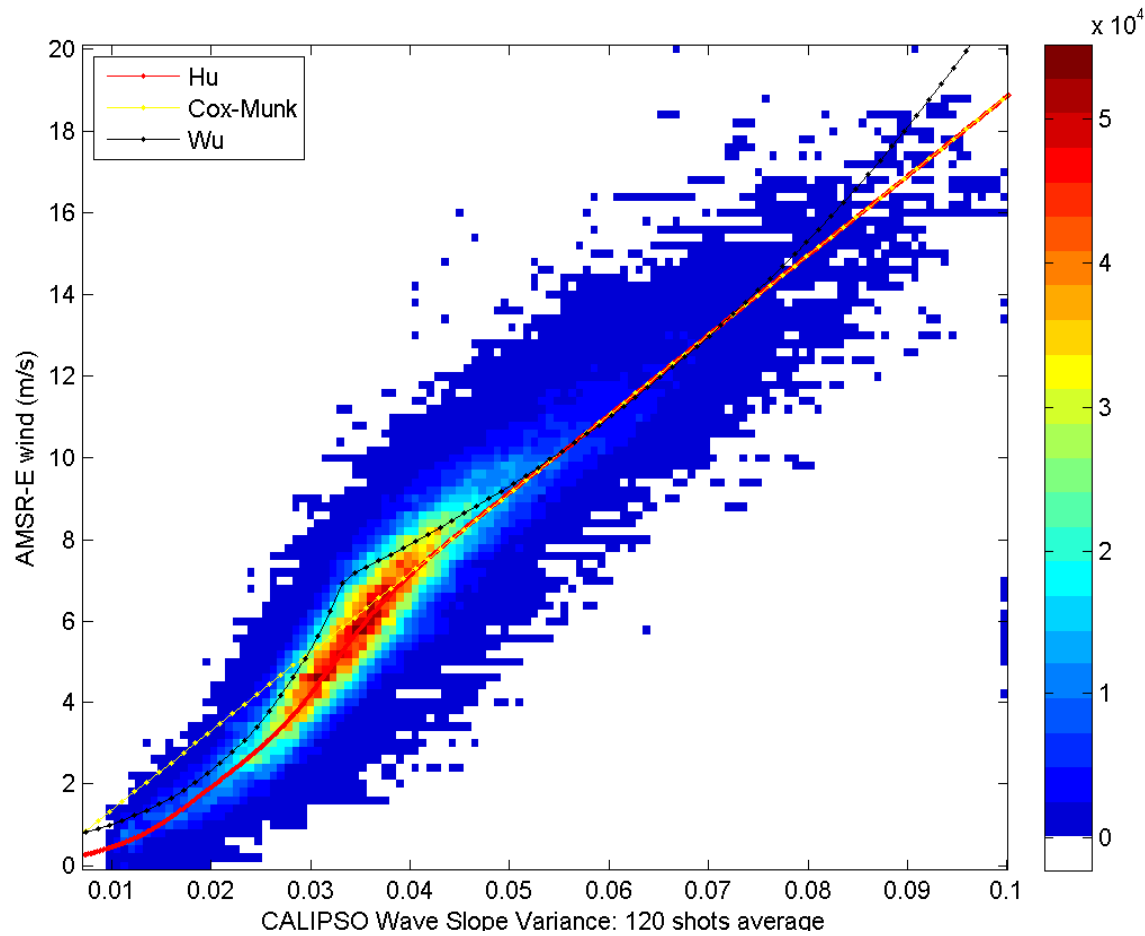
AMSR-E wind speed: derived from AMSR-E instrument (12 microwave channels, 6.92 to 89 GHz), 0.25 X 0.25 degree resolution

AMSR-E is on Aqua satellite: 75 seconds ahead of CALIPSO

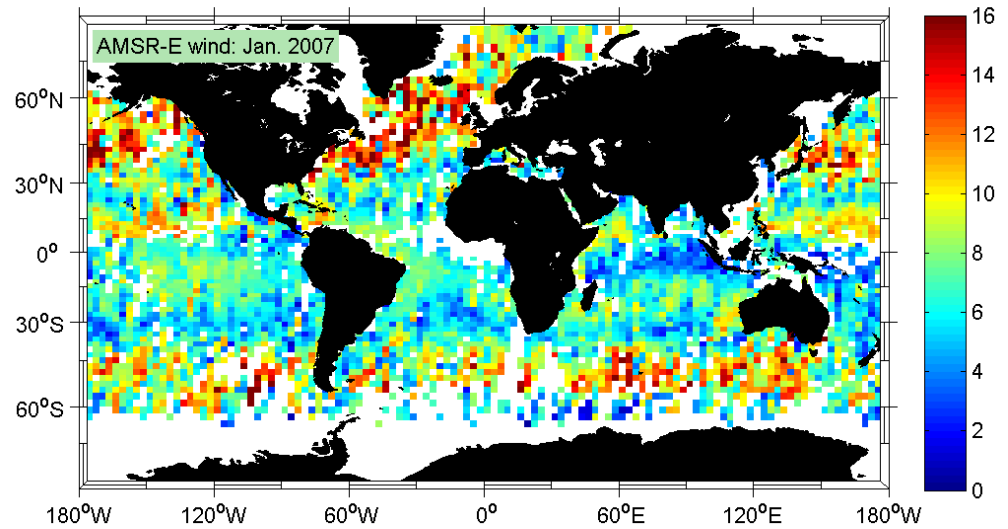
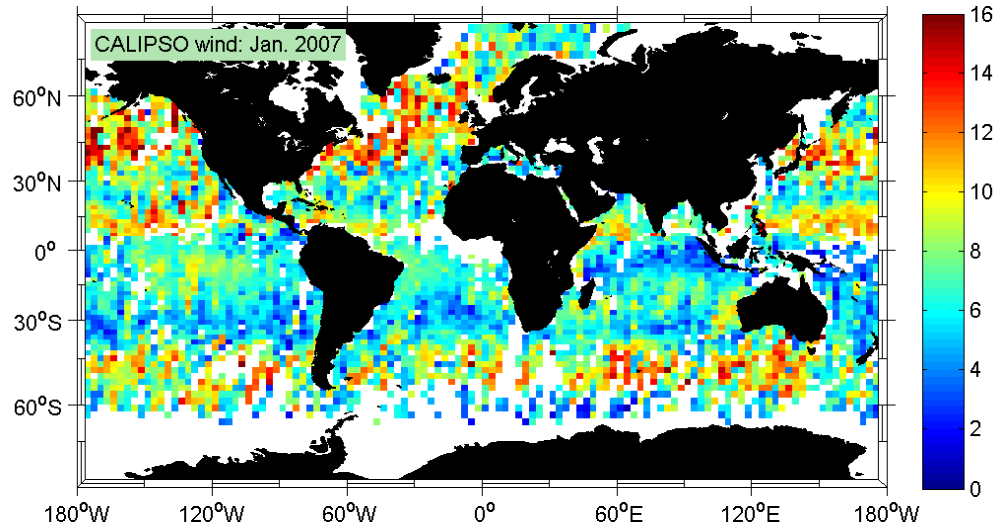


CALIPSO wave slope variance vs AMSR-E wind speed

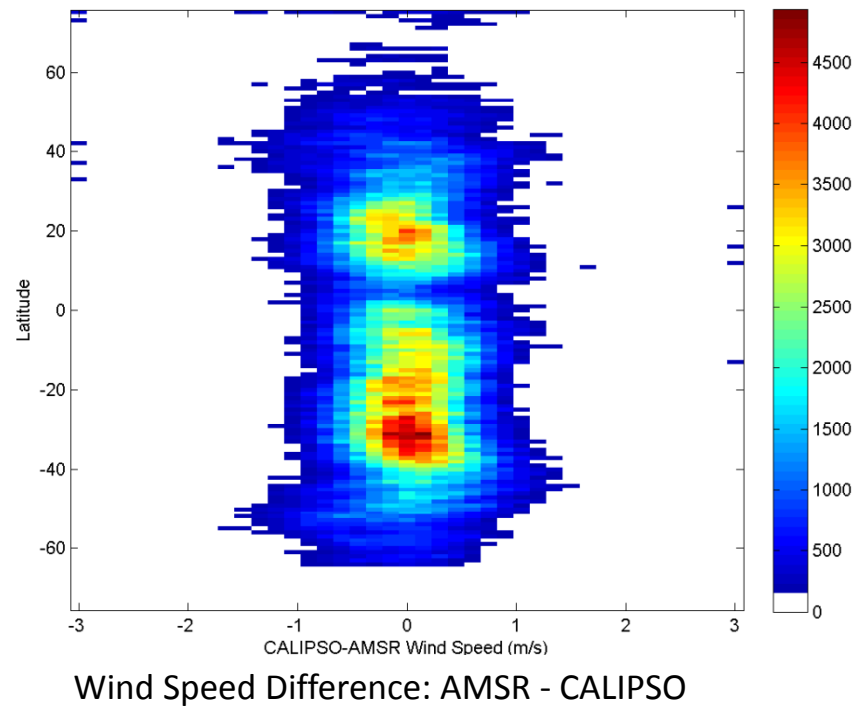
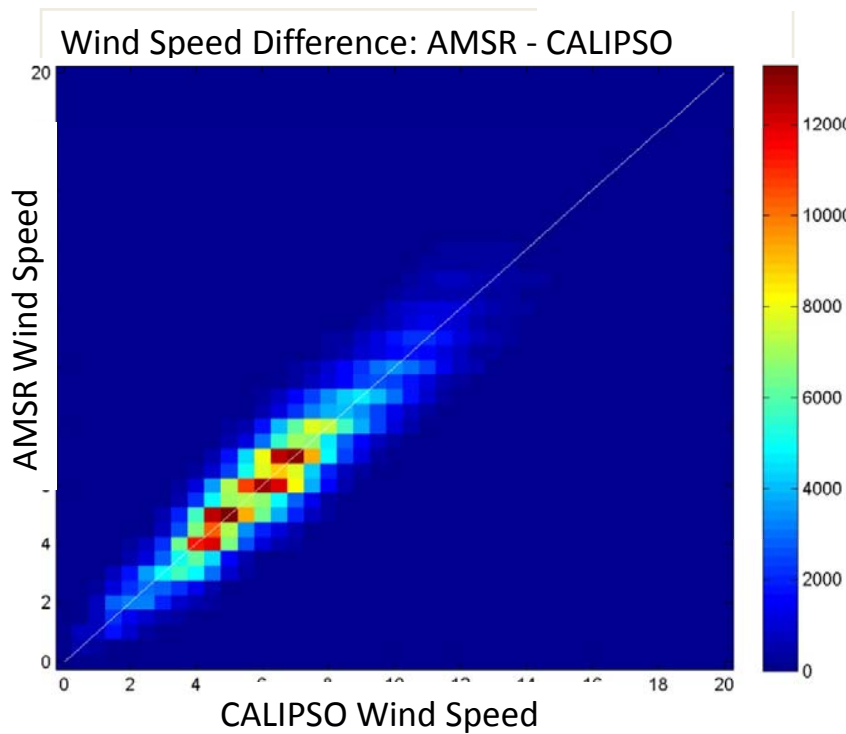
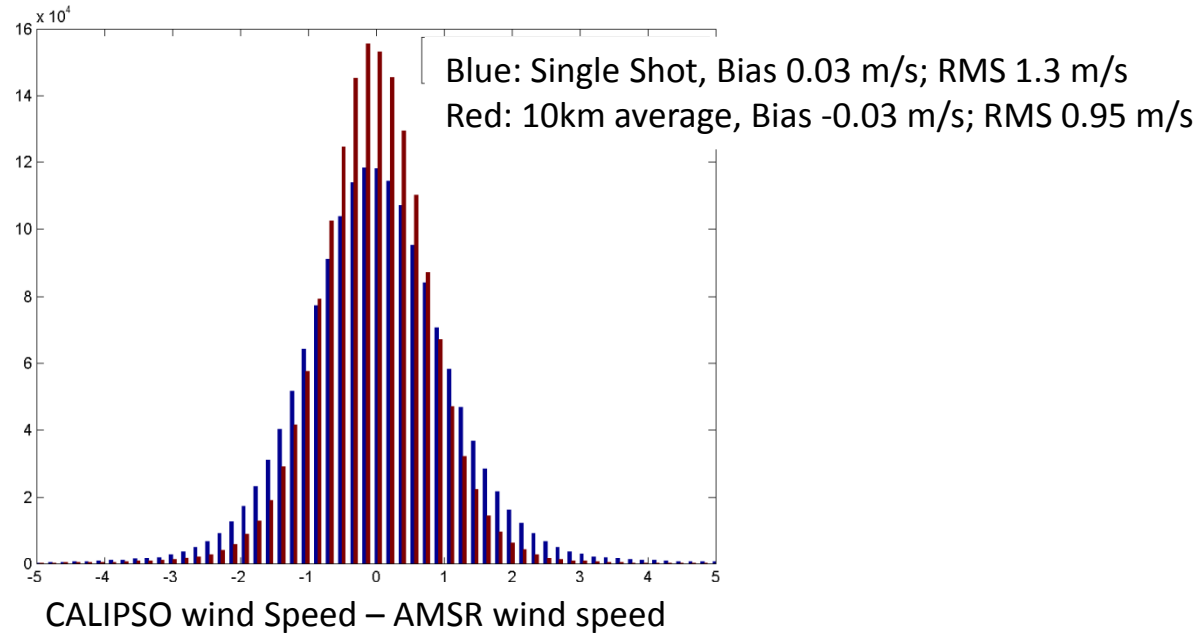
$$\text{'Wave Slope Variance'} = \begin{cases} a V^{0.5} & (V < 7 \text{ m/s}) \\ c V + b & (V > 7 \text{ m/s}) \end{cases}$$



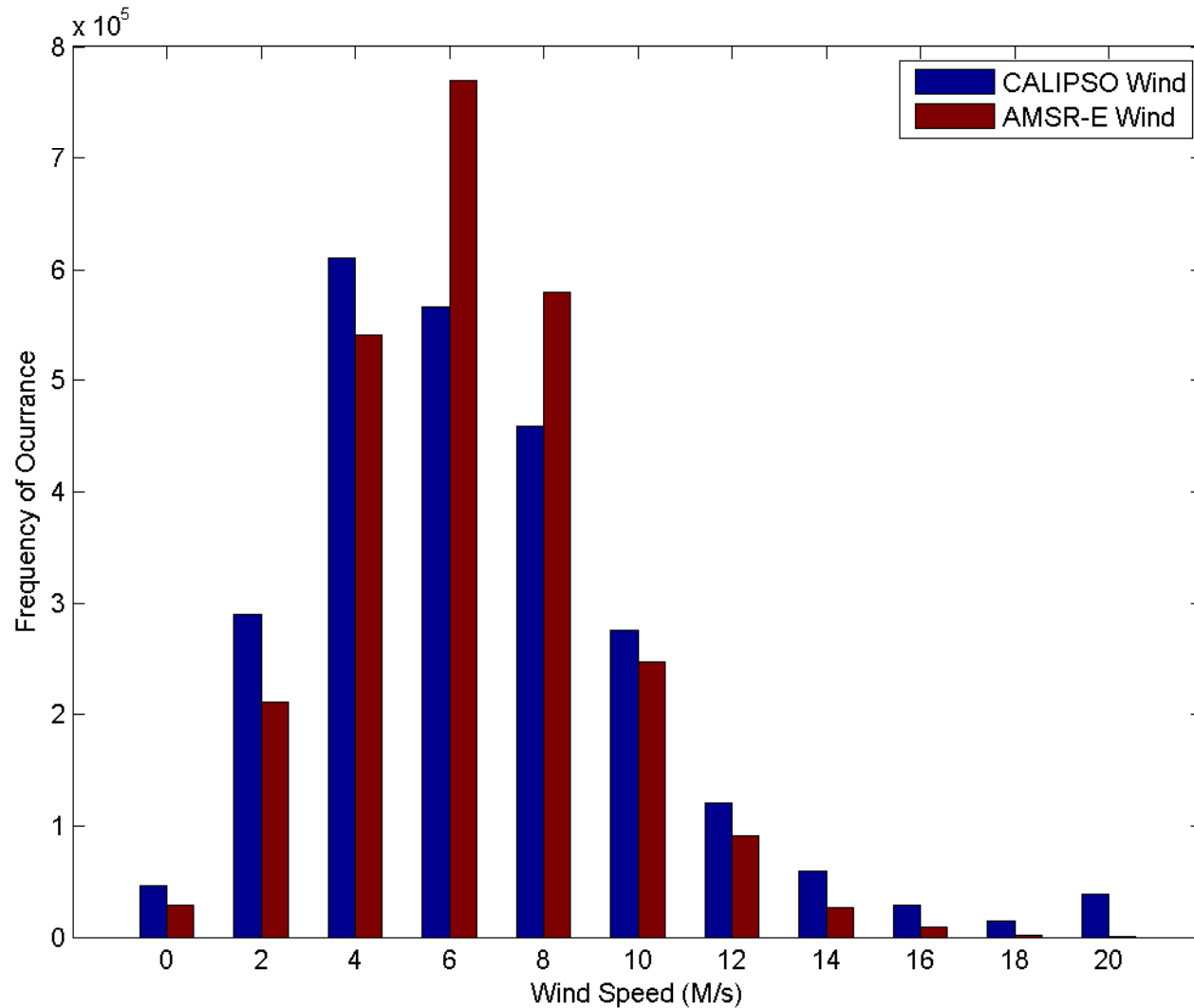
Comparison with CALIPSO wind speed from AMSR-E



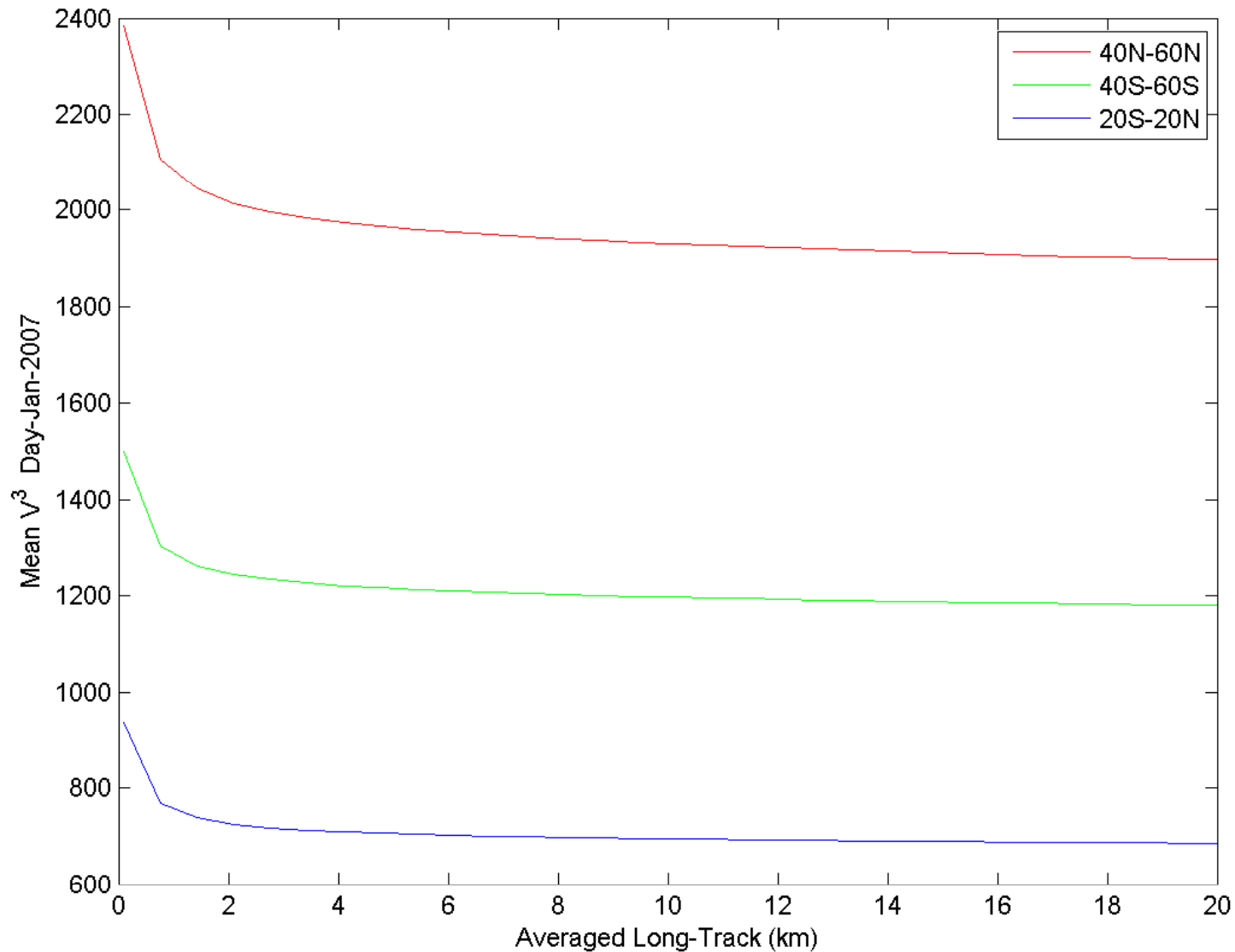
Wind Speed Comparison: CALIPSO vs AMSR-E



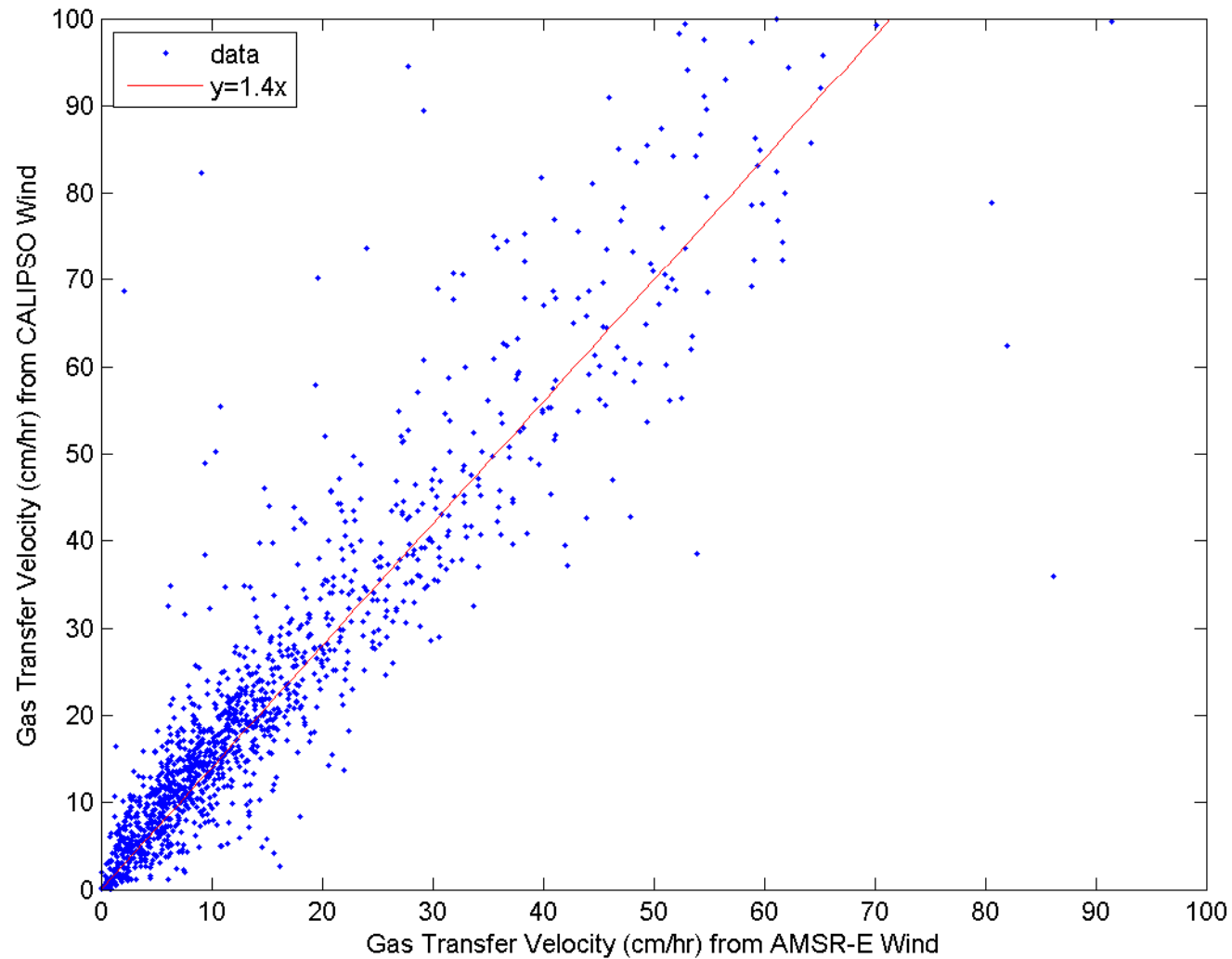
CALIPSO high resolution wind speed: Broader distribution, equal mean value, larger higher order moments



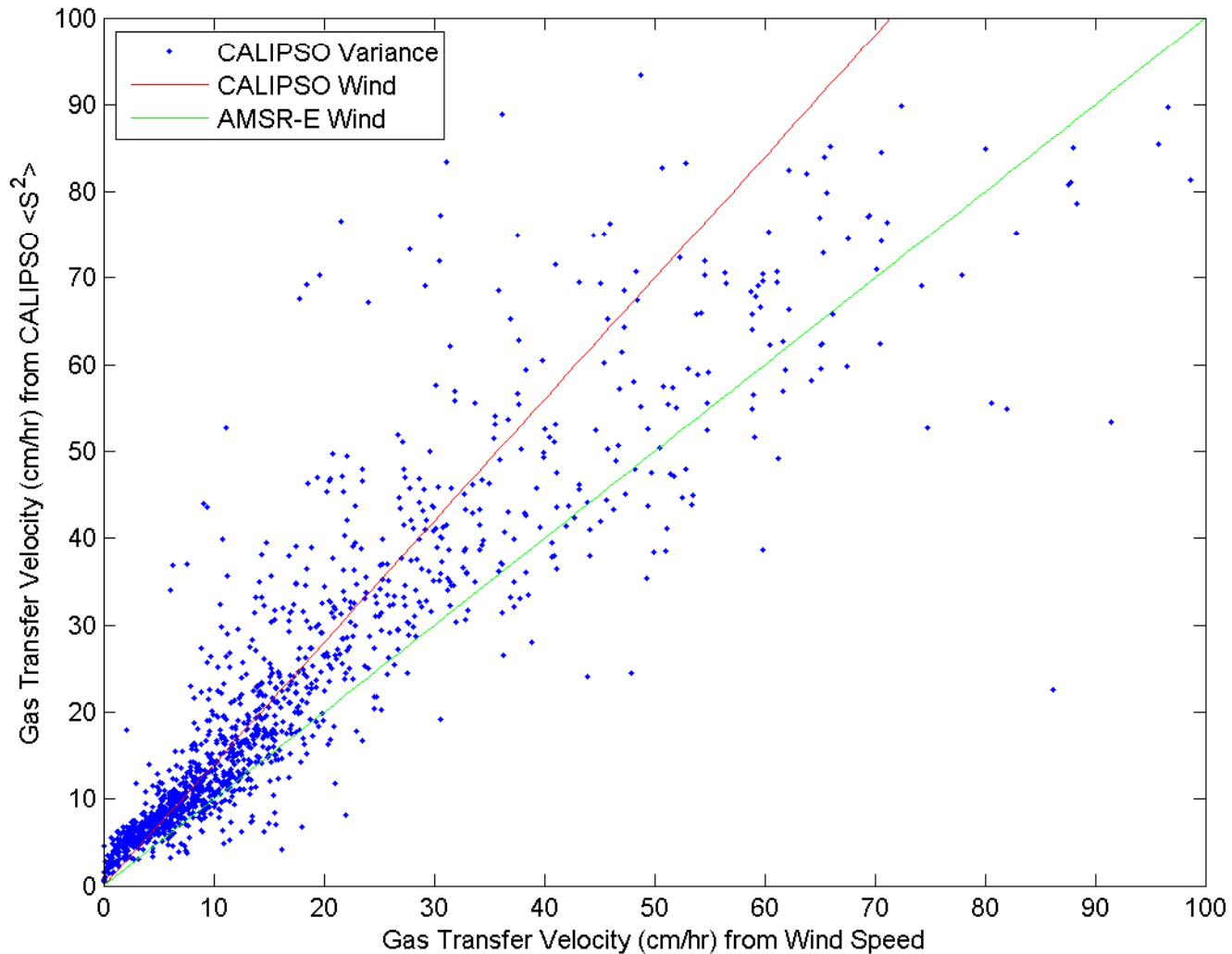
Gas Exchange vs wind speed spatial averaging



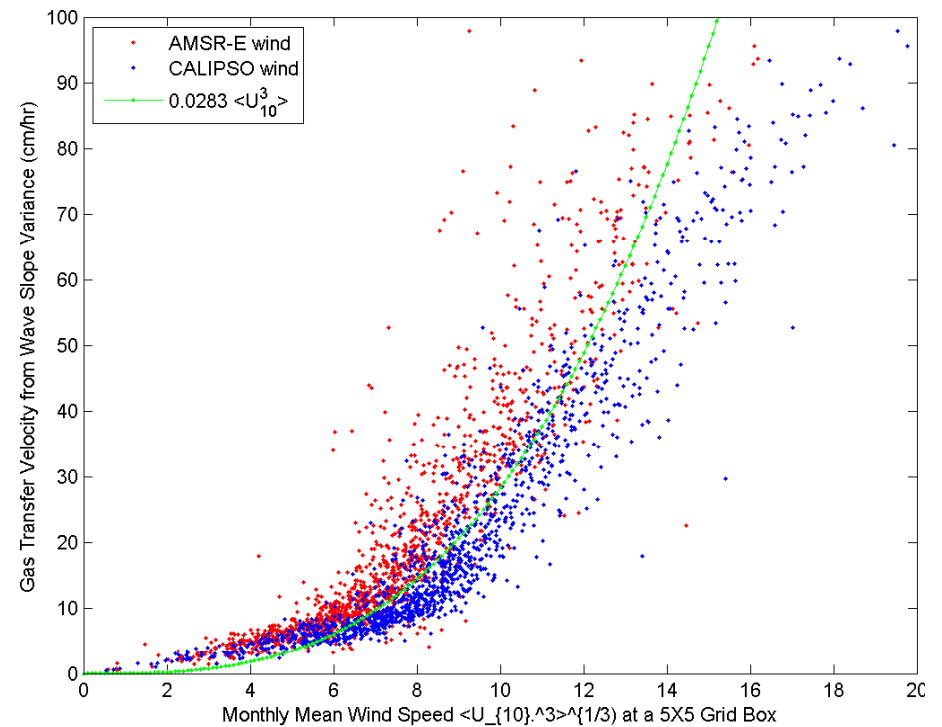
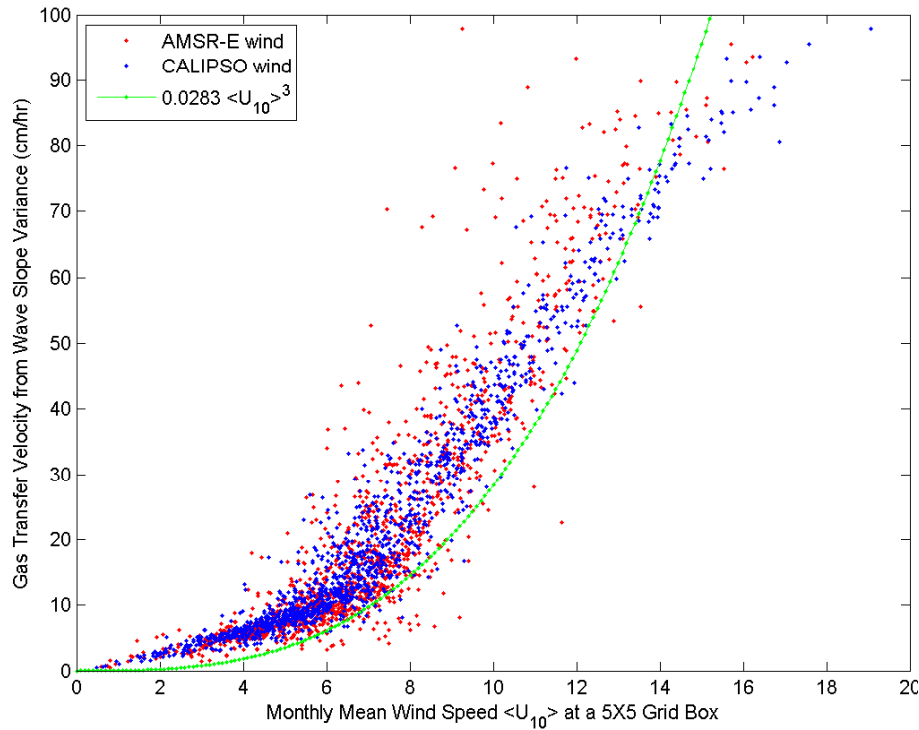
Gas transfer velocity derived from high resolution wind (CALIPSO) is 40% higher than the one from lower resolution wind (AMSR-E)



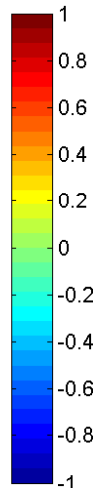
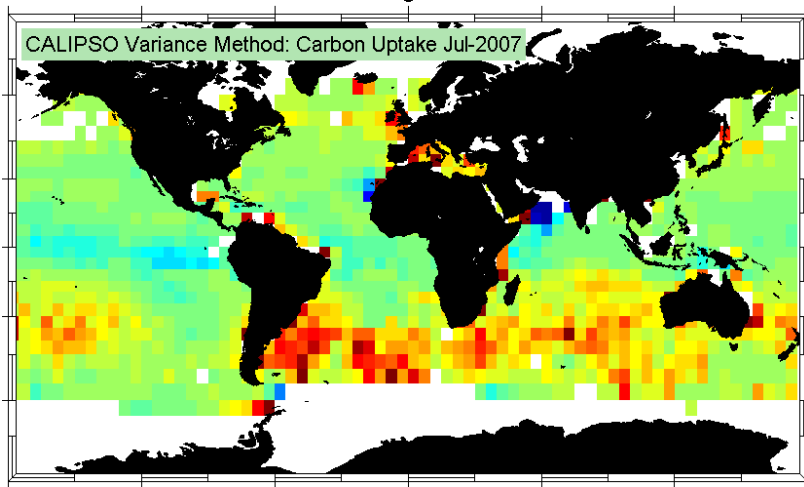
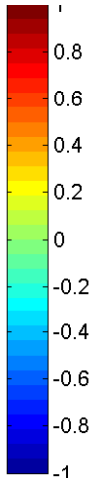
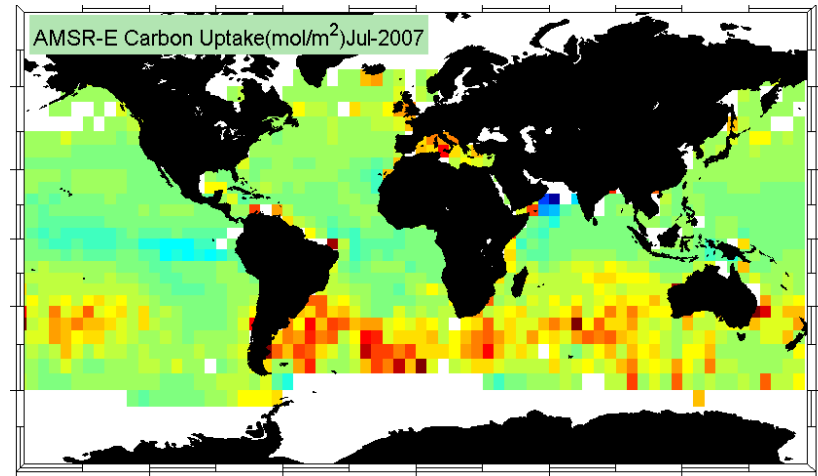
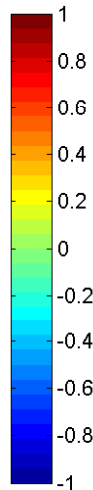
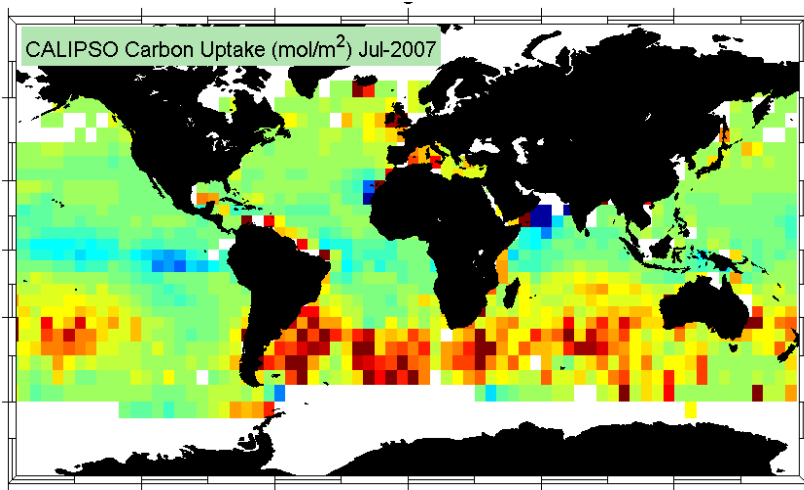
Gas transfer velocity derived from wave slope variance (CALIPSO) agree with the one from higher resolution wind (CALIPSO) better than the one from lower resolution wind (AMSR-E), except at high wind condition



Verifying the cubic short term wind parameterization (Wanninkhof, 1999)



Carbon Uptake Comparison: Wind (CALIPSO), Wind (AMSR) and $\langle S^2 \rangle$ (CALIPSO)



1. Carbon uptake derived from CALIPSO wind is significantly higher than AMSR-E wind;
2. Carbon uptake derived from CALIPSO wave slope variance method is in between

Collaboration?

e.g., Studying empirical relation between wave slope variance and radar backscatter cross section Using combined lidar / radar measurements

Empirical relation between wave slope variance and nadir viewing Ku and C band (Glover et al 2002; Frew et al 2007):

$$\text{Wave slope variance} = 666 \left\{ 3.8/\sigma(\text{ku}) - 4.8/[\sigma(\text{c})+0.5] \right\}$$

1. What is the uncertainty of the empirical relation?
2. How to extend to other Radar viewing geometry?
3. Wave slope variance from CALIPSO vs radar measurements such as CloudSat (94GHz) and SAR (using SAR to remove long wavelength signal from CloudSat)
?
4. Assessment and improvement of variance method at high wind situation
5. Inter-comparison/Validation of CALIPSO high resolution wind data

Summary

1. Wave slope variance (mean square wave slope) correlates with gas transfer velocity better than wind speed and wind stress (Jahne, Hara, Bock, Zappa, Frew, ...)
2. CALIPSO lidar measures wave slope variance of all wavelengths directly, thus provide accurate gas transfer velocity
3. Gas transfer velocity estimated from wave slope variance derived from CALIPSO is compared with the one derived from AMSR-E wind speed
4. High resolution surface wind speed can be estimated from CALIPSO. After averaging, the wind speed agrees well with AMSR-E wind measurements but gas transfer velocity increase by 40%
5. Looking for collaboration (inter-comparison/validation, ...) with your group