Marine carbon observation by satellite remote sensing

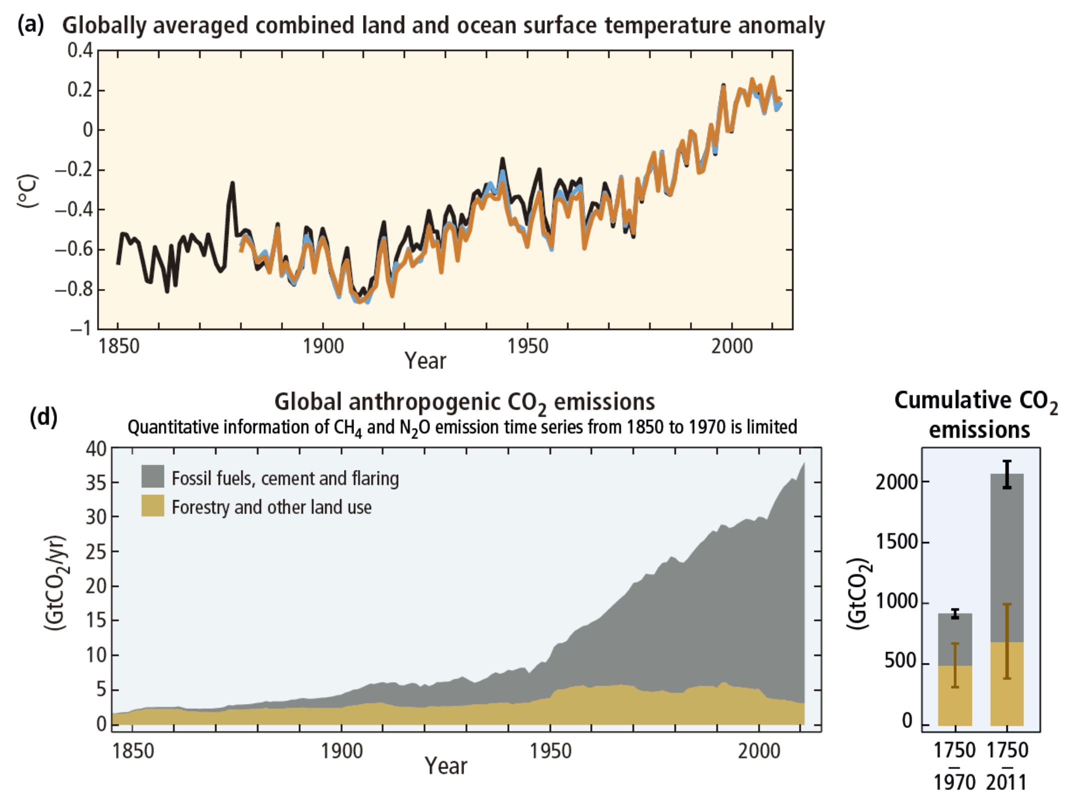
Yan Bai,
Xianqiang He, Xiaoyan Chen, Teng Li, Shujie Yu, Chen-Tung Arthur Chen, Wei-Jun Cai,etc.

State Key Laboratory of
Satellite Ocean Environment Dynamics (SOED)
Second Institute of oceanography(SIO), China

Outline

- **Framework of satellite-based marine carbon research**
- **Inorganic Carbon : pCO_2**
- **Carbon flux estimation**
- **SatCO2-- Satellite-based marine carbon monitoring and analysis system**

CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78 % of the total green house gas (GHG) emission increase from 1970 to 2010 (IPCC, 2014)



The globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85° C over the period 1880 to 2012 (IPCC 2014).

The goal of the Global Carbon Project (GCP) is to develop comprehensive, policy relevant understanding of the global carbon cycle, encompassing its natural and human dimension and their interactions.

Three Science Themes

1. Patterns and variability

What are the current temporal and geographical distributions of the major pools and fluxes in the global carbon cycle?

2. Processes and Interactions

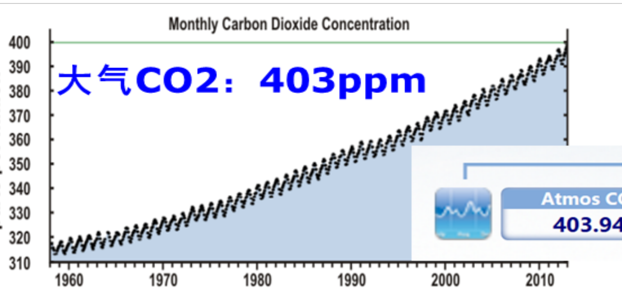
What are the control and feedback mechanisms - both anthropogenic and non-anthropogenic - that determine the dynamics of the carbon cycle?

3. Carbon Management

What are the likely dynamics of the carbon-climate-human system into the future, and what points of intervention and windows of opportunity exist for human societies to manage this system?

GCP Report No. 1

Carbon cycle and Anthropogenic CO2



人为排放CO_2的去处

2017-8-3(CDIAC)

7.9±0.5 GtC/yr（92%）
化石燃料等排放

+

1.0±0.7 GtC/yr（8%）
土地利用变化等排放

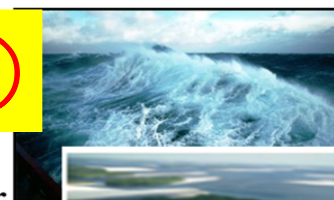
Atmosphere

45%停留在大气
4.1±0.2 GtC/yr

Ocean

27%被海洋吸收
2.9±0.8 GtC/yr

①



Land

27%被陆地吸收
0.9±1.4 GtC/yr
由大气、海洋推算

0.1±0.05 GtC/yr

②

1.0±0.5 GtC/yr

① Air-sea CO2 flux

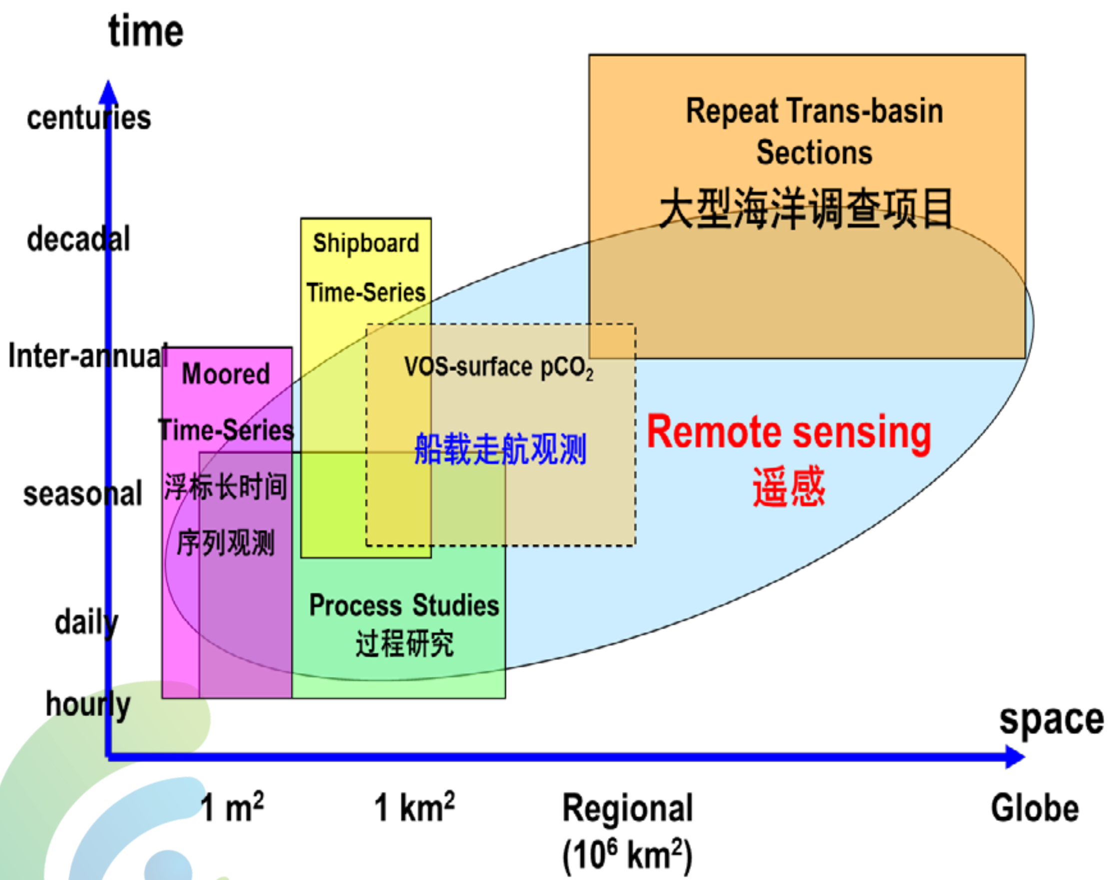
② Riverine flux

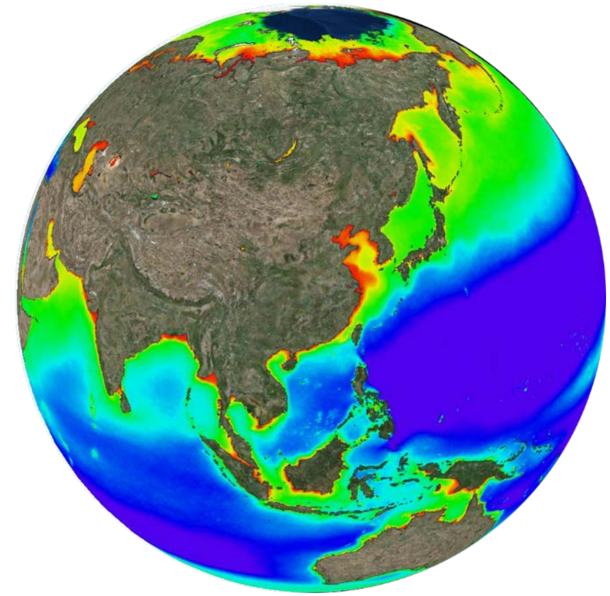
Source: Le Quéré et al 2013; CDIAC Data; Global Carbon Project 2013, Regnier et al. *Nature Geo science, 2013*

Gt=10亿吨

Marine Satellite Remote sensing

SatCO2





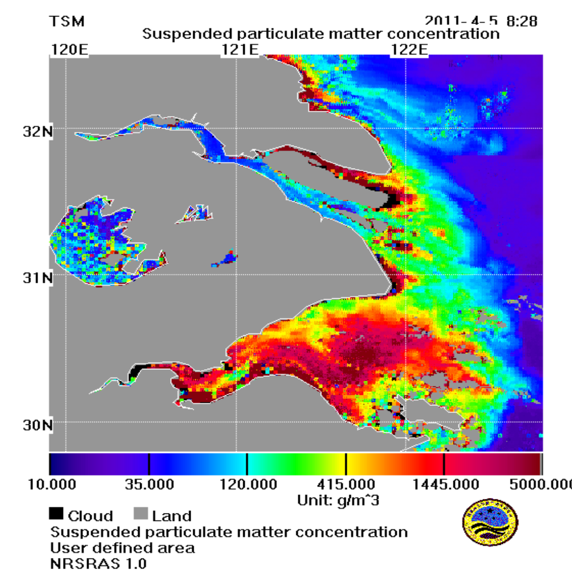
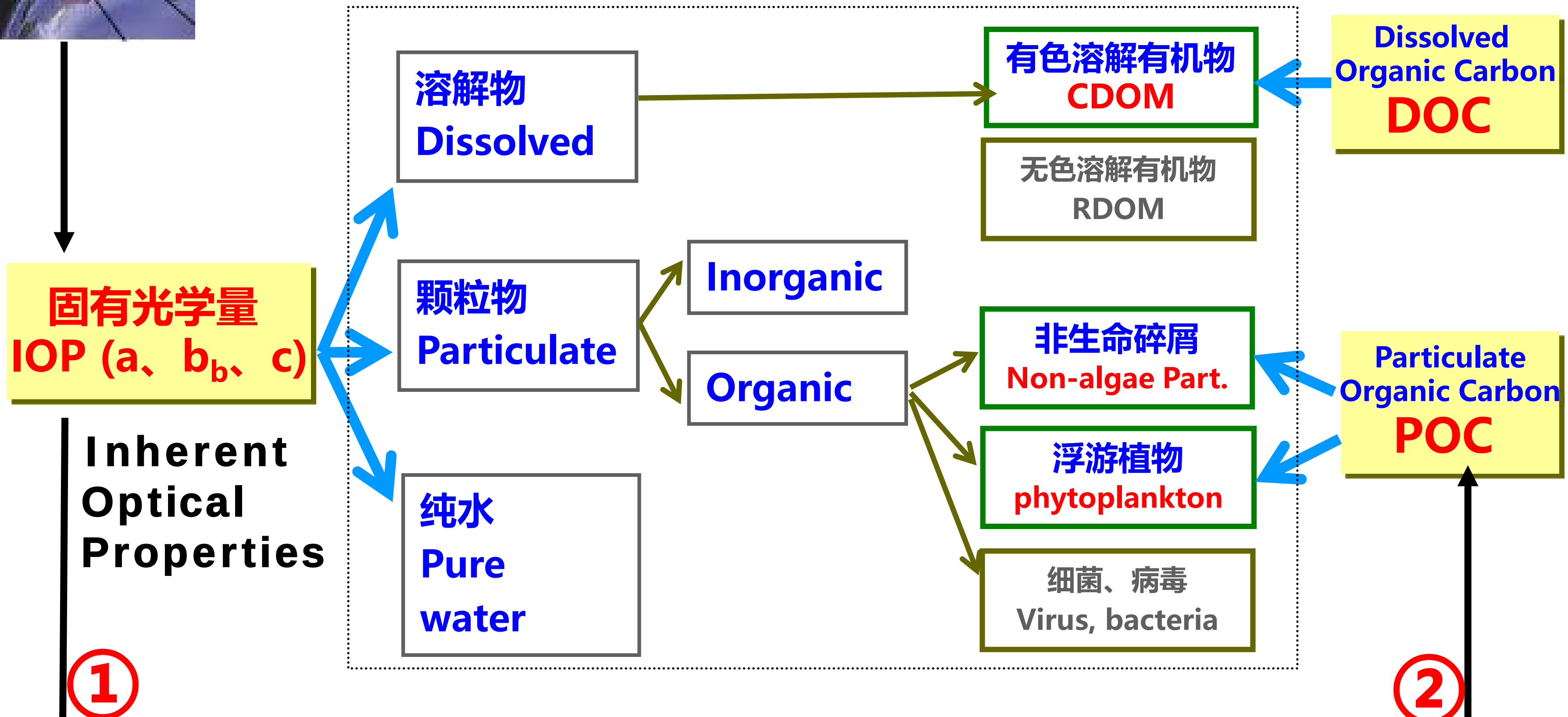
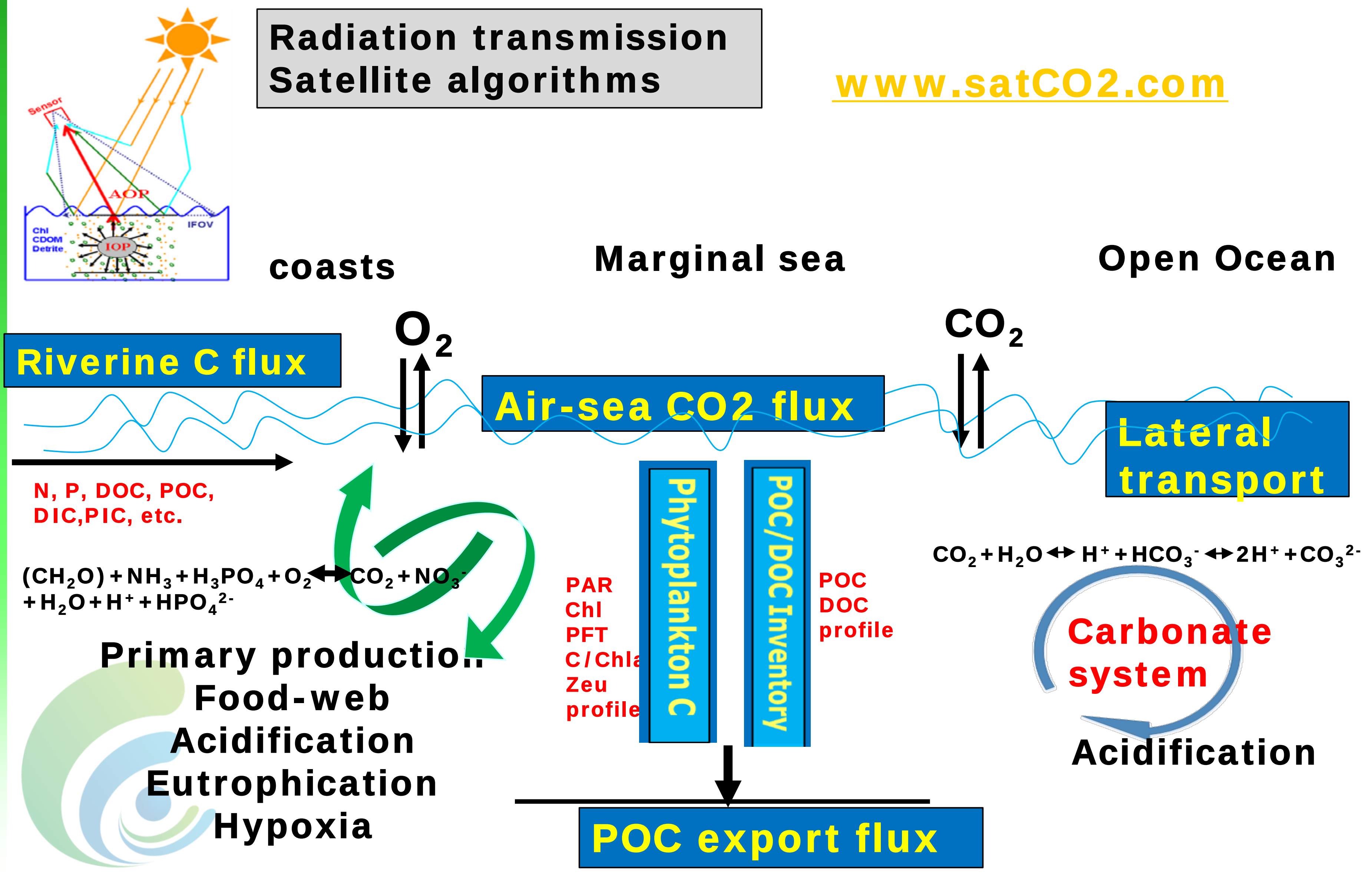


Diagram of inverse radiative transfer elements. Many further parameters are derived from these constituents, such as DOC, POC and productivity. (IOCCG 5, p9)



- absorption $a(\lambda) = a_w(\lambda) + a_{CDOM}(\lambda) + a_{phy}(\lambda) + a_{NAP}(\lambda)$
- backscattering $b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$
- beam attenuation $c(\lambda) = a(\lambda) + b(\lambda)$

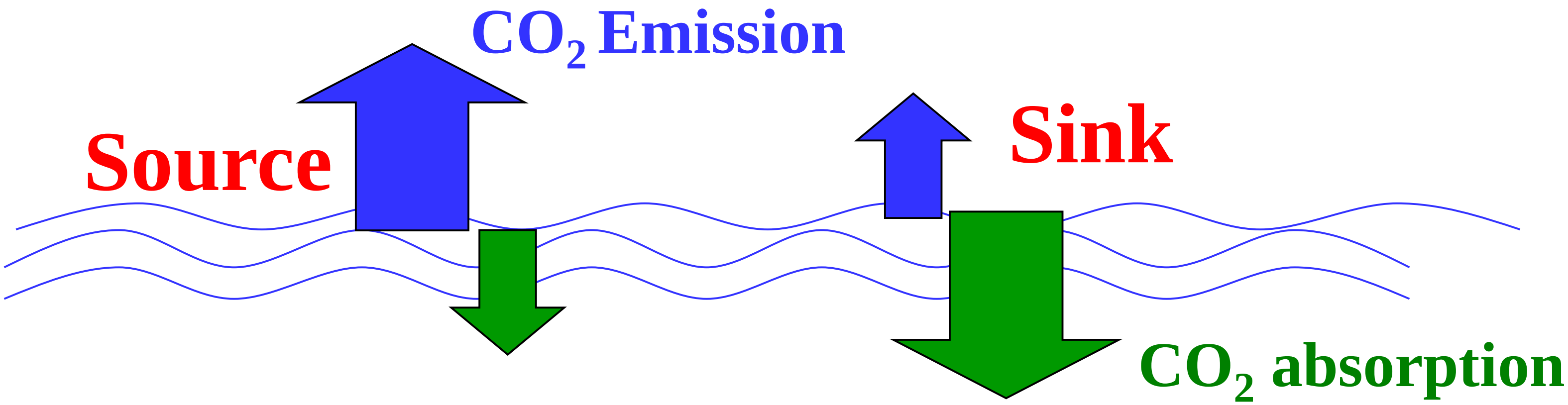
Framework of satellite-based marine carbon research



Outline

- Framework of satellite-based marine carbon research
- Inorganic Carbon : $p\mathrm{CO}_2$
- Carbon flux estimation
- SatCO2-- Satellite-based marine carbon monitoring and analysis system

Estimation of CO_2 flux



Flux = s(solubility) × k (gas transfer velocity) × (pCO_{2sw}-pCO_{2atm})

The equilibrium of gaseous and aqueous CO_2:

$$CO_{2(g)} \leftrightarrow CO_{2(aq)}$$

Subsequent hydration and dissociation reactions:

$$CO_{2(aq)} + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+$$

$$K_1^* = \frac{\{H^+\}[HCO_3^-]}{[CO_2]}$$

$$HCO_3^- \leftrightarrow CO_3^{-2} + H^+$$

$$K_2^* = \frac{\{H^+\}[CO_3^{2-}]}{[HCO_3^-]}$$

Asterisk (*) indicates a "stoichiometric" constant

Marine Carbonate System

Photosynthesis

$106CO_2 + 122H_2O + 16HNO_3 + H_3PO_4$ <-> $(CH_2O)106(NH_3)$ $16H_3PO_4 + 138O_2$

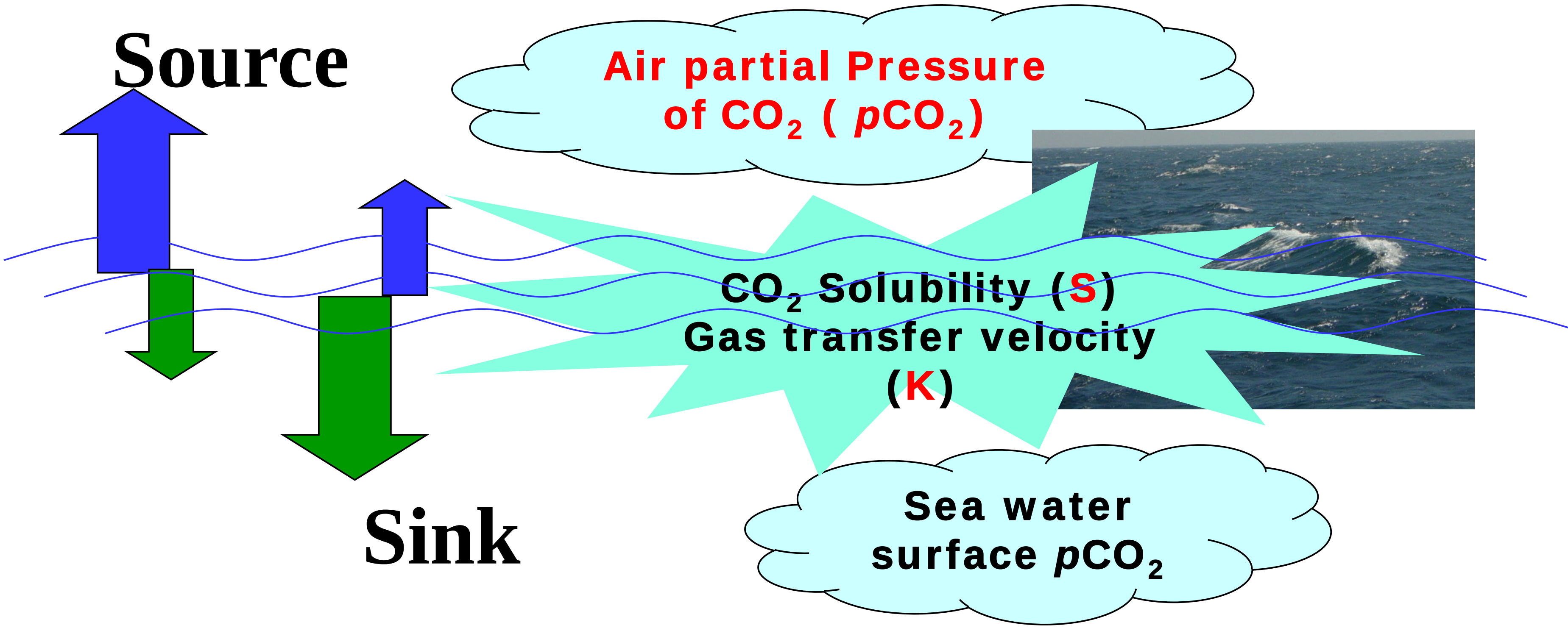
Respiration, Mineralization, etc.

(pCO_2, DIC, pH, TA)

Parameters of the flux calculation

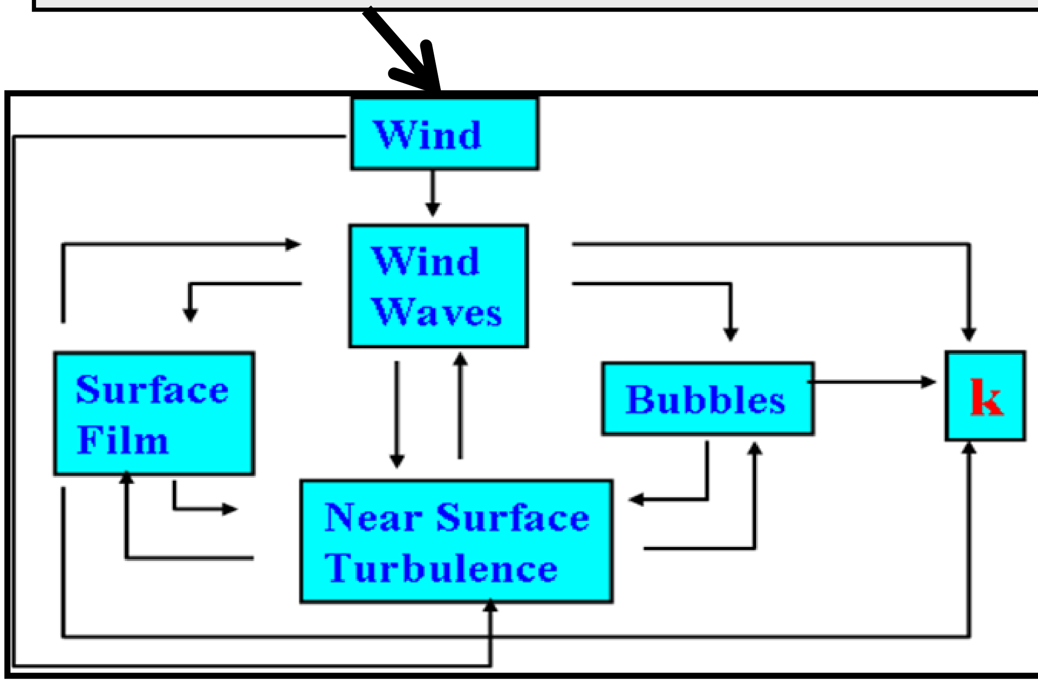
Air-sea CO_2 flux

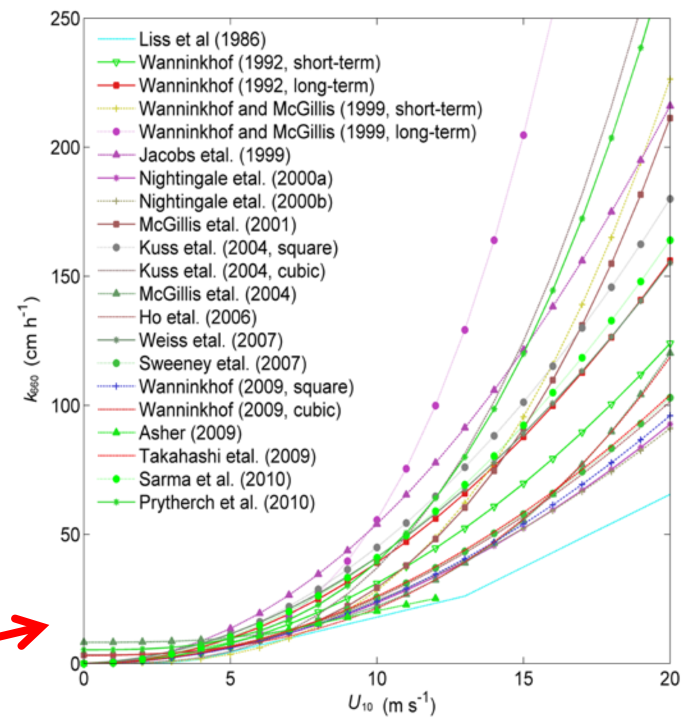
$$F = S \times K \times (pCO_{2sea} - pCO_{2air})$$



CO_2 gas transfer velocity (K)

$$F = S \times K \times (pCO_{2sea} - pCO_{2air})$$





$K = f(u^*)\ Sc^{-n}$

u^* – frictional velocity

Sc – schmit number (v/D)

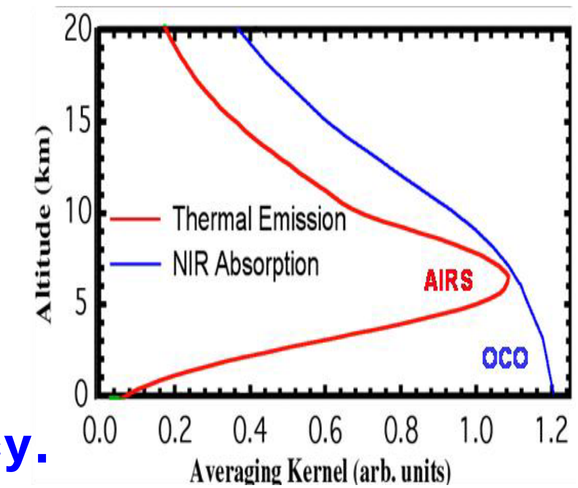
s – solubility

Parameterization of the K with sea wind, wave height, etc. with can obtained from satellite products

e.g. Wanninkhof et al. (2002), Sweeney et al. (2007), Jiang et al. (2008), etc.

Satellite observation of atmosphere CO_2

- **Lidar-can measure CO_2 at bottom layer, low spatial resolution.**
- **Thermal emission- measure CO_2 at middle layer, insensitive to the bottom layer**
- **Reflected Sunlight (NIR CO_2 absorption)- measure CO_2 at whole column, high accuracy.**



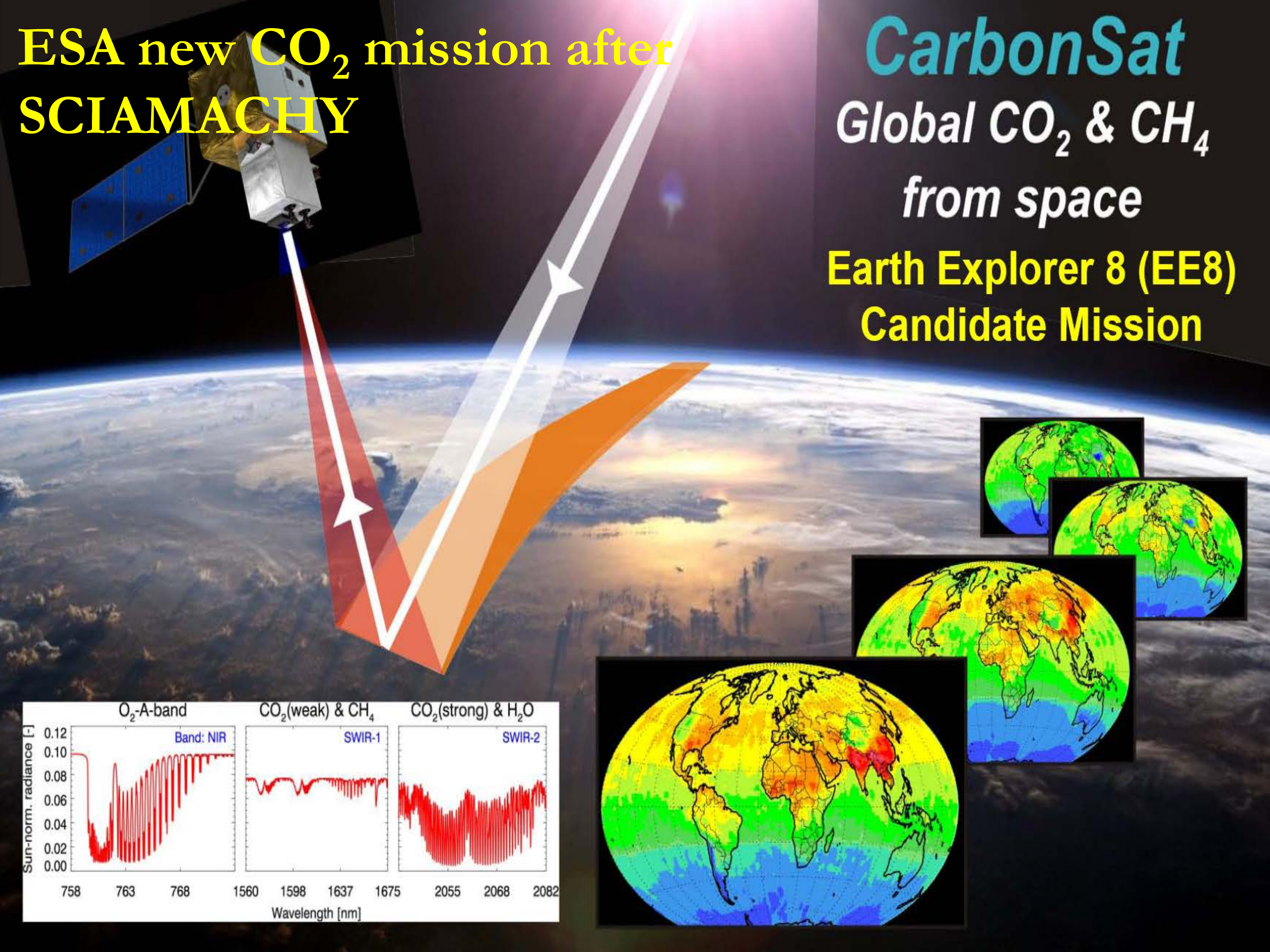
Measurement Method	Instrument	CO_2 Measurement	Measurement Precision	Down-track Sampling
Reflected Sunlight	OCO	Total Column	1 ppm	2.3 km
	SCIAMACHY	Total Column	3-10 ppm	60 km
	GOSAT	Total Column	4 ppm	10.5 km
Thermal Emission	AIRS	Mid-Trop	1 – 2 ppm	45 km
	IASI	Mid-Trop	38 ppm	100 km
	TES	Mid-Trop	~5 ppm	~50 km
Active (LIDAR)	ASCOPE	Lower-trop	2 – 4 ppm	~100 km
	ASCENDS	Lower-trop	2 – 4 ppm	~100 km

OCO—NASA

- **NASA approved the OCO satellite (Orbiting Carbon Observatory) mission in 2002 to monitoring global atmosphere CO_2. Accuracy goal of 0.3~0.5%(1-2ppm). Reflected Sunlight method**
- **OCO was launched on 24 Feb. 2009, but failed.**
- **NASA launched in Jul. 2014 successfully.**

GOSAT-JAXA (Japan)

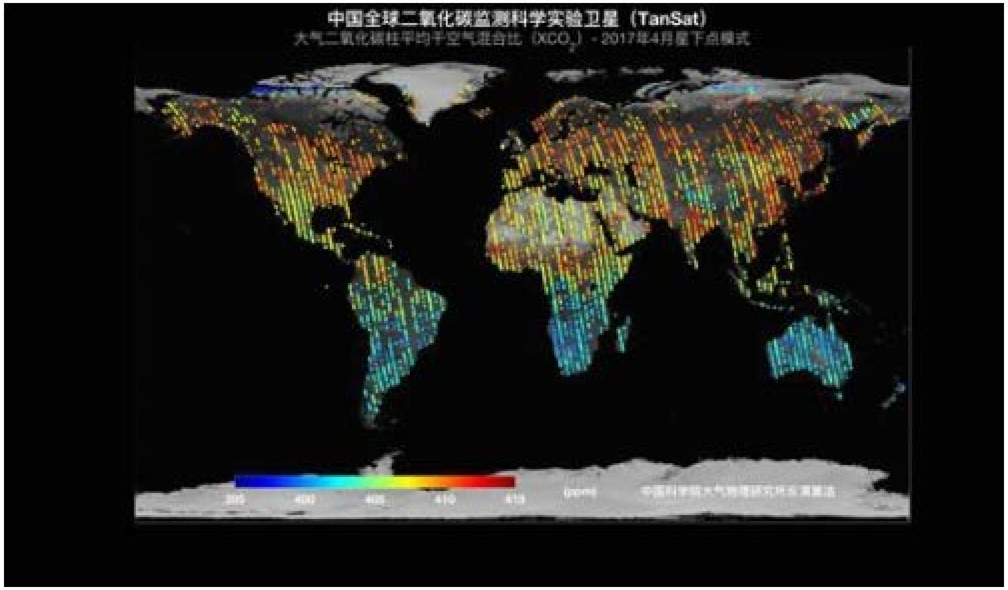
- **GOSAT-Greenhouse Gases Observing Satellite, launched on 23 Jan. 2009. Reflected Sunlight method.**
- **GOSAT-2 was launched in Oct. 29, 2018.**

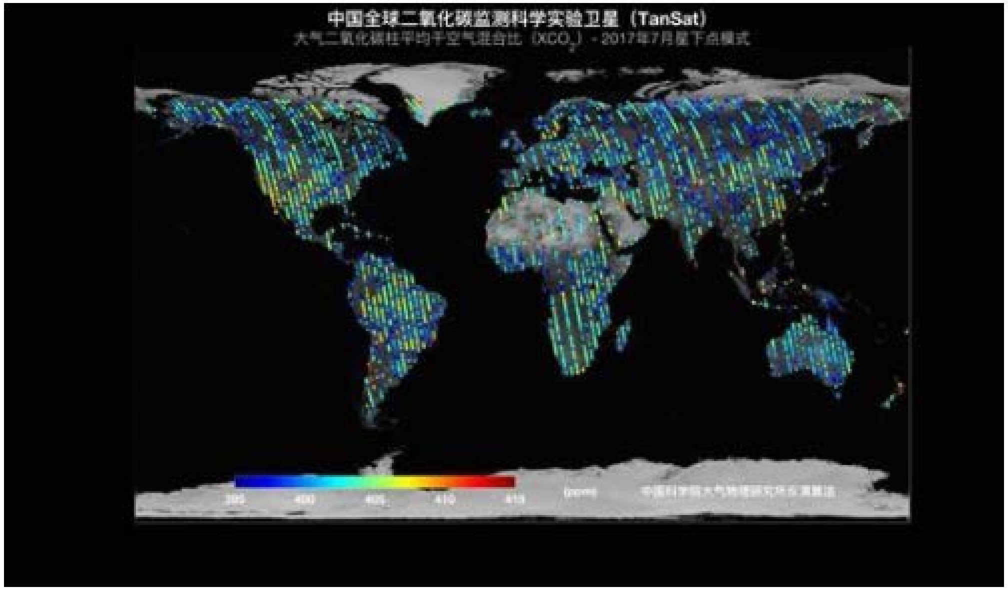


ESA new CO_2 mission after SCIAMACHY
CarbonSat
Global CO_2 & CH_4 from space
Earth Explorer 8 (EE8) Candidate Mission
O_2-A-band
CO_2(weak) & CH_4
CO_2(strong) & H_2O
Band: NIR
SWIR-1
SWIR-2
Sun-norm. radiance [-]
0.12
0.10
0.08
0.06
0.04
0.02
0.00
758
763
768
1560
1598
1637
1675
2055
2068
2082
Wavelength [nm]

Chinese CO_2 satellite mission

- **Scientific experimental satellite. Main payloads include high spectral CO_2 sensor, multiple channel cloud and aerosol.**
- **Launched in 2017. CO_2 measuring accuracy to be 4ppm.**



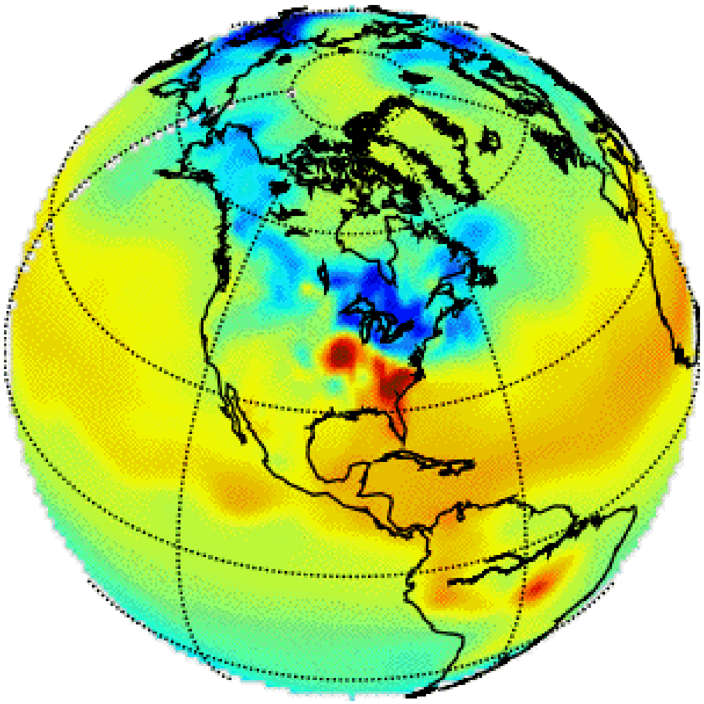


The first global map of atmospheric carbon dioxide in China's carbon satellite, (above) April 2017, (below) July 2017. The color indicates the average dry air mixing ratio (XCO2) of the atmospheric Carbon dioxide column.

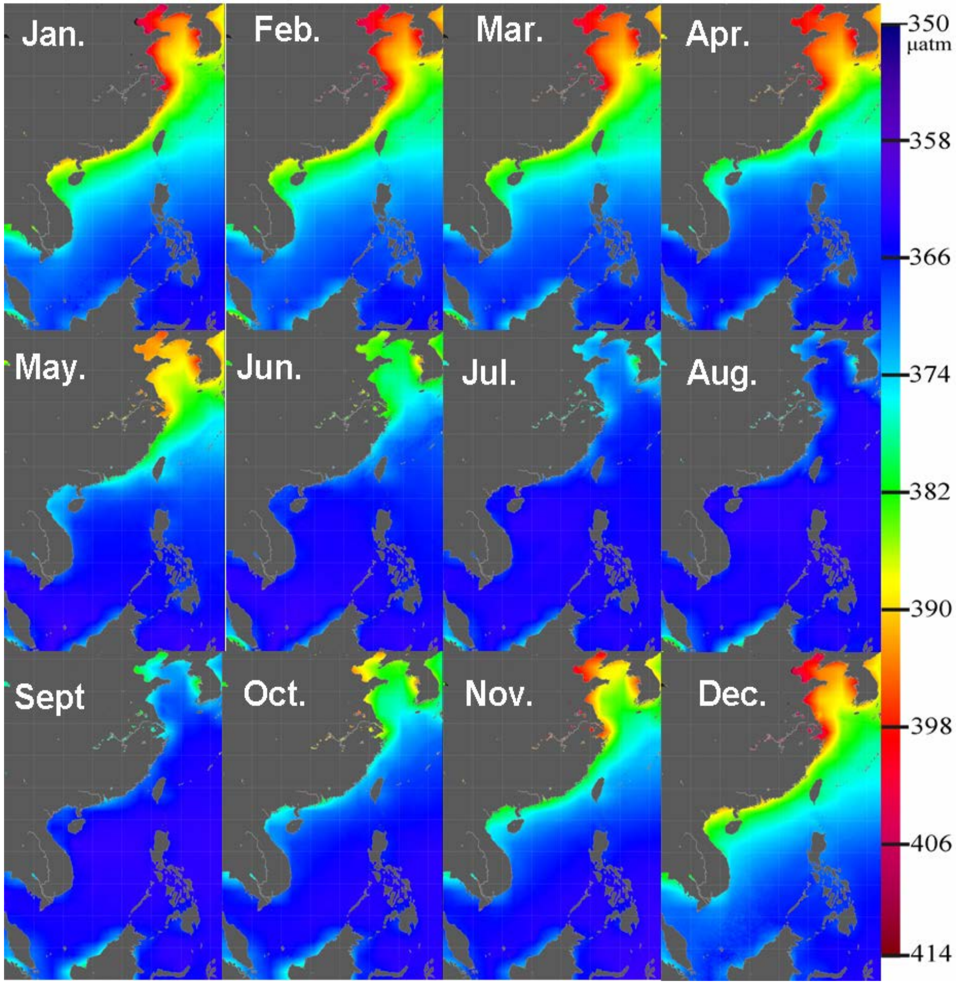
Air CO_2 from the model simulation data

$$pCO_{2atm} = xCO_{2atm} \times (P_{atm} / 1013.25 - pH_2O)$$

- **NOAA/CMDL/Carbon Tracker**
- xCO_{2atm} = CO_2 Dry Air Mole Fraction



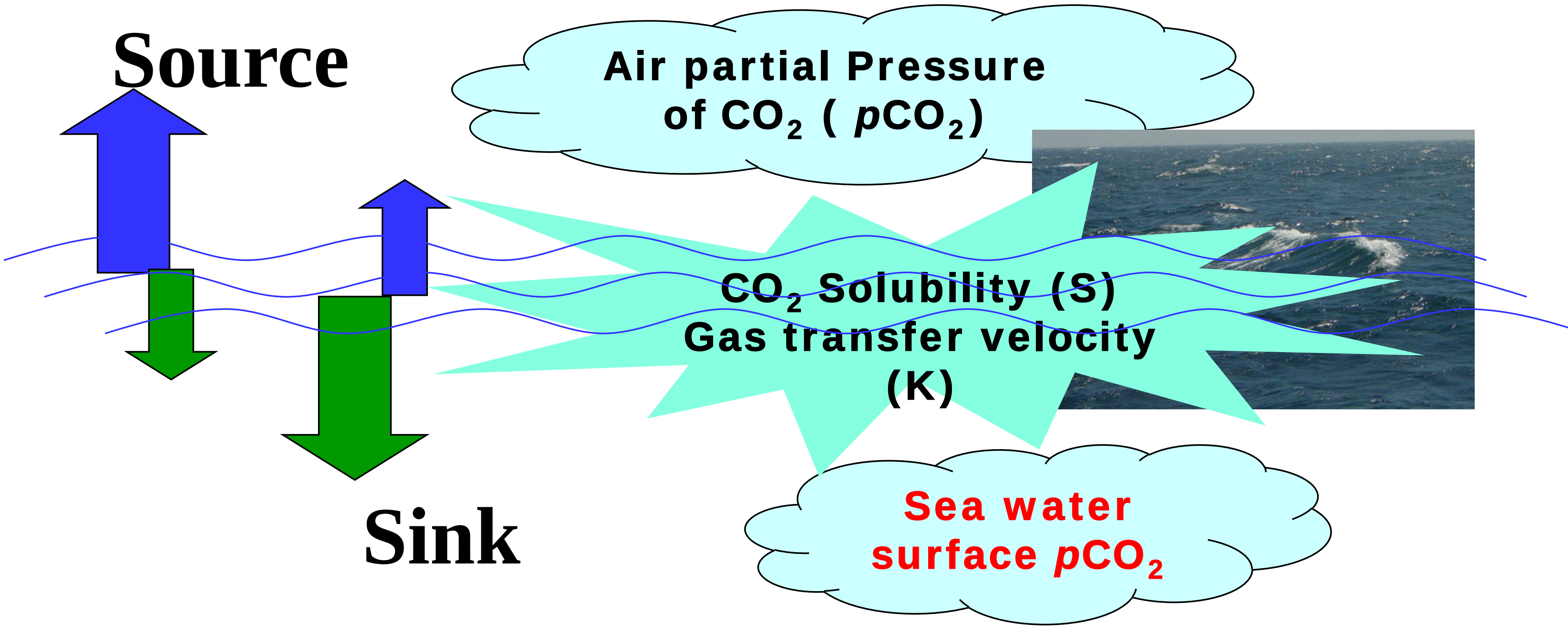
Climatologic atmospheric pCO_2 (2003-2009) monthly-averaged



Parameters of the flux calculation

Air-sea CO_2 flux

$$F = S \times K \times (pCO_{2sea} - pCO_{2air})$$



CO_2 Speciation

CO_2(g) has many possible transformations upon dissolution in H_2O

Major dissolved forms:

- $CO_{2(aq)}$ (*aqueous carbon dioxide* – a dissolved gas)
- H_2CO_3 (*carbonic acid* – trace amount)
- HCO_3^- (*bicarbonate ion*)
- CO_3^{-2} (*carbonate ion*)

The equilibrium of gaseous and aqueous CO_2:

$$CO_{2(g)} \leftrightarrow CO_{2(aq)}$$

Subsequent hydration and dissociation reactions:

$$CO_{2(aq)} + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+$$

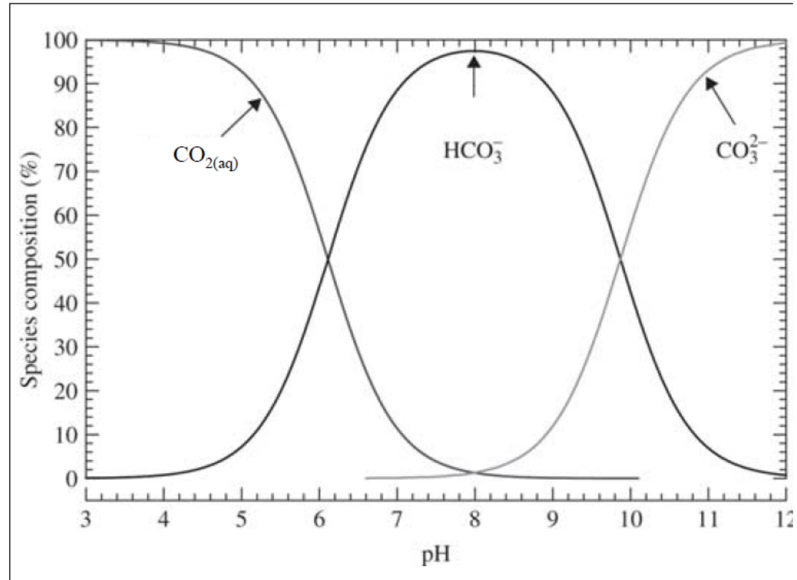
$$K_1^* = \frac{\{H^+\}[HCO_3^-]}{[CO_2]}$$

$$HCO_3^- \leftrightarrow CO_3^{-2} + H^+$$

$$K_2^* = \frac{\{H^+\}[CO_3^{2-}]}{[HCO_3^-]}$$

Asterisk (*) indicates a "stoichiometric" constant

Partial pressure of carbon dioxide (pCO_2)



Seawater values shown --- freshwater curves are shifted left

- pH = - log $\{H^+\}$
- *Total Alkalinity (TA)* represents ability of seawater to resist pH change upon addition of acid
- Any two of the four CO_2 properties (ΣCO_2, P_{CO2}, pH, and carbonate alkalinity) can be used to determine the CO_2 system

Remote sensing algorithm of Aquatic pCO_2

Sea-air flux of CO_2 in the North Pacific using shipboard and satellite data

Mark P. Stephens, Geoffrey Samuels, Donald B. Olson, and Rana A. Fine
Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida

Taro Takahashi
Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. C7, PAGES 13,571–13,583, JULY 15, 1995

pCO_2 vs. SST

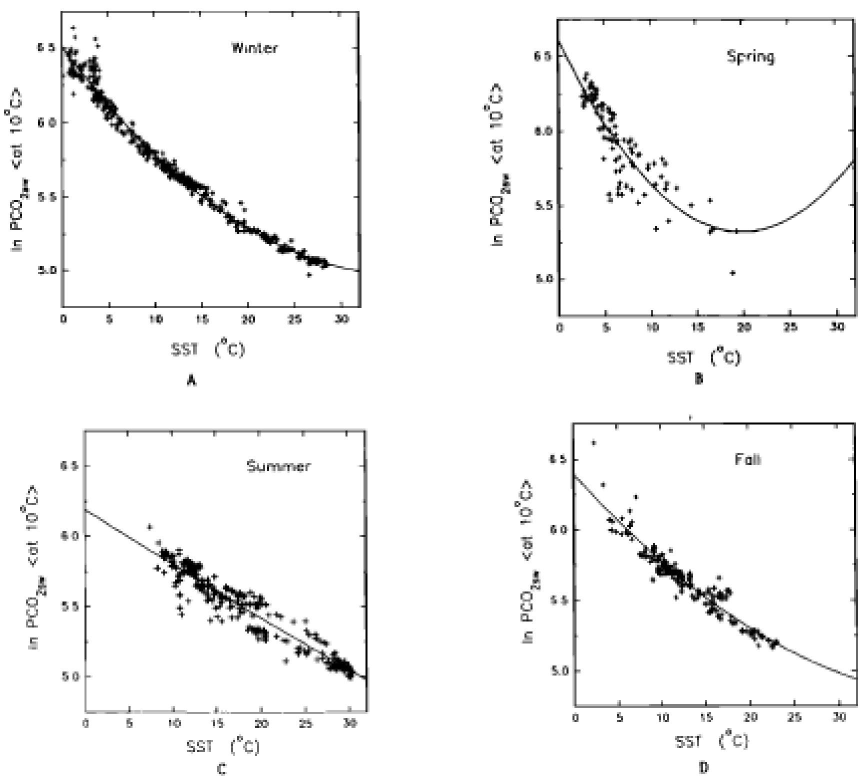
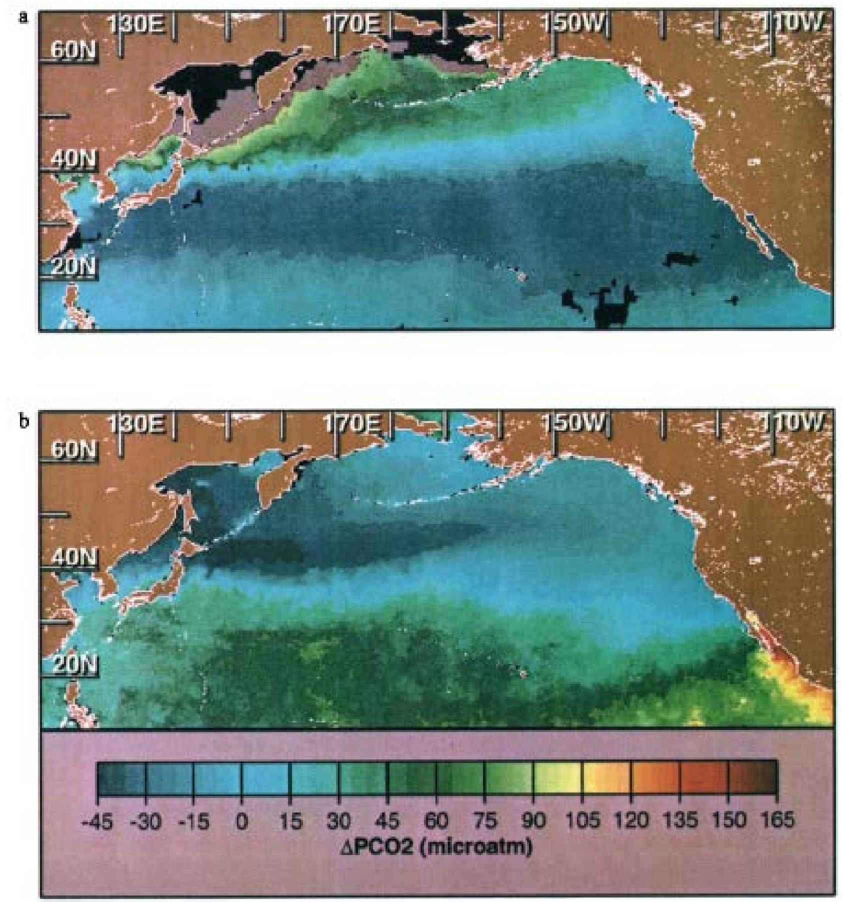


Figure 4. Seasonal relationship between ln $pCO_{2(t=10°C)}$ and SST. The curves represent the least squares fits of ln $pCO_{2(t=10°C)}$ to SST. The curves for (a and b) winter and spring represent the equations used to calculate ln $pCO_{2(t=10°C)}$ from satellite SST, but the equations for (c and d) summer and fall include a longitude term, not included in these curves.



Remote sensing of pCO_2-regression

Empirical algorithms

√ ×

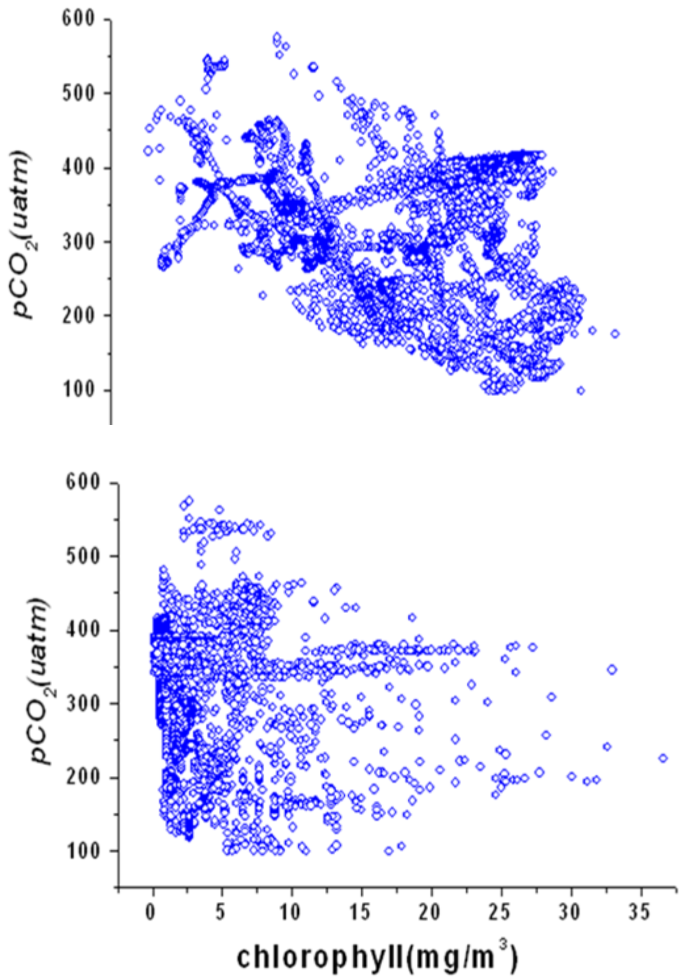
Aquatic pCO_2

Proxies: SST, Chla, Lon, Lat, Salinity, Mixing Layer Depth, etc.

Estimation the Aquatic pCO2 from Empirical algorithms (e.g. Linear Regression)

Proxy	Equation	Research area (References)
SST	f(T)	e.g.North Pacific(Stephens et al. 1995; Olsen et al., 2003, 2004;), Green land(Hood, et al., 1999;), Sargasso Sea(Nelson, et al., 2001), Caribbean Sea(Cosca et al., 2003;), Chile coastal(Levefre et al., 2002), sub-Antarctic Ocean(Metzl et al., 1999;), North Atlantic(Lefèvre et al., 2004;)
Chloraphyll a	f(T and/or Chla)	e.g. North Pacific (Ono et al., 2004) Southern Ocean (Rangama, et al., 2005) Northern SCS (Zhu, et al., 2009)
Location (Lon, Lat)	f(T, Lon, Lat)	e.g. Caribbean Sea (e.g. Wanninkhof, et al., 2007; Lueger, et al.,2009)
Mixing layer depth	f(T, MLD, Lon, Lat)	e.g. North Atlantic (Lueger, et al.,2009)
CDOM	f(T, aCDOM)	e.g. Hudson Bay (Else, et al., 2008),
Salinity	f(S, etc.)	e.g. North Pacific(Sarma et al., 2006)
Neutral Network (T, S, Chlorophyll, ect.)		e.g.Northern SCS (Yan et al., 2011)
Principal Component analysis		e.g.Northern Gulf of Mexico (Lohrenz and Cai, 2006)
Satellite data with Model		e.g.Mediterranean (D'Ortenzio)

ECS: 2009 summer



Sea surface pCO_{2sea} (Marginal Sea)

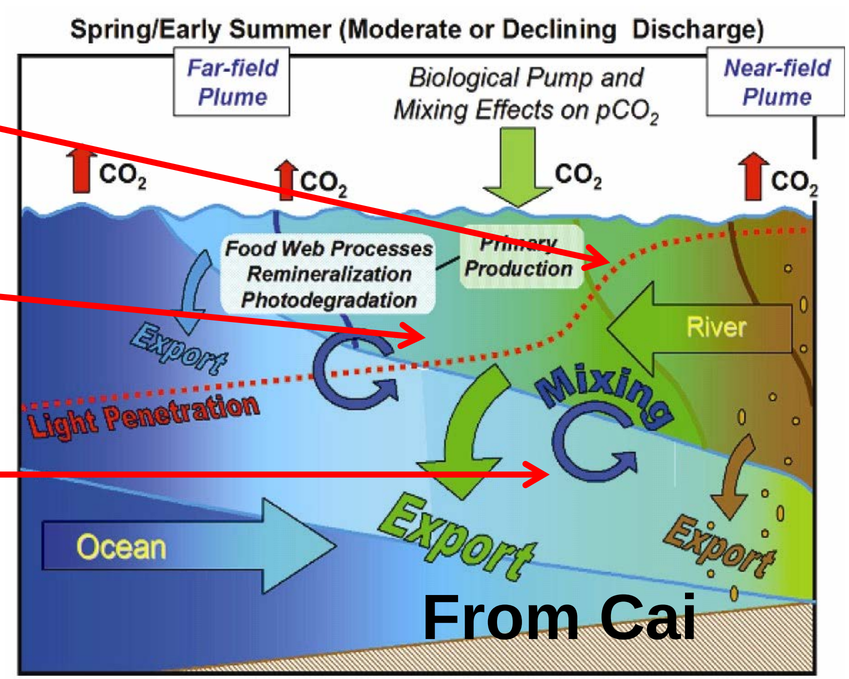
$$F = S \times K \times (pCO_{2sea} - pCO_{2air})$$

pCO_{2sea}

Biology

SST

Transport



Marine carbonate system

$$dpCO2 = \left(\frac{\partial pCO2}{\partial T}\right)dT + \left(\frac{\partial pCO2}{\partial TCO2}\right)dTCO2 + \left(\frac{\partial pCO2}{\partial TALK}\right)dTALK + \left(\frac{\partial pCO2}{\partial S}\right)dS$$

The controlling factors in the marginal sea system are very complicated, including biological, thermodynamic (SST), and mixing (transport) effects, etc.

Remote sensing algorithm of Aquatic pCO_2

pCO_2 vs. SST

Sea-air flux of CO_2 in the North Pacific using shipboard and satellite data

Mark P. Stephens, Geoffrey Samuels, Donald B. Olson, and Rana A. Fine
Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida

Taro Takahashi
Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. C7, PAGES 13,571–13,583, JULY 15, 1995

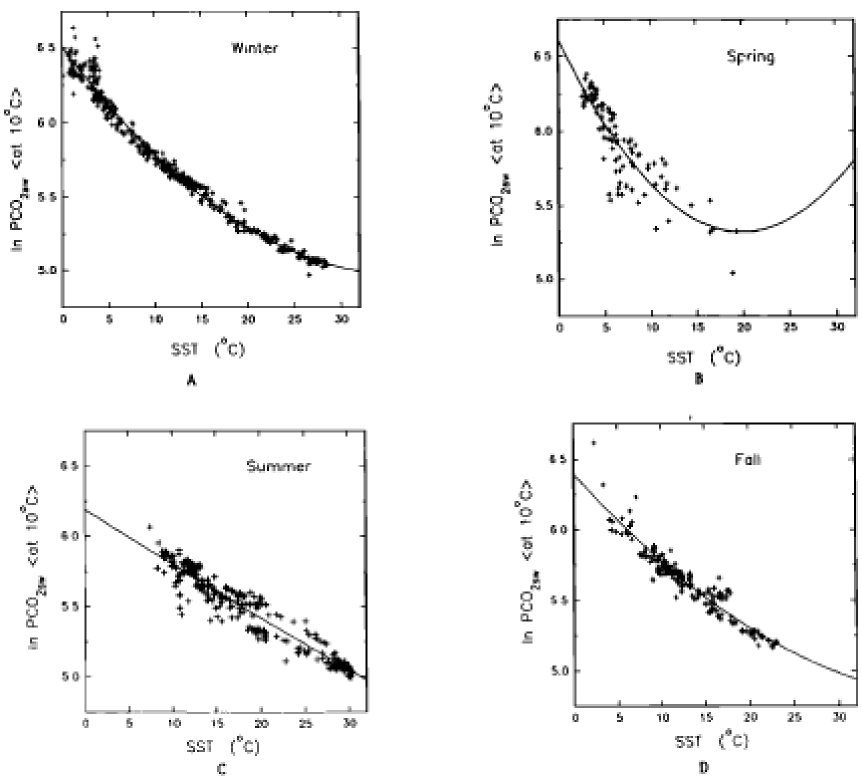
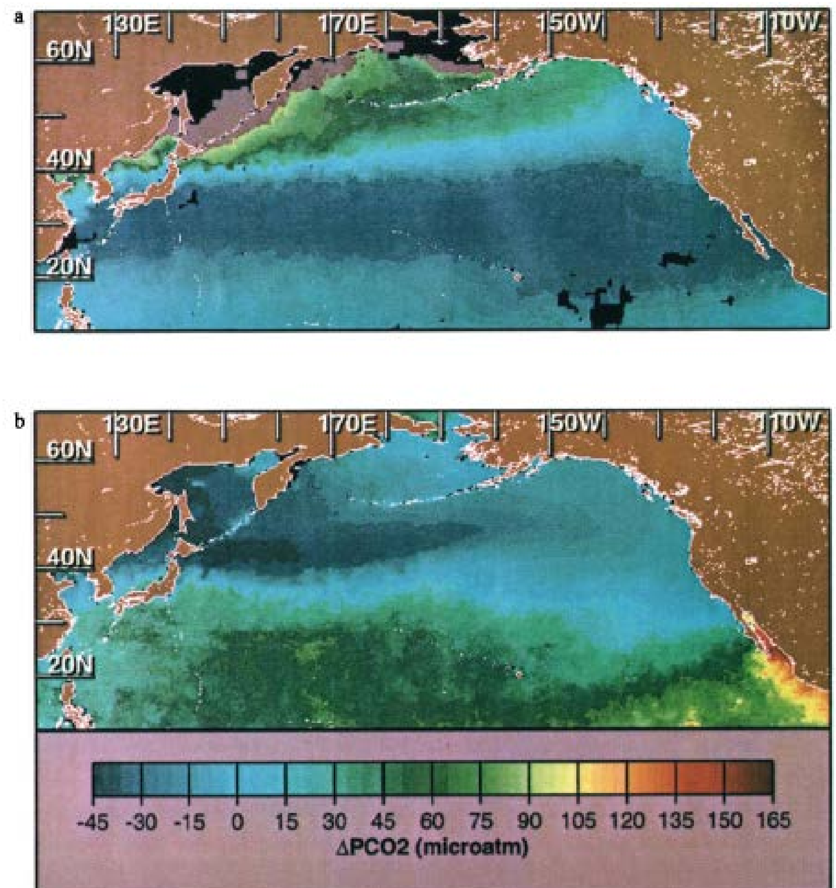


Figure 4. Seasonal relationship between ln $pCO_{2(t=10°C)}$ and SST. The curves represent the least squares fits of ln $pCO_{2(t=10°C)}$ to SST. The curves for (a and b) winter and spring represent the equations used to calculate ln $pCO_{2(t=10°C)}$ from satellite SST, but the equations for (c and d) summer and fall include a longitude term, not included in these curves.



Mechanistic-based semi-analytical algorithms (MeSAA-pCO_2)

Mixing

Biological effect

Mixing index
Carbonate system

Photosynthesis indirectly

$$\Delta pCO_2 = \left(\frac{\partial pCO_{2@therm}}{\partial V_{therm}}\right) \times \Delta V_{therm} + \left(\frac{\partial pCO_{2@mix}}{\partial V_{mix}}\right) \times \Delta V_{mix} + \left(\frac{\partial pCO_{2@bio}}{\partial V_{bio}}\right) \times \Delta V_{bio}$$
$$+ \left(\frac{\partial pCO_{2@flux}}{\partial V_{flux}}\right) \times \Delta V_{flux} + \ldots\ldots + \left(\frac{\partial pCO_{2@factor\text{-}n}}{\partial V_{factor\text{-}n}}\right) \times \Delta V_{factor\text{-}n} + \varepsilon,$$

Iterative Computing

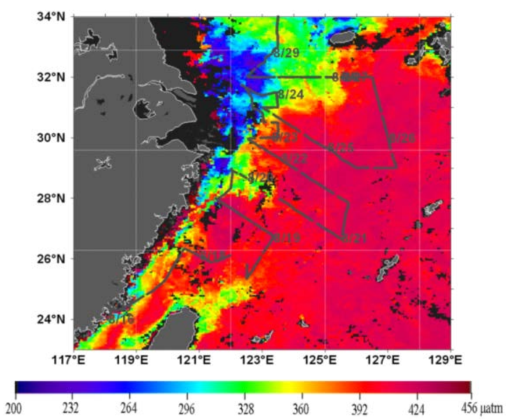
Air-sea CO_2 flux

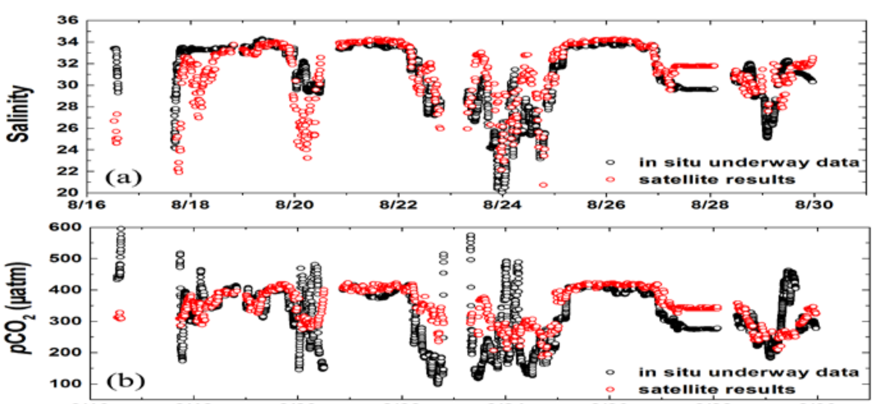
The variation of pCO_2 is analytically expressed as the sum of the first-order partial-difference of individual pCO_2 components contributed by each process or controlling factor. Hence, the critical issue is how to derive the analytical expressions of each process?

Mechanistic-based semi-analytical algorithms (MeSAA-pCO_2)

ECS (RioMar)

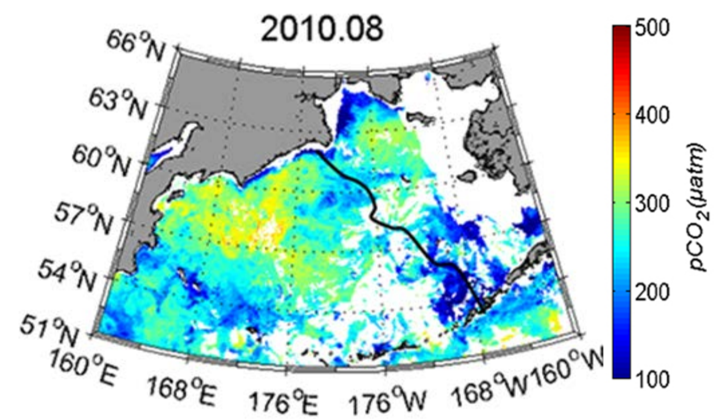
(Bai et al, 2013,2014 , 2015, JGR)

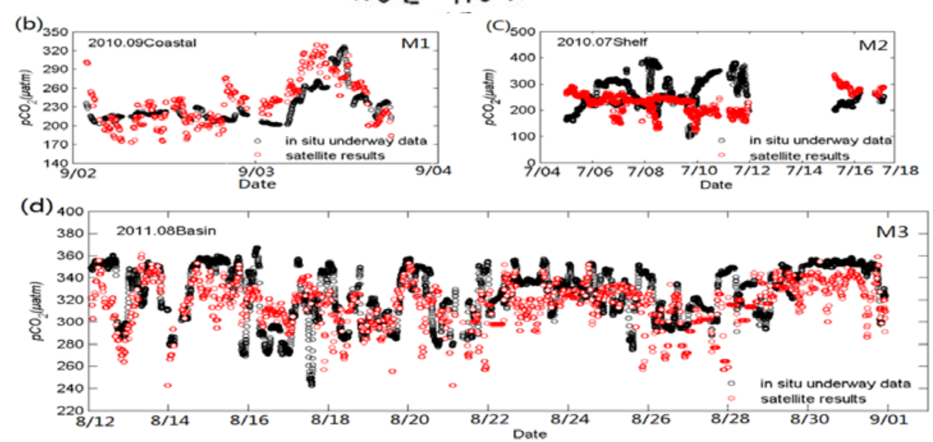




Bering Sea (OceMar)

(Song, Bai* et al, 2016, RS)





1) Prediction of thermodynamic control

- **Here we only consider the temperature-dependent component of the thermodynamic effects on sea surface *p*CO_2. This fractional thermodynamic effect is known to have an effect of 4.23% / 1° C [Takahashi *et al.*, 1993, 2002, 2009] as:**

$$pCO_2 @ \mathrm{T}_{est} = pCO_2 @ \mathrm{T}_{obs} \times \exp[0.0423 \times (T_{est} - T_{obs})]$$

- **In our method, we combine the variation of *p*CO_2 contributed by temperature change with that caused by the water mass mixing process using the calculation of the carbonate system; we do put the thermodynamic effect as a separately item.**

Mechanistic-based semi-analytical algorithms (MeSAA-$p\mathrm{CO_2}$)

Mixing

Biological effect

Mixing index
Carbonate system

Photosynthesis
indirectly

$$\Delta pCO_2 = \left(\frac{\partial pCO_{2@\mathrm{therm}}}{\partial V_{\mathrm{therm}}}\right)\times\Delta V_{\mathrm{therm}} + \left(\frac{\partial pCO_{2@\mathrm{mix}}}{\partial V_{\mathrm{mix}}}\right)\times\Delta V_{\mathrm{mix}} + \left(\frac{\partial pCO_{2@\mathrm{bio}}}{\partial V_{\mathrm{bio}}}\right)\times\Delta V_{\mathrm{bio}}$$
$$+\left(\frac{\partial pCO_{2@\mathrm{flux}}}{\partial V_{\mathrm{flux}}}\right)\times\Delta V_{\mathrm{flux}} + \ldots\ldots + \left(\frac{\partial pCO_{2@\mathrm{factor\text{-}n}}}{\partial V_{\mathrm{factor\text{-}n}}}\right)\times\Delta V_{\mathrm{factor\text{-}n}} + \varepsilon,$$

Iterative Computing

Air-sea CO_2 flux

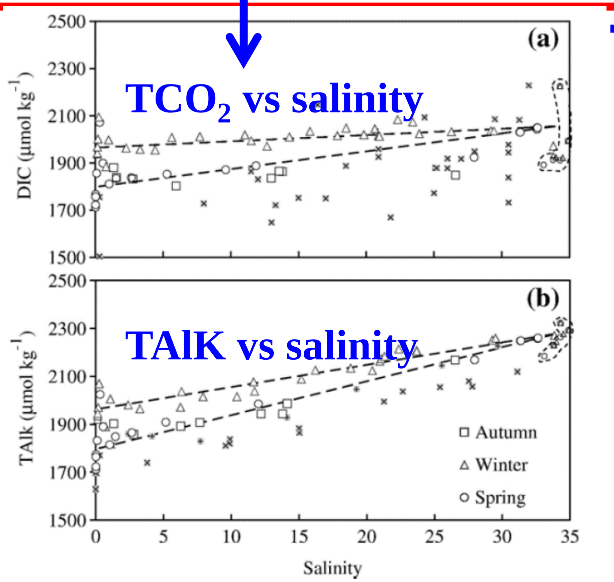
The variation of $p\mathrm{CO_2}$ is analytically expressed as the sum of the first-order partial-difference of individual $p\mathrm{CO_2}$ components contributed by each process or controlling factor. Hence, the critical issue is how to derive the analytical expressions of each process?

Marine carbonate calculation

Parameterization of the two end-members mixing model（两端元混合作用）

$$dpCO2 = \left(\frac{\partial pCO2}{\partial T}\right)dT + \left(\frac{\partial pCO2}{\partial TCO2}\right)dTCO2 + \left(\frac{\partial pCO2}{\partial TALK}\right)dTALK + \left(\frac{\partial pCO2}{\partial S}\right)dS$$

Fresh water (Changjiang)	+ mixing	Marine water (Kurishio)



Conservative mixing behavior

Zhai et al., Marine Chemistry, 2007

- The mixing and thermodynamically predicted mixing contributed pCO_2 can be calculated via marine carbonate system equilibrium equations.

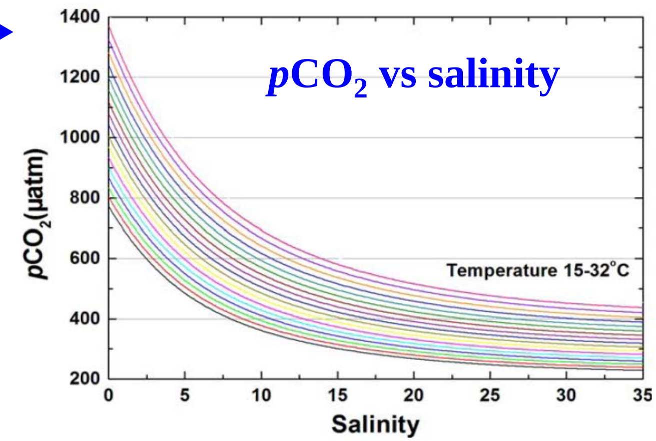
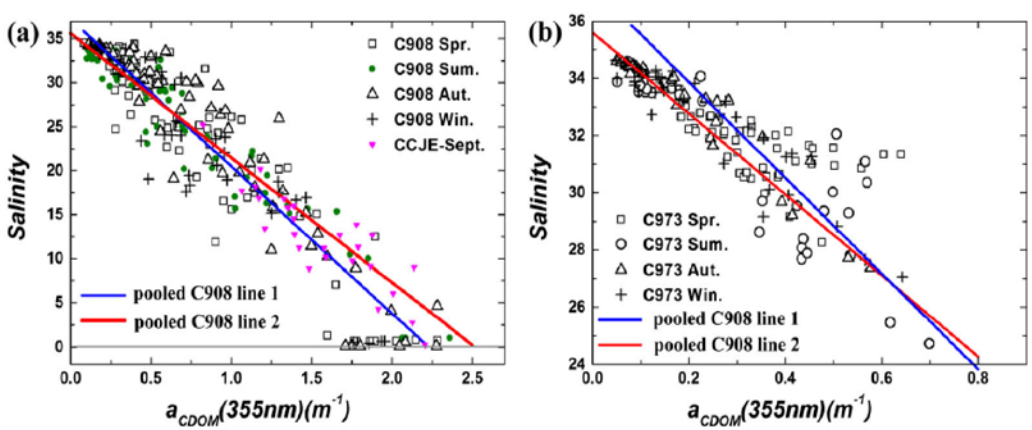


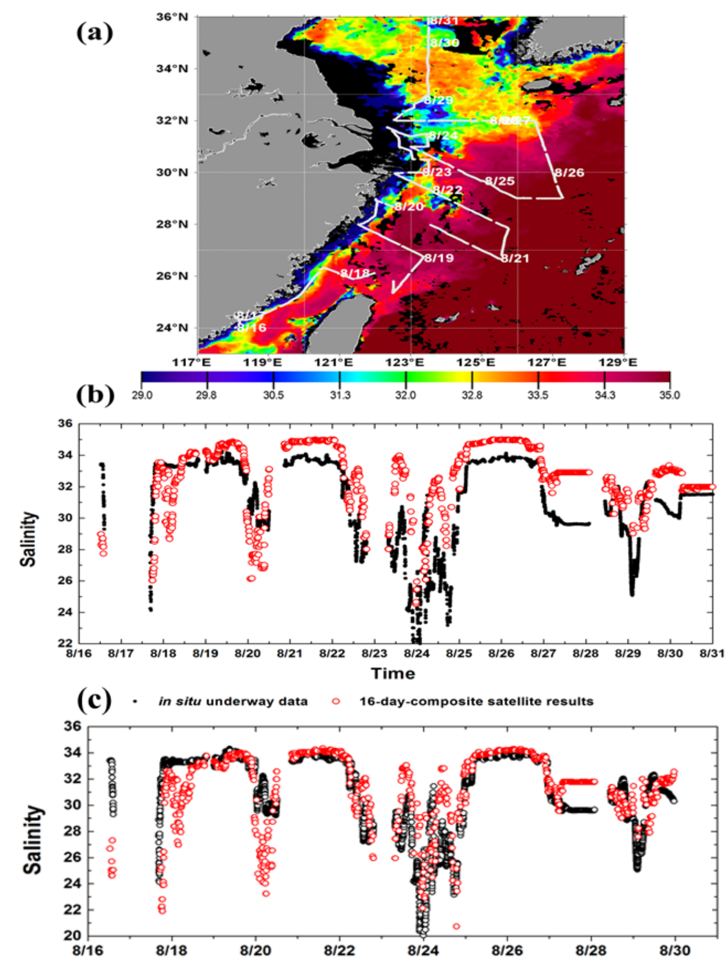
Figure 2. pCO_2 variation with salinity. Individual curves are calculated by CO2SYS with DIC and TA under the conservative mixing of two end-members (DIC = TA = 1850 μmol/kg at salinity = 0; NDIC = 1970 μmol/kg and NTA = 2300 μmol/kg at salinity = 35) at given temperatures. Colored curves from bottom to top are the temperature setting from 15 to 32°C at 0.5°C step.

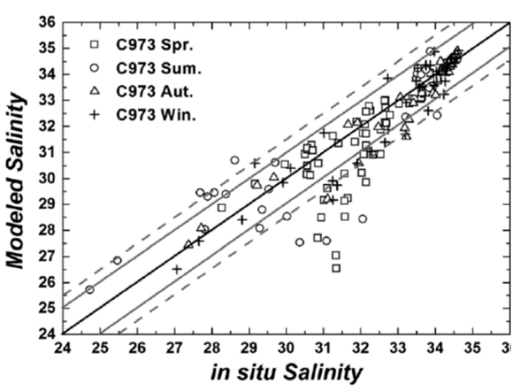
Mixing index

Satellite-derived salinity by ocean color remote sensing in Changjiang River plume can be used as the mixing index in the ECS

BAI ET AL.: SATELLITE SALINITY OF CHANGJIANG PLUME







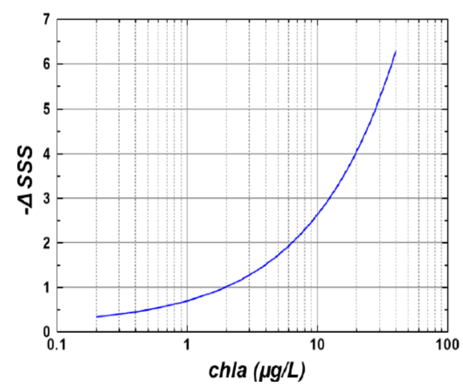


Figure 10. Underestimated salinities (ΔSSS) vary with the increase of *chla* concentration based on the bio-optical model of equation 10. $\Delta SSS < 1$ when $chla \leq 2$ μg/L, $\Delta SSS < 1.5$ when $chla \leq 4$ μg/L, and $\Delta SSS = 2.6$, when $chla = 10$ μg/L.

Bai et al., JGR-Oceans, 2013

Bio-Effect

3) Parameterization of the biological effect

we assume that there is a general relationship between pCO_2 and *chla*,

ε represents the pCO_2 contribution from other factors, which does not overlap the contribution from the biological effects.

$$pCO_2 = \text{A-B} \times \log(chla) + \varepsilon$$

partial-difference of pCO_2 due to *chla*

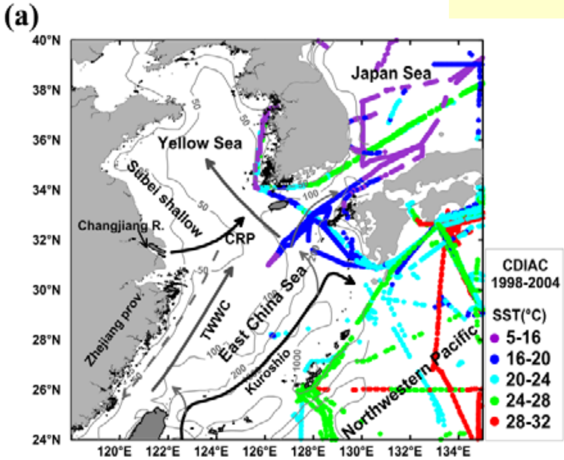
$$\frac{\partial(pCO_{2@bio})}{\partial(chla)} = \frac{\partial[\mathrm{A} - \mathrm{B} \times \log(chla) + \varepsilon]}{\partial(chla)} = -\frac{\mathrm{B}}{\ln(10)} \frac{1}{chla}$$

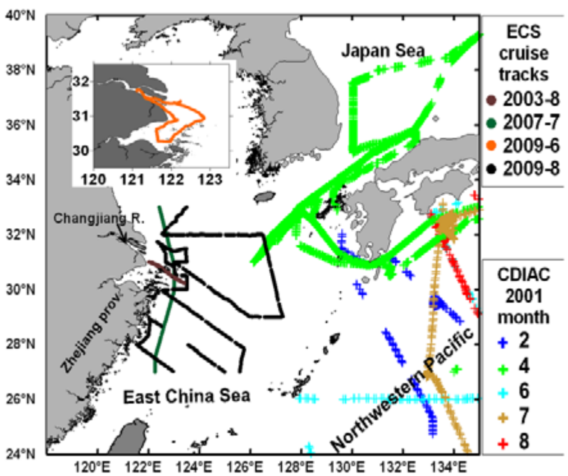
an integration of the increment of *chla* with time because the biological drawdown of pCO_2 is a cumulative process.

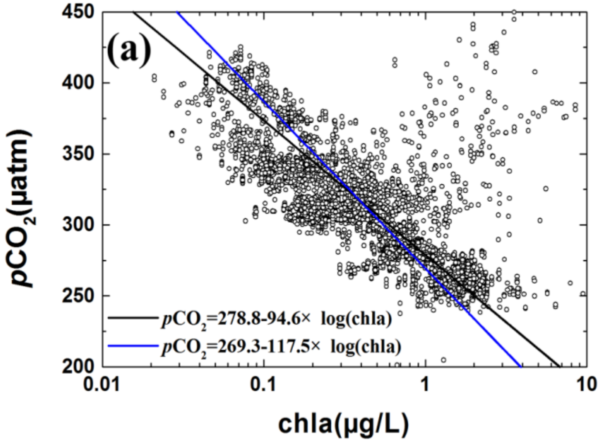
$$\Delta pCO_{2@bio} = \frac{\partial pCO_{2@_{\mathrm{bio}}}}{\partial V_{\mathrm{bio}}} \Delta V_{\mathrm{bio}} = \int_{chla_0}^{chla_n} -\frac{\mathrm{B}}{\ln(10)} \frac{1}{chla} d\left(chla\right)$$
$$= -\frac{\mathrm{B}}{\ln(10)} \times \left[\ln(chla_n) - \ln(chla_0)\right]$$

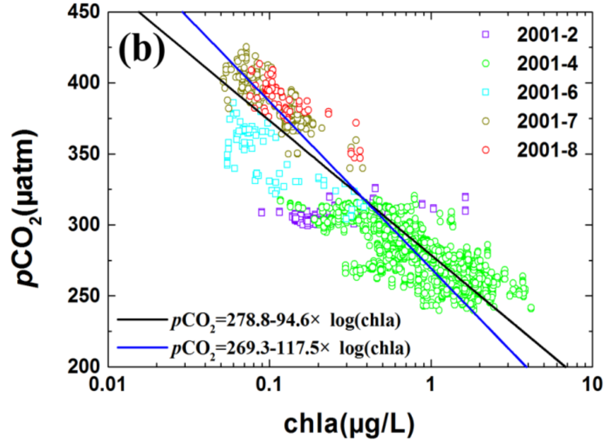
3) Parameterization of the biological effect

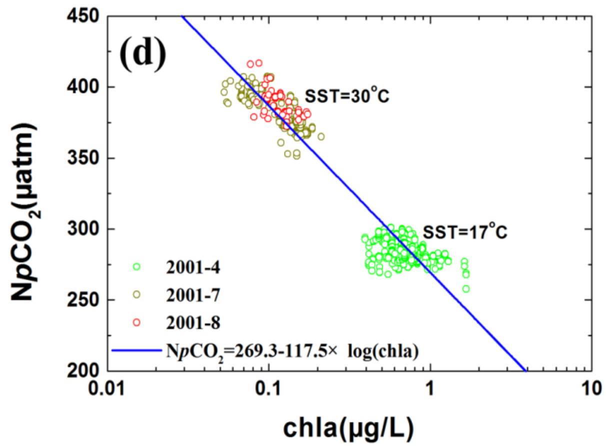
$$pCO_2 = \text{A-B} \times \log(chla) + \varepsilon$$

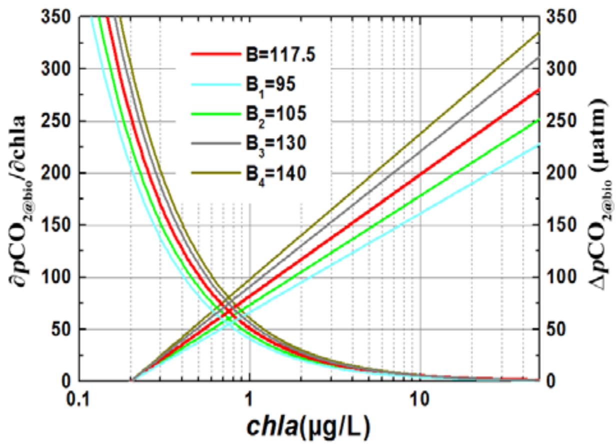












underway pCO_2 from CDIAC and matching 8-day composite satellite-derived *chla*

we also set a ±20% deviation of B (95-140) to test the corresponding variation of $\Delta pCO_{2@bio}$

MeSAA algorithm in ECS in summertime

$$pCO_2 = pCO_{2@Hmix} + \Delta pCO_{2@bio}$$

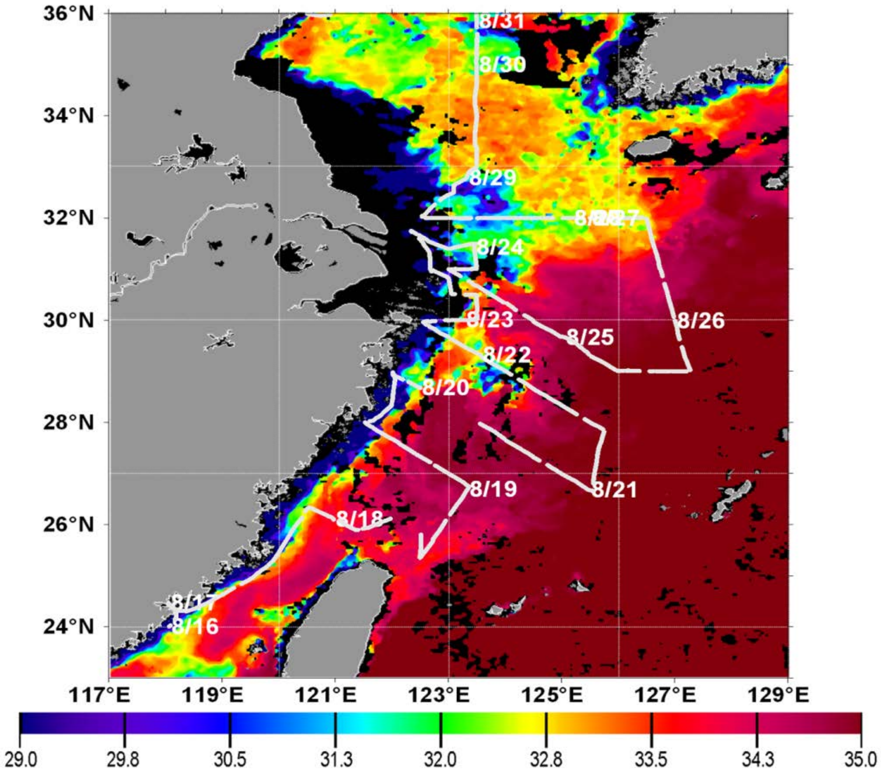
$$pCO_{2@Hmix} = LUT(TA_0, DIC_0, NTA_{35}, NDIC_{35}, SST, Salinity)$$

$$\Delta pCO_{2@bio} = -117.5 \times [\log(chla) - \log(0.2)]$$

Satellite Result and validation

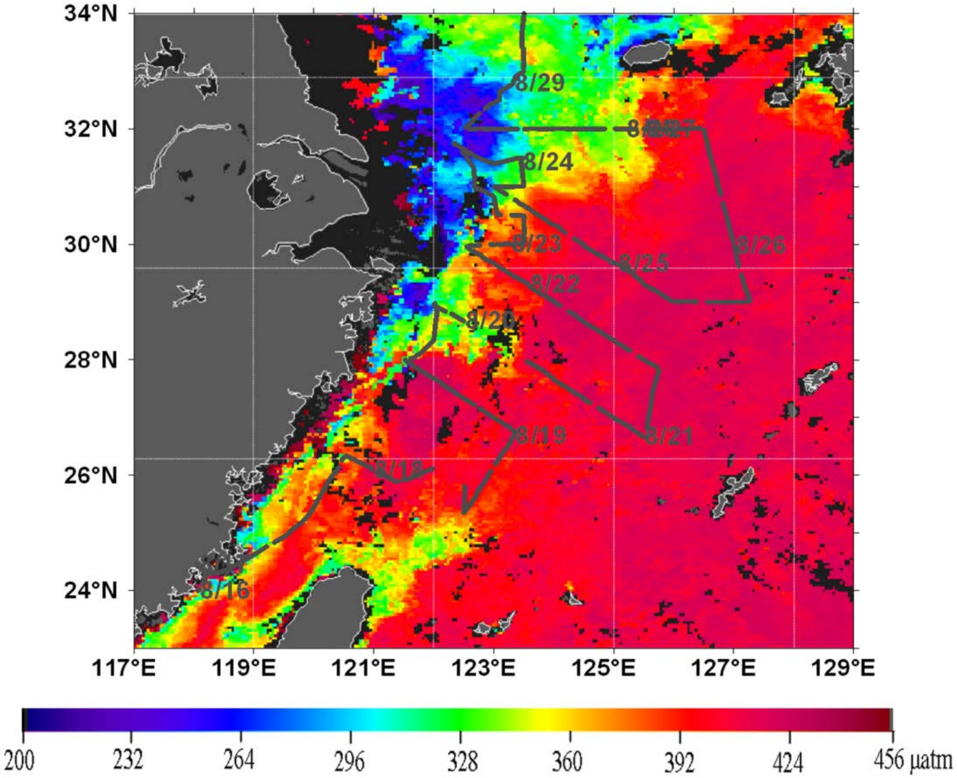
The inputs of MSAA include satellite products of *chla*, SST, salinity, and DIC and TA values for two pairs of end-members.

Satellite *salinity* in August 2009



Bai, et al., 2013, JGR

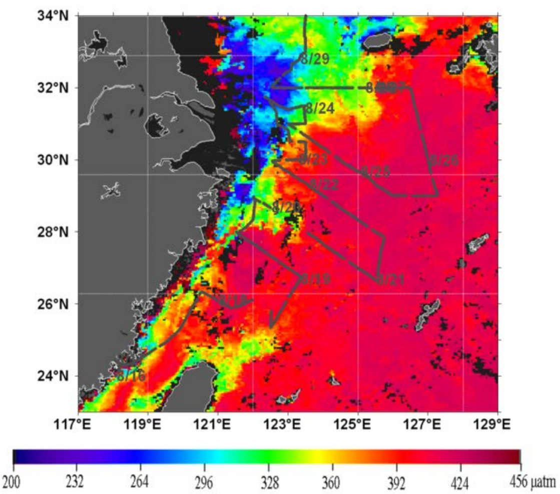
Satellite pCO_2 in August 2009

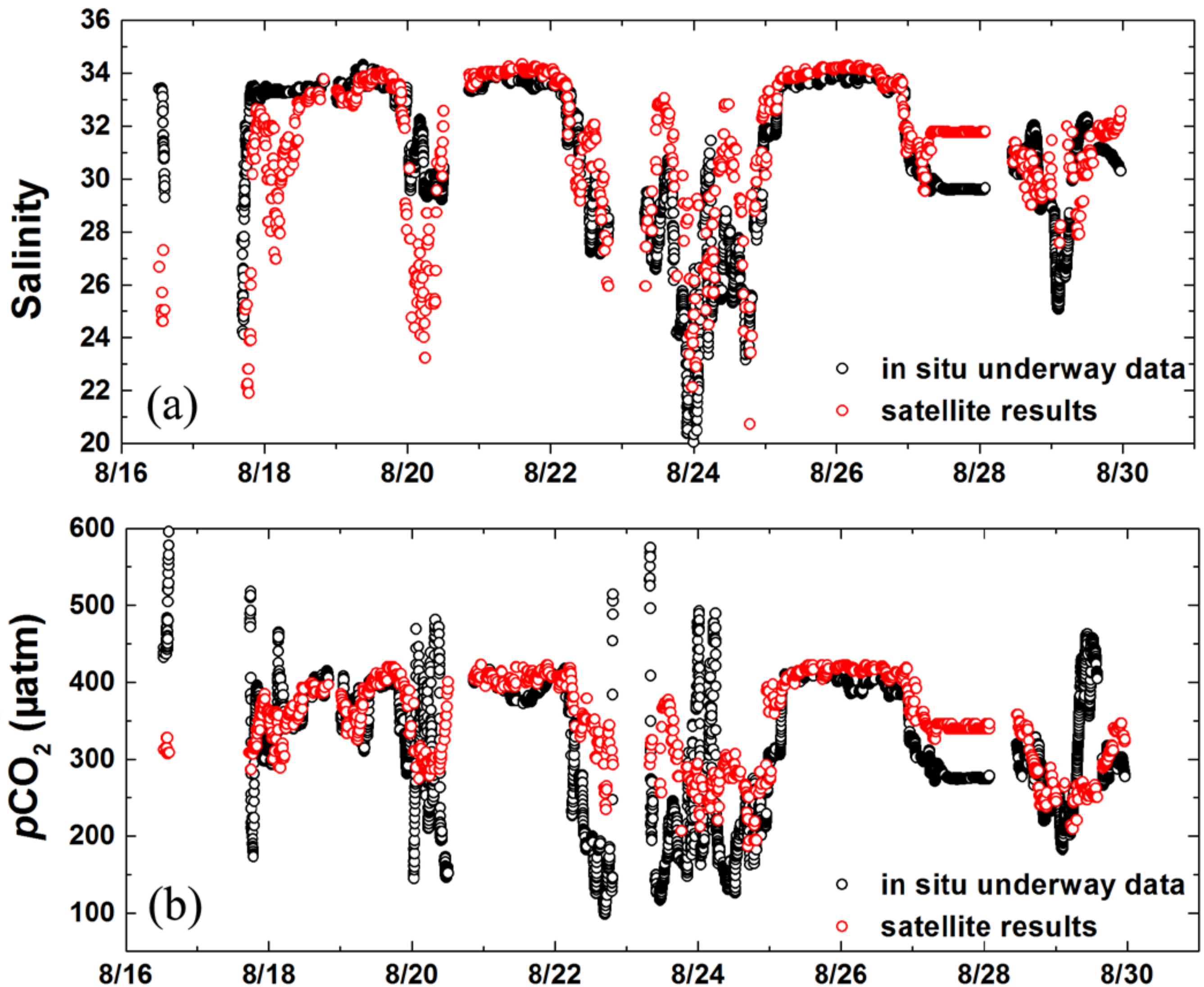


Bai, et al., 2015, JGR

Satellite Result and validation

Satellite *p*CO_2
in August 2009
16 day composite
during the cruise





Lateral mixing

Vertical mixing

$$\Delta pCO_2 = \left(\frac{\partial pCO_{2@\,\mathrm{therm}}}{\partial V_{\mathrm{therm}}}\right)\Delta V_{\mathrm{therm}} + \left(\frac{\partial pCO_{2@\,\mathrm{mix}}}{\partial V_{\mathrm{mix}}}\right)\Delta V_{\mathrm{mix}} + \left(\frac{\partial pCO_{2@\,\mathrm{bio}}}{\partial V_{\mathrm{bio}}}\right)\Delta V_{\mathrm{bio}}$$

$$+ \left(\frac{\partial pCO_{2@\,\mathrm{flux}}}{\partial V_{\mathrm{flux}}}\right)\Delta V_{\mathrm{flux}} + \ldots\ldots + \left(\frac{\partial p\mathrm{CO}_{2@\mathrm{factor\text{-}n}}}{\partial V_{\mathrm{factor\text{-}n}}}\right)\Delta V_{\mathrm{factor\text{-}n}} + \varepsilon$$

Ocean Color

Semi-Analytical pCO_{2sw} Algorithms
All seasons

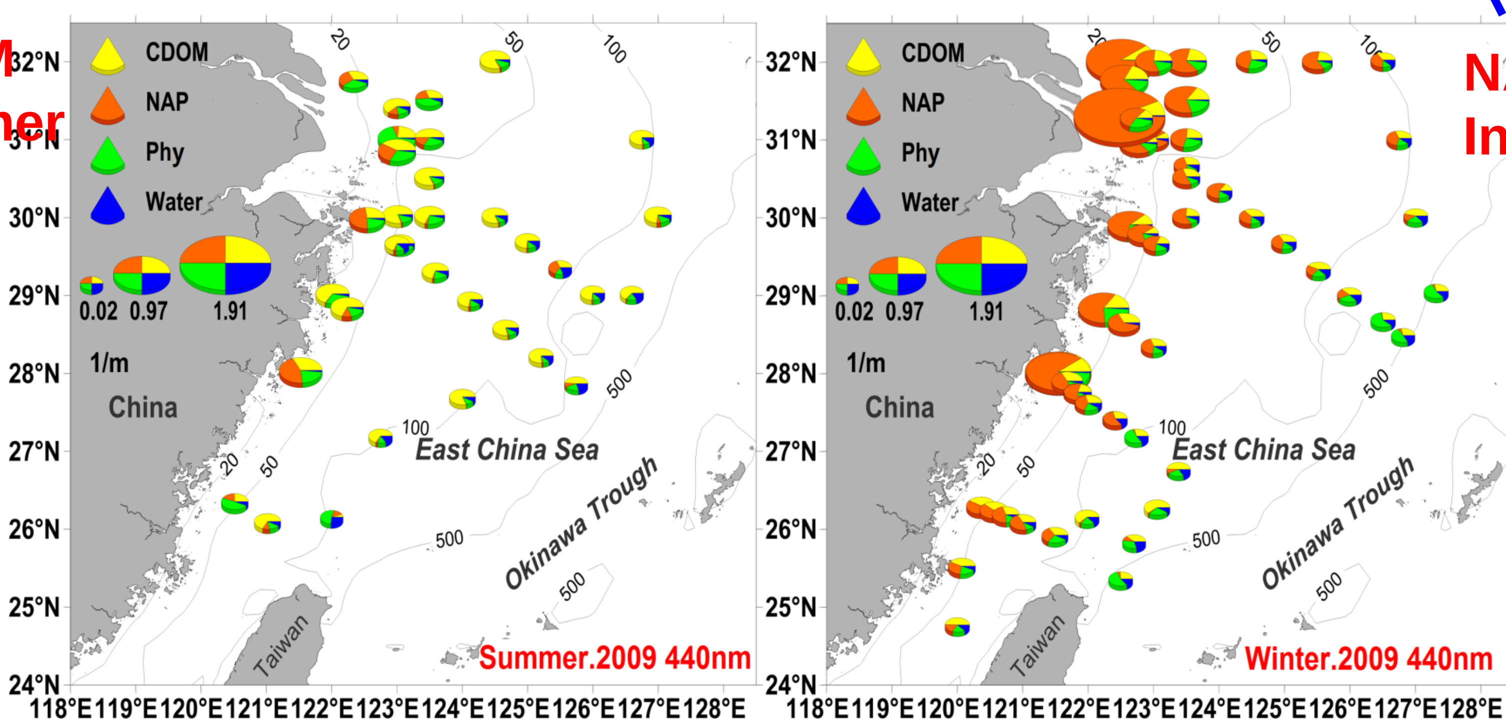
Particle optics can denote the mixing state of water column both at vertical and horizontal directions.

$$\Delta pCO_2 = \left(\frac{\partial pCO_{2@therm}}{\partial V_{therm}}\right)\Delta V_{therm} + \left(\frac{\partial pCO_{2@mix}}{\partial V_{mix}}\right)\Delta V_{mix} + \left(\frac{\partial pCO_{2@bio}}{\partial V_{bio}}\right)\Delta V_{bio} + \left(\frac{\partial pCO_{2@flux}}{\partial V_{flux}}\right)\Delta V_{flux} + \ldots\ldots + \left(\frac{\partial pCO_{2@factor\text{-}n}}{\partial V_{factor\text{-}n}}\right)\Delta V_{factor\text{-}n} + \varepsilon$$

Proxy Salinity

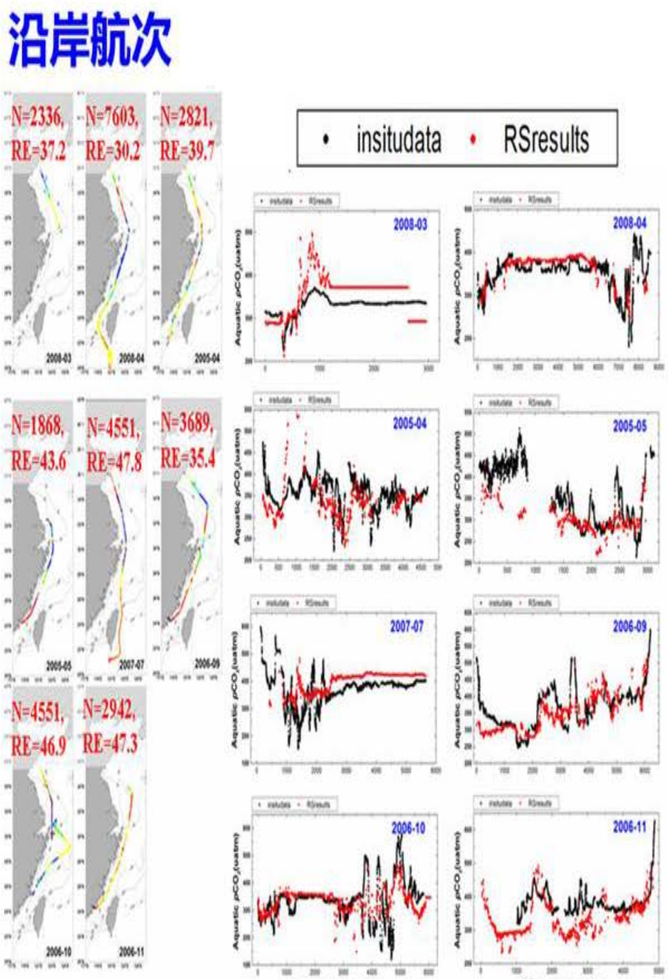
CDOM Summer

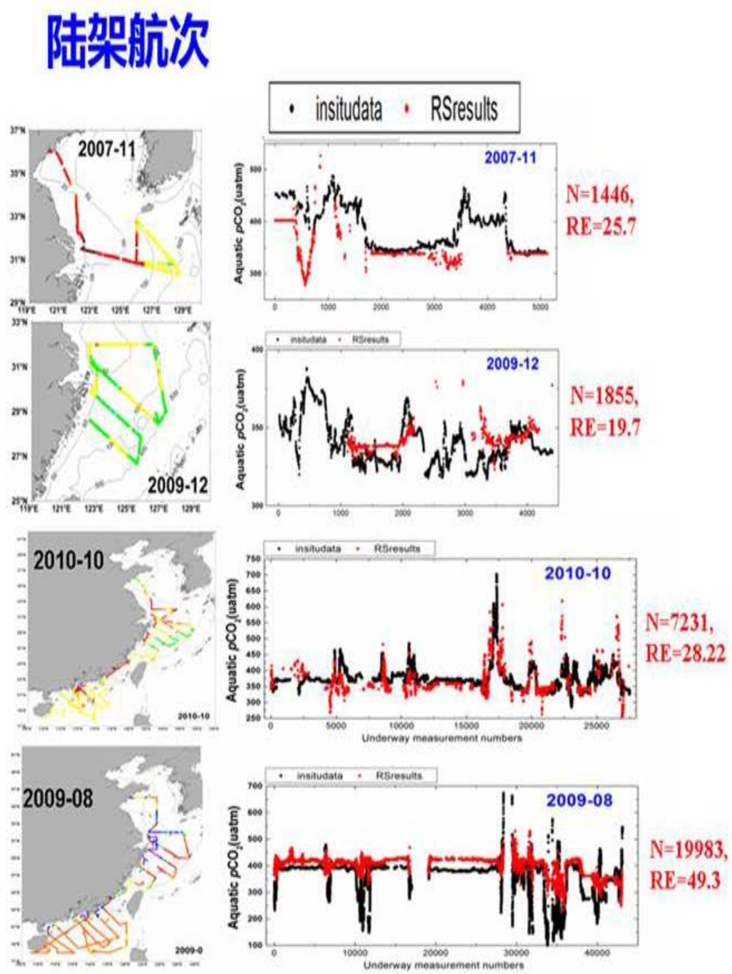
NAP In Winter



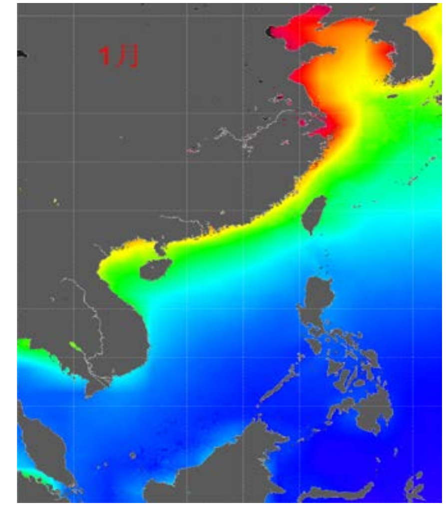
SOED

Validation- Aquatic pCO_2

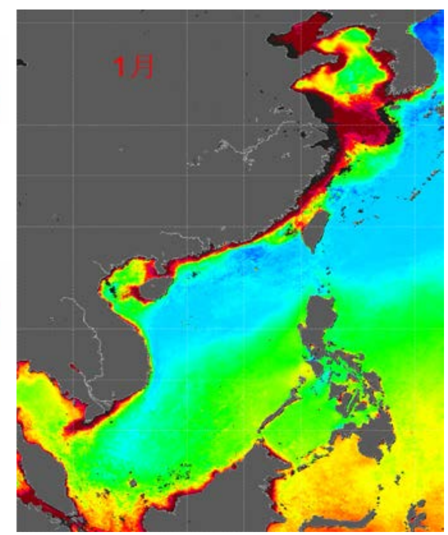


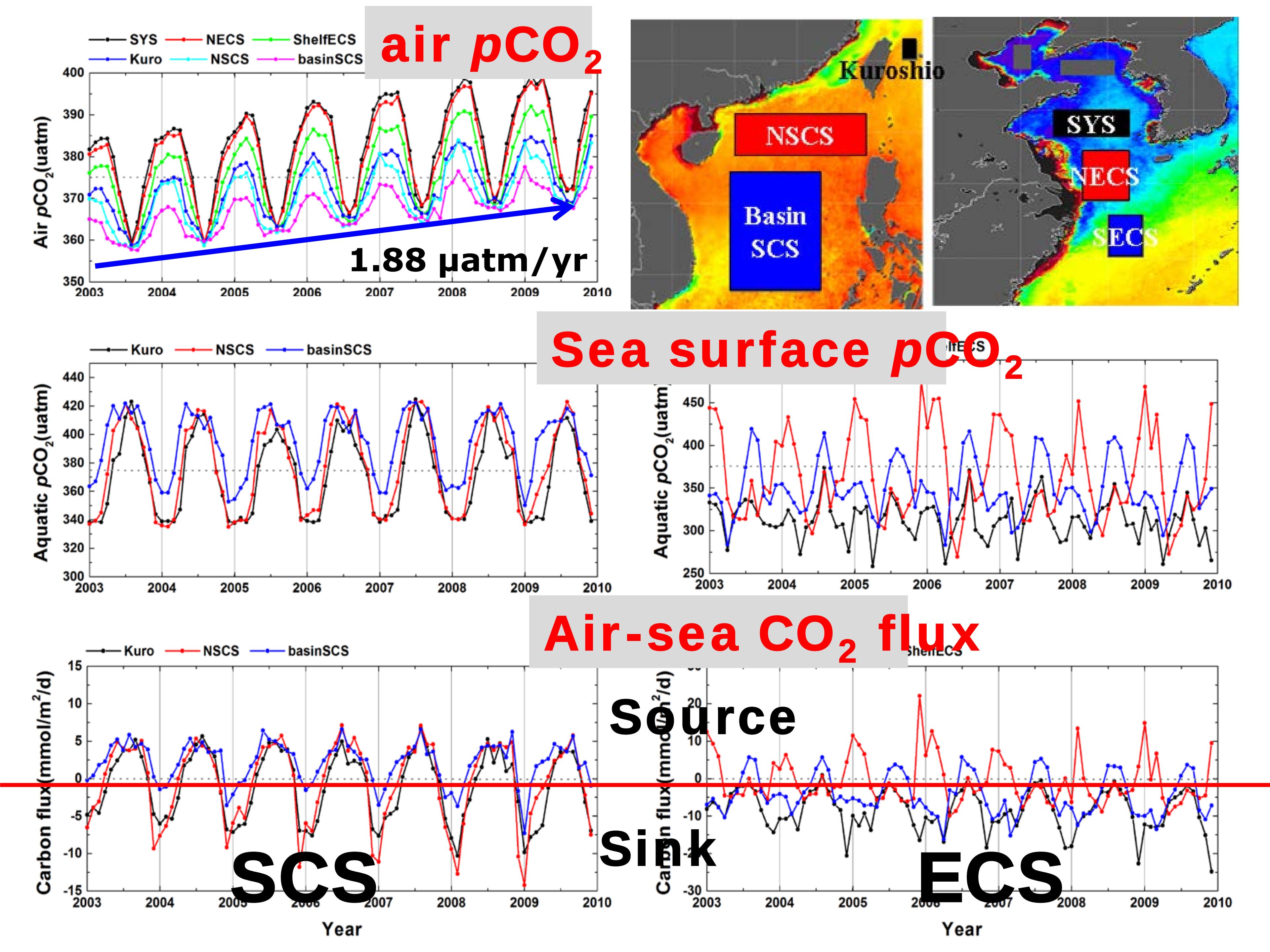


大气CO_2分压



海水CO_2分压



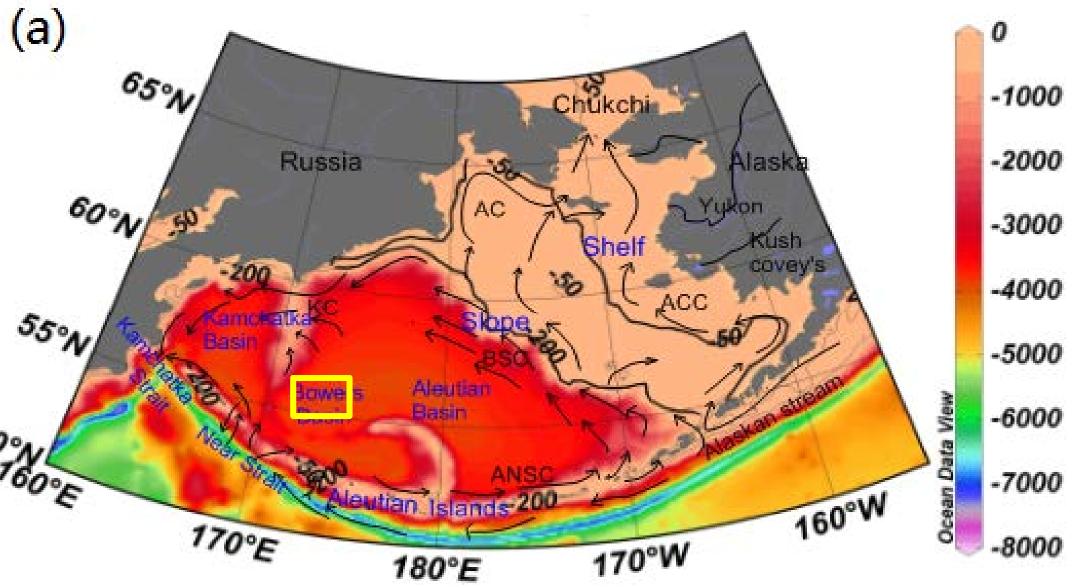


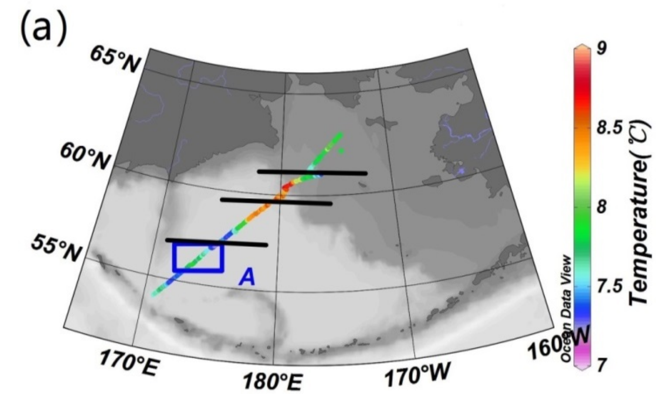
air pCO_2
SYS
NECS
ShelfECS
Kuro
NSCS
basinSCS
Air pCO_2(uatm)
1.88 μatm/yr
Kuroshio
NSCS
Basin SCS
SYS
NECS
SECS
Sea surface pCO_2
Kuro
NSCS
basinSCS
Aquatic pCO_2(uatm)
Air-sea CO_2 flux
Kuro
NSCS
basinSCS
ShelfECS
Carbon flux(mmol/m^2/d)
Source
Sink
SCS
ECS
Year

Bering Sea

Selection of reference water-mass

$$pCO_2 = pCO_{2(o)} + (\frac{\partial pCO_{2@therm}}{\partial V_{therm}})\Delta V_{therm} + (\frac{\partial pCO_{2@bio}}{\partial V_{bio}})\Delta V_{bio} + \varepsilon$$

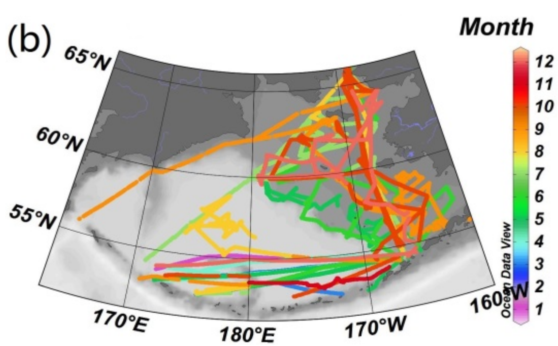


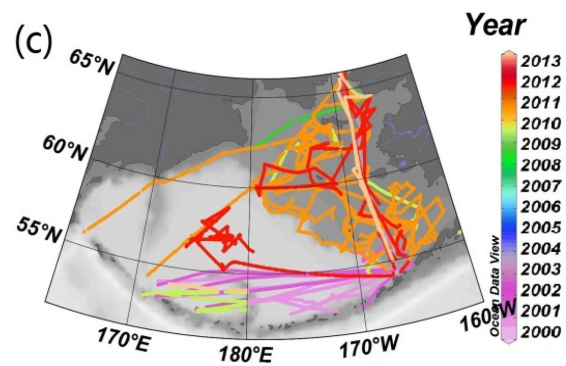


July 2010 cruise

Selected $\boldsymbol{pCO_{2(o)}}$

= ***381.8±5.08 uatm***





Calculated $\boldsymbol{pCO_{2(summer)}}$
= 385.9 μatm

Song, Bai* et al., RS, 2016

Mechanistic-based semi-analytical algorithms (MeSAA-pCO$_2$)

Mixing

Biological effect

Mixing index
Carbonate system

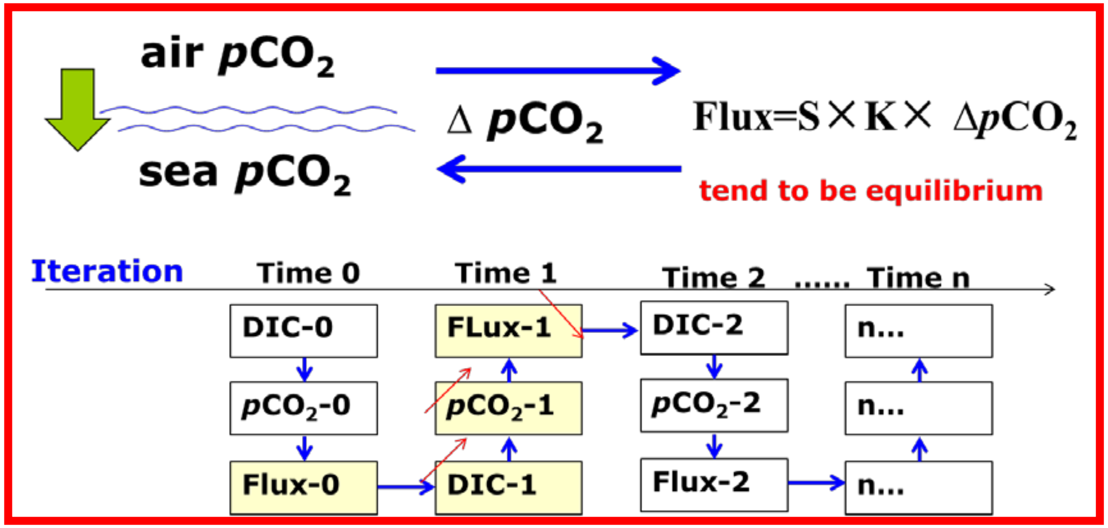
Photosynthesis indirectly

$$\Delta pCO_2 = \left(\frac{\partial pCO_{2@therm}}{\partial V_{therm}}\right)\times\Delta V_{therm} + \left(\frac{\partial pCO_{2@mix}}{\partial V_{mix}}\right)\times\Delta V_{mix} + \left(\frac{\partial pCO_{2@bio}}{\partial V_{bio}}\right)\times\Delta V_{bio}$$

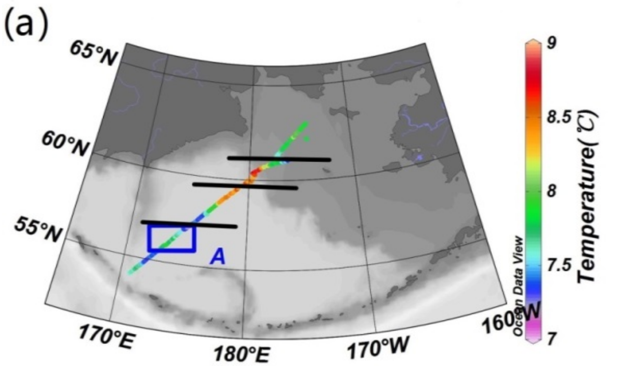
$$+\left(\frac{\partial pCO_{2@flux}}{\partial V_{flux}}\right)\times\Delta V_{flux} + \ldots\ldots + \left(\frac{\partial pCO_{2@factor\text{-}n}}{\partial V_{factor\text{-}n}}\right)\times\Delta V_{factor\text{-}n} + \varepsilon,$$

Iterative Computing

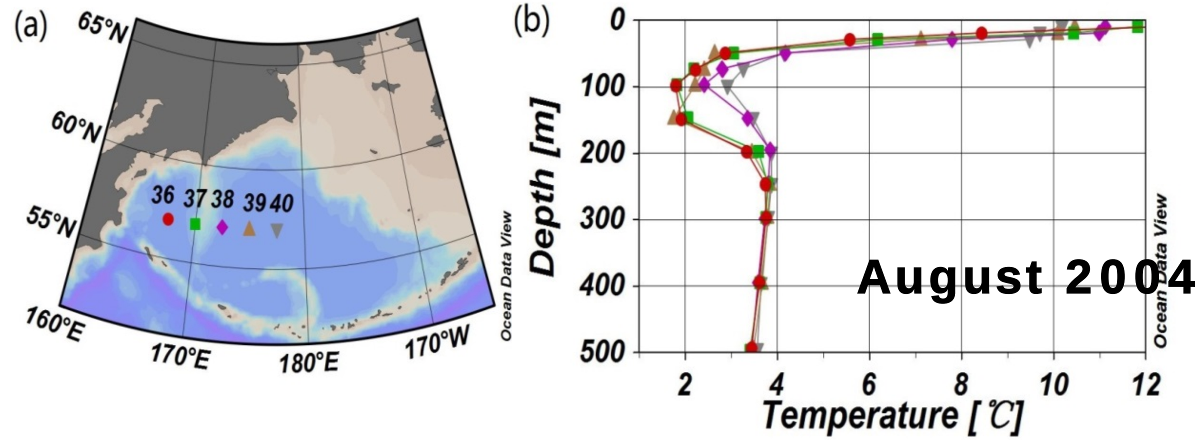
Air-sea CO_2 flux



pCO_2 change from last winter to summer



July 2010



385.9 μatm

381.8 μatm

Calculated $pCO_{2(summer)}$ = *Selected* $pCO_{2(o)}$

1) biological alteration ($\Delta pCO_{2(bio)}$)=- 65 μatm

2) Warming + air-sea exchange ($\Delta pCO_{2(air\text{-}sea)}$) =35.8 μatm

Redfield Ratio (ΔDIC_{bio} =106*AOU/138)

ΔDIC_{bio}

summer

***DIC, TA in* temp. minimum layer**

415.2 μatm

$pCO_{2(winter)}$

well-mixed winter water bottom high DIC data

***DIC, TA in* winter**

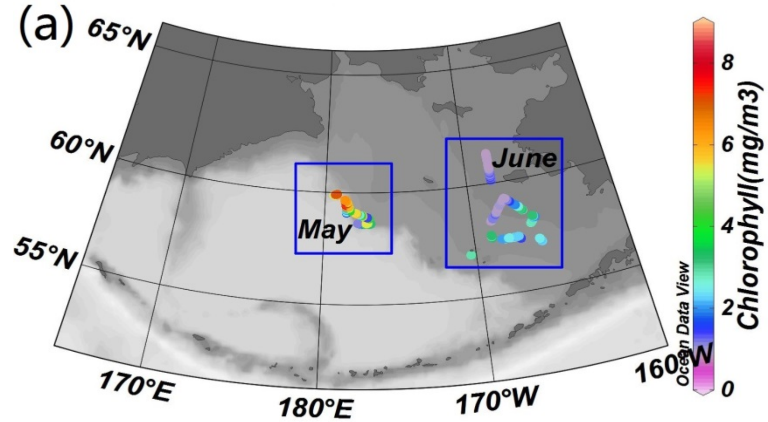
Surface $pCO_{2(summer)}$

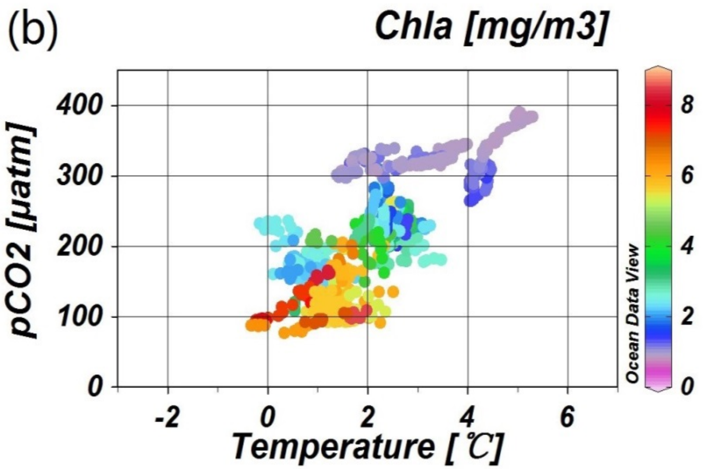
The climatological monthly average mixing layer depth was 50.7 m during March to July

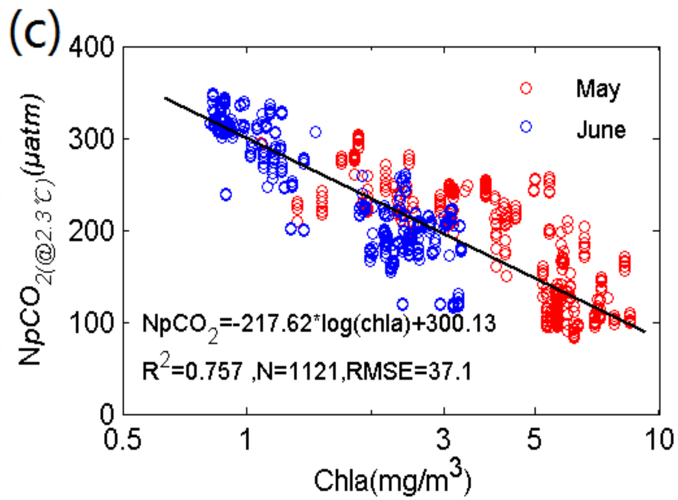
$$pCO_2 = \text{A-B} \times \log(chla) + \varepsilon$$

BS: B=217.62

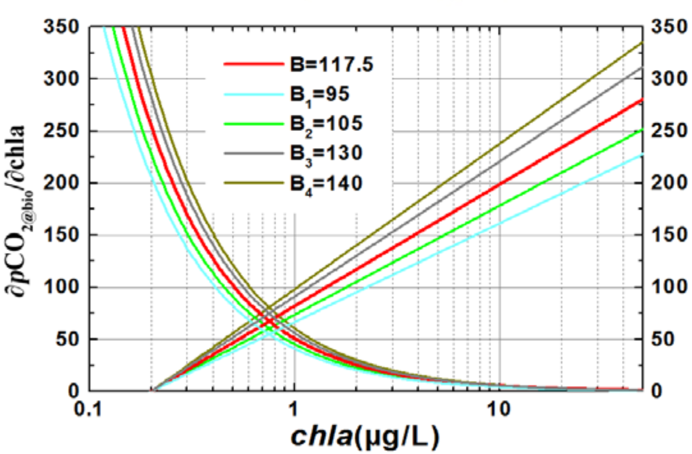
ECS: B=117.5

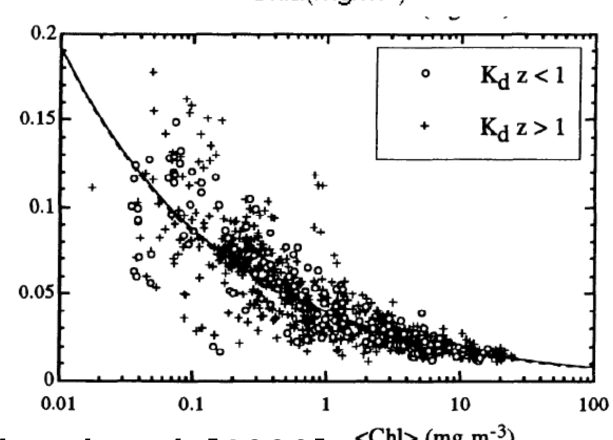






low *chla* regime
small size
large
$\partial pCO_{2@bio}/\partial chla$

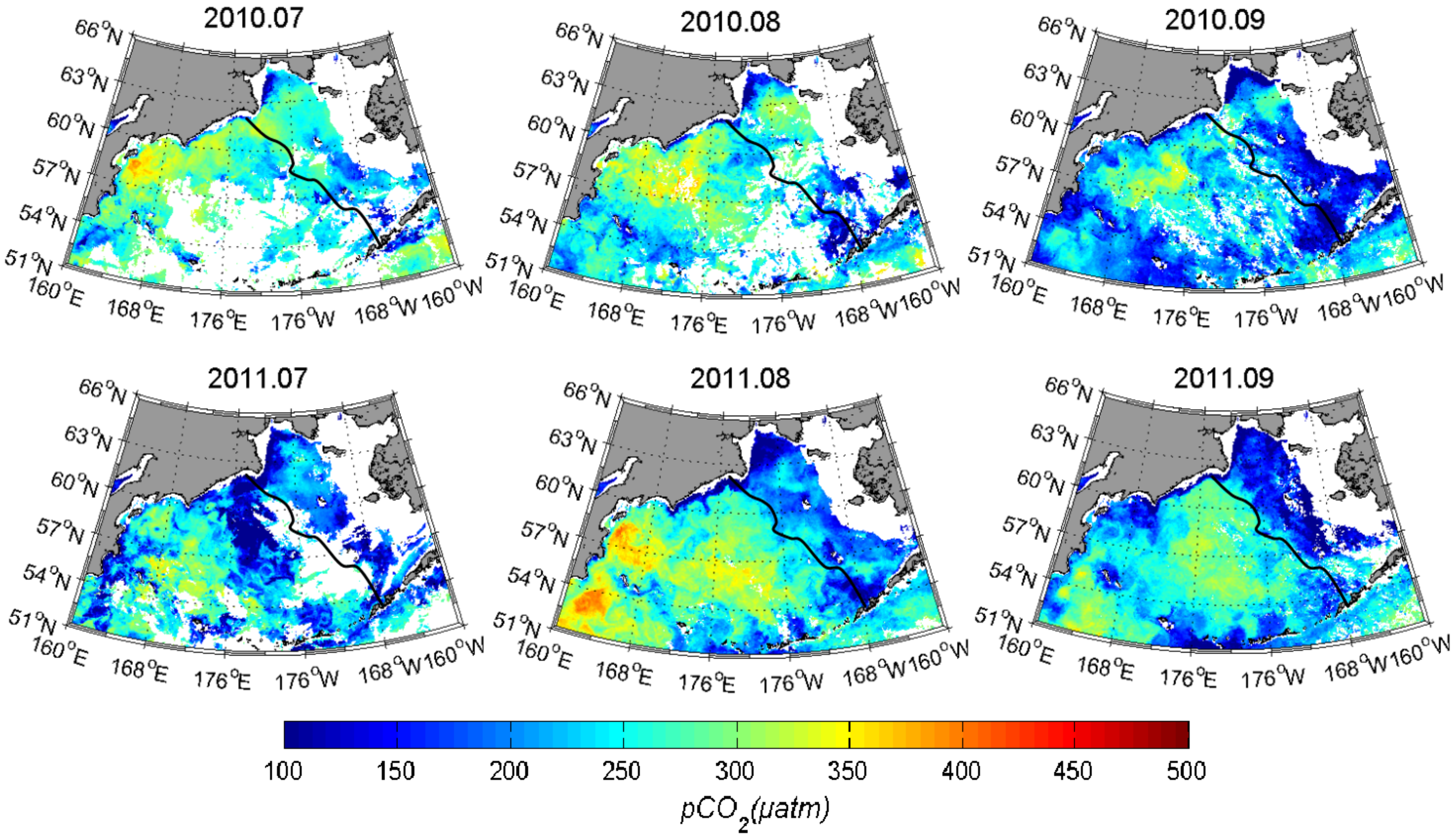




***Bricaud et al.* [1996]**

***chla*-specific absorption coefficients also showed an exponential decay relationship with log(*chla*) due to the package effect**

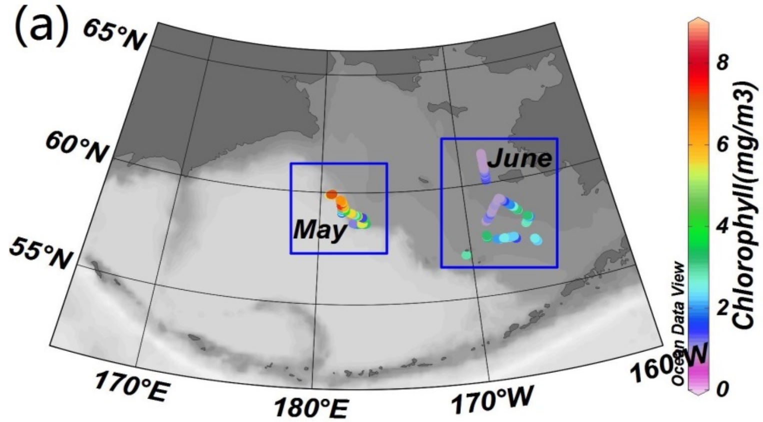
Satellite-derived pCO_2 in summer

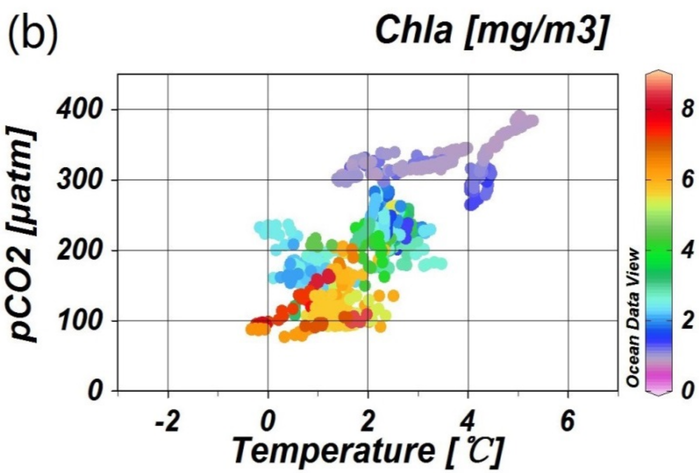


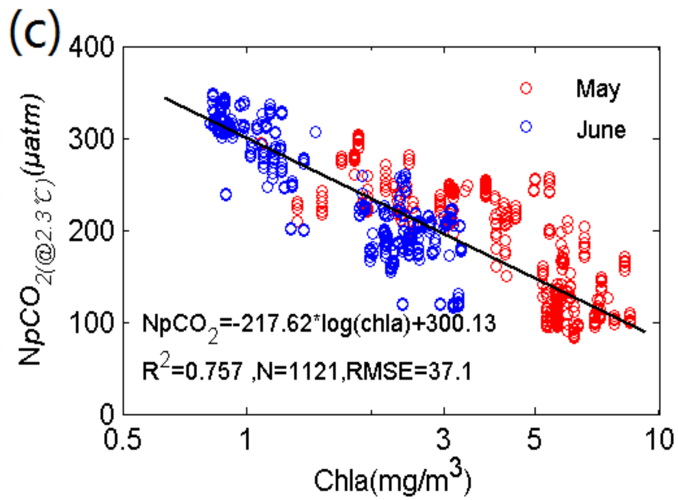
$$pCO_2 = \text{A-B} \times \log(chla) + \varepsilon$$

BS: B=217.62

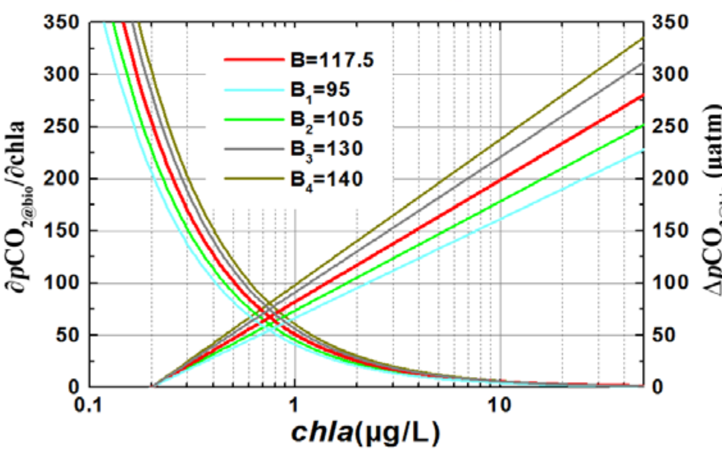
ECS: B=117.5

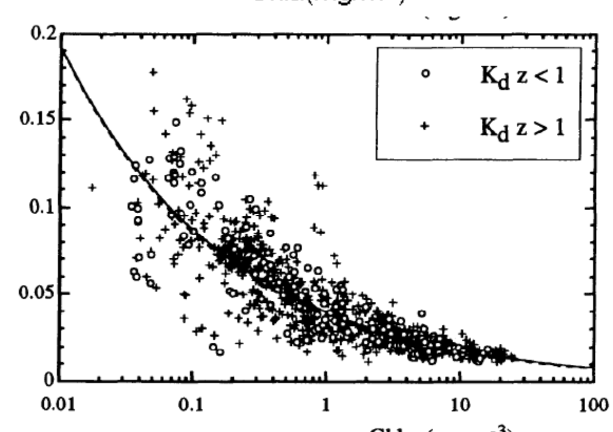






low *chla* regime
small size
large
$\partial pCO_{2@bio}/\partial chla$



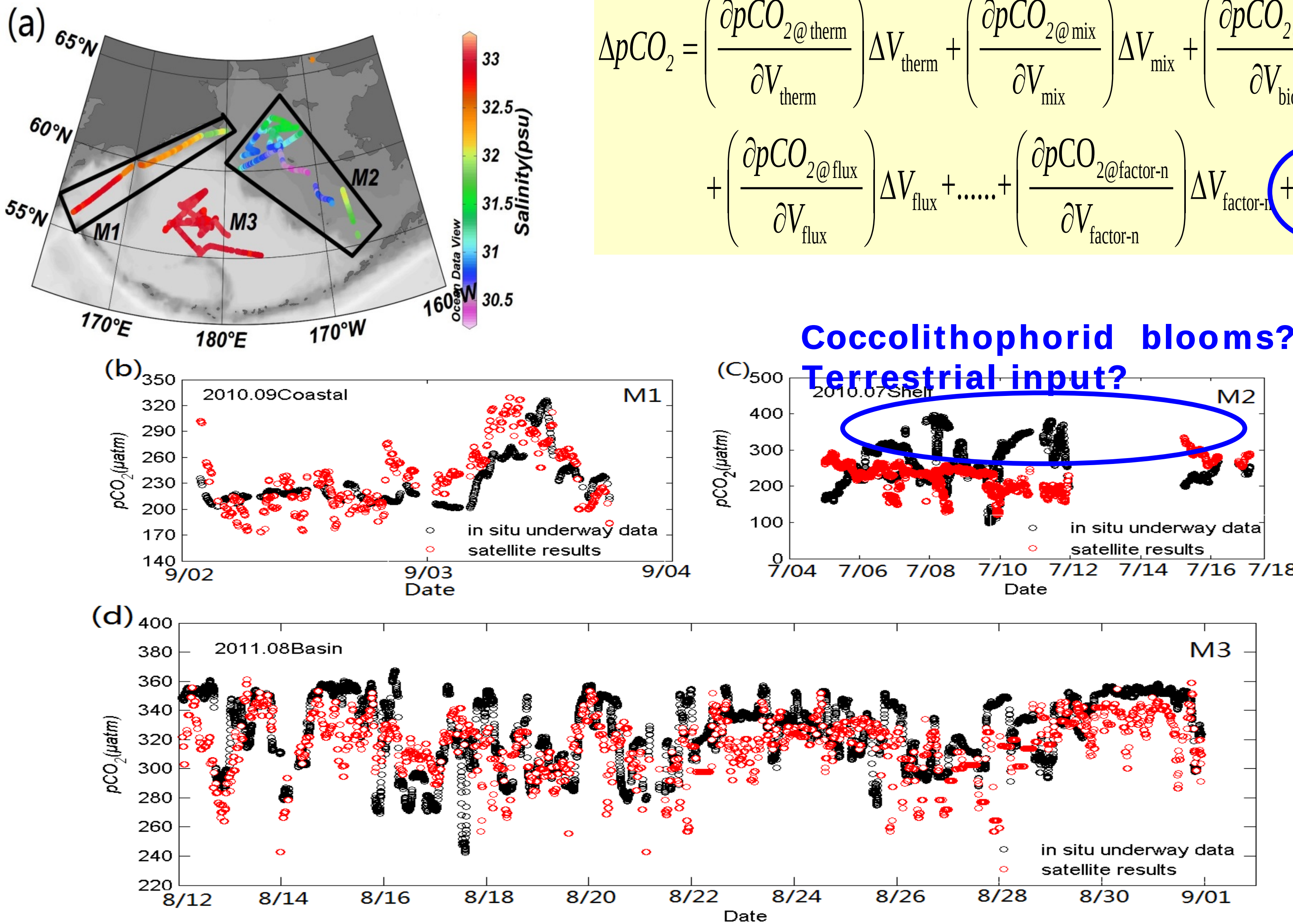


***Bricaud et al.* [1996]**

***chla*-specific absorption coefficients also showed an exponential decay relationship with log(*chla*) due to the package effect**

Validation (1)-monthly

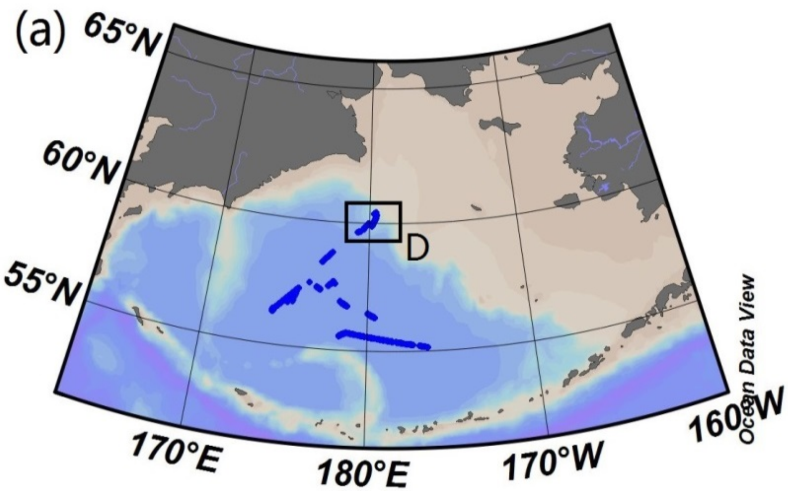
$$\Delta pCO_2 = \left(\frac{\partial pCO_{2@therm}}{\partial V_{therm}}\right)\Delta V_{therm} + \left(\frac{\partial pCO_{2@mix}}{\partial V_{mix}}\right)\Delta V_{mix} + \left(\frac{\partial pCO_{2@bio}}{\partial V_{bio}}\right)\Delta V_{bio} + \left(\frac{\partial pCO_{2@flux}}{\partial V_{flux}}\right)\Delta V_{flux} + \ldots\ldots + \left(\frac{\partial pCO_{2@factor\text{-}n}}{\partial V_{factor\text{-}n}}\right)\Delta V_{factor\text{-}n} + \varepsilon$$

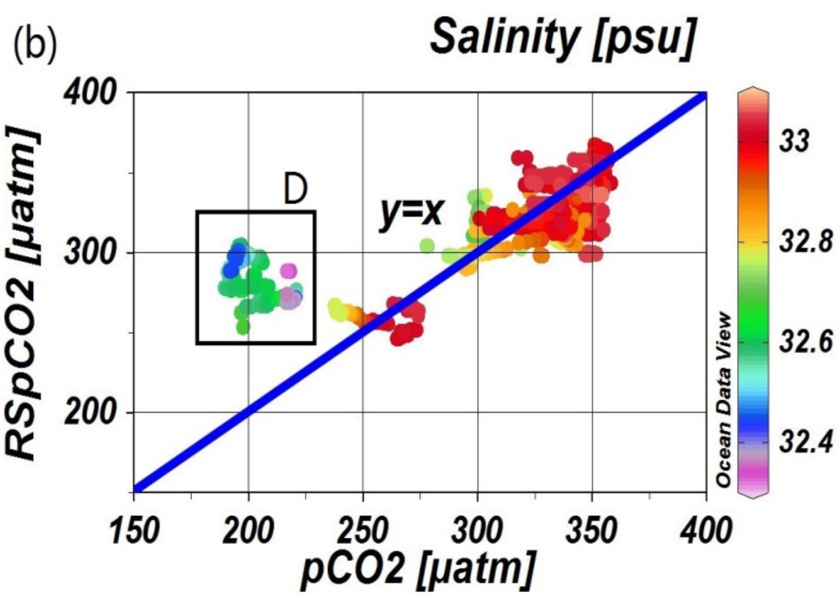


Coccolithophorid blooms?
Terrestrial input?

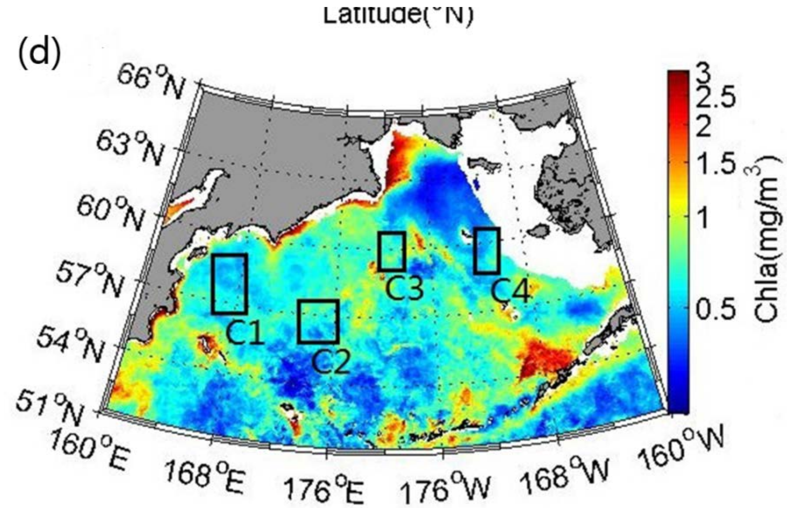
Song, Bai* et al., RS, 2016

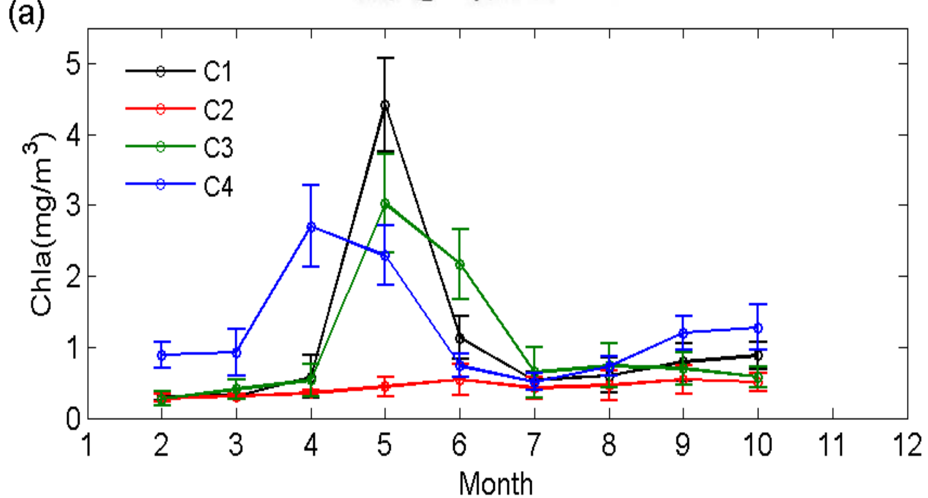
Validation (2)-daily





Influence by pervious spring algae bloom on summer $p\mathrm{CO}_2$

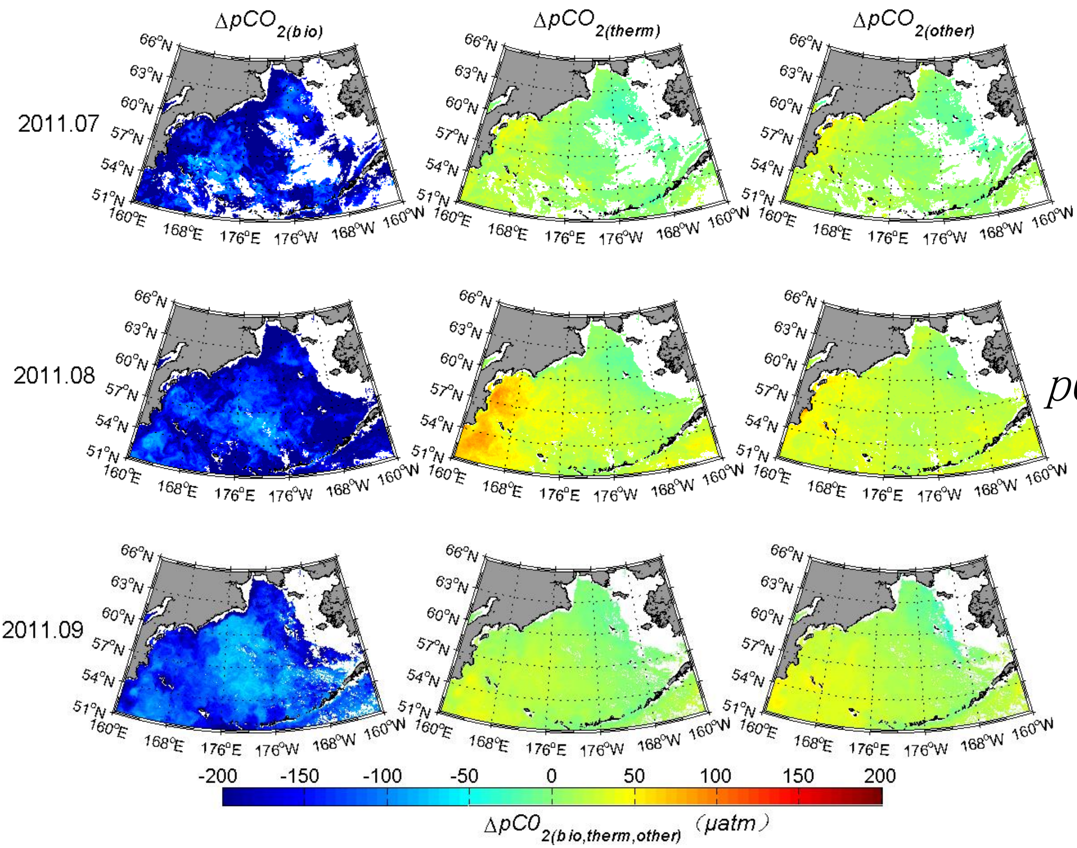




The re-equilibrium time triggered by the air-sea CO_2 flux (40-60 day)

Contribution of different controlling factors on the variation of $p\mathrm{CO_2}$

$$pCO_2 = pCO_{2(o)} + \left(\frac{\partial pCO_{2@therm}}{\partial V_{therm}}\right)\Delta V_{therm} + \left(\frac{\partial pCO_{2@bio}}{\partial V_{bio}}\right)\Delta V_{bio} + \varepsilon$$



$$npCO_{2(sea)} = pCO_{2(sea)@T_{obs}} * e^{(0.0423*(T(o)-T_{obs}))}$$

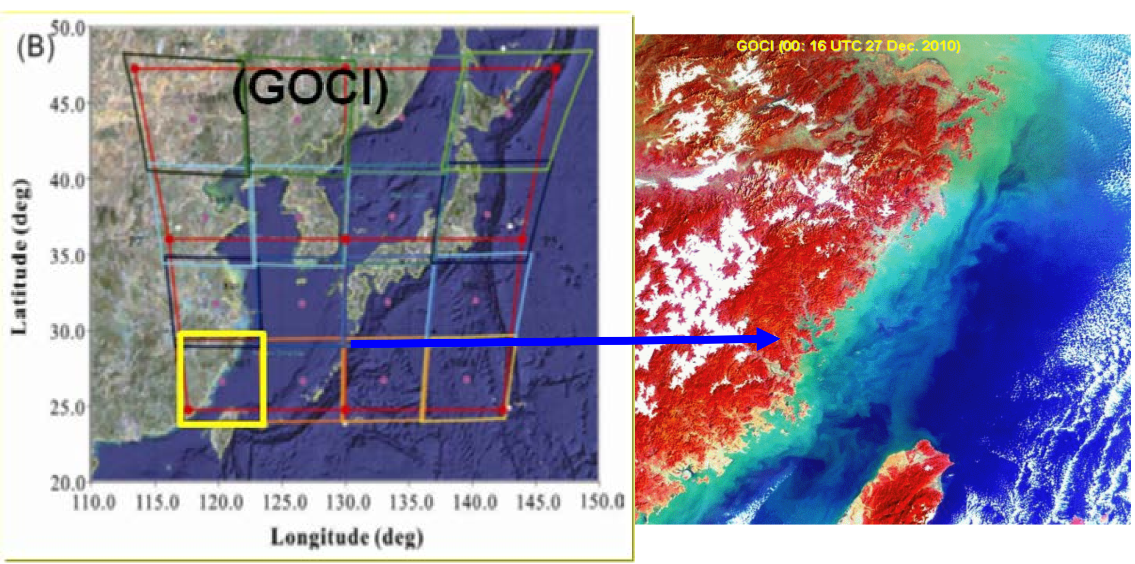
$$B^* = n\Delta pC0_{2(sea-air)}$$

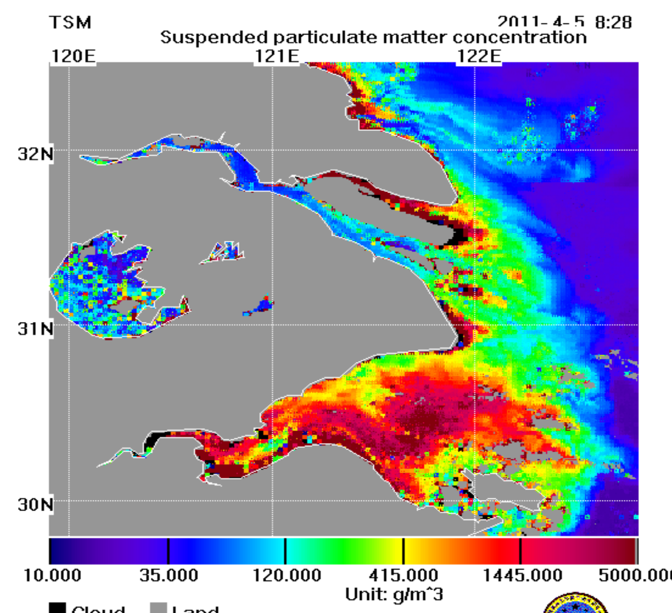
$$pC0_{2(therm)} = \Delta pC0_{2(sea-air)} - npC0_{2(sea-air)}$$

$$\Delta pCO_{2(other)} = B^* - \Delta pCO_{2@bio}$$

Ongoing work…… （MeSAA-pCO_2）

1. **Parameterization of the Physical Mixing Effect or Meso-scale processing (mixing index, SSS, SST, MLD, other proxy?)**
2. **Parameterization of the Biological Effect (C/chla, NCP, phytoplankton types, etc.)**
3. **Parameterization of Processes at Different Time Scales (re-equilibrium time?)**





Outline

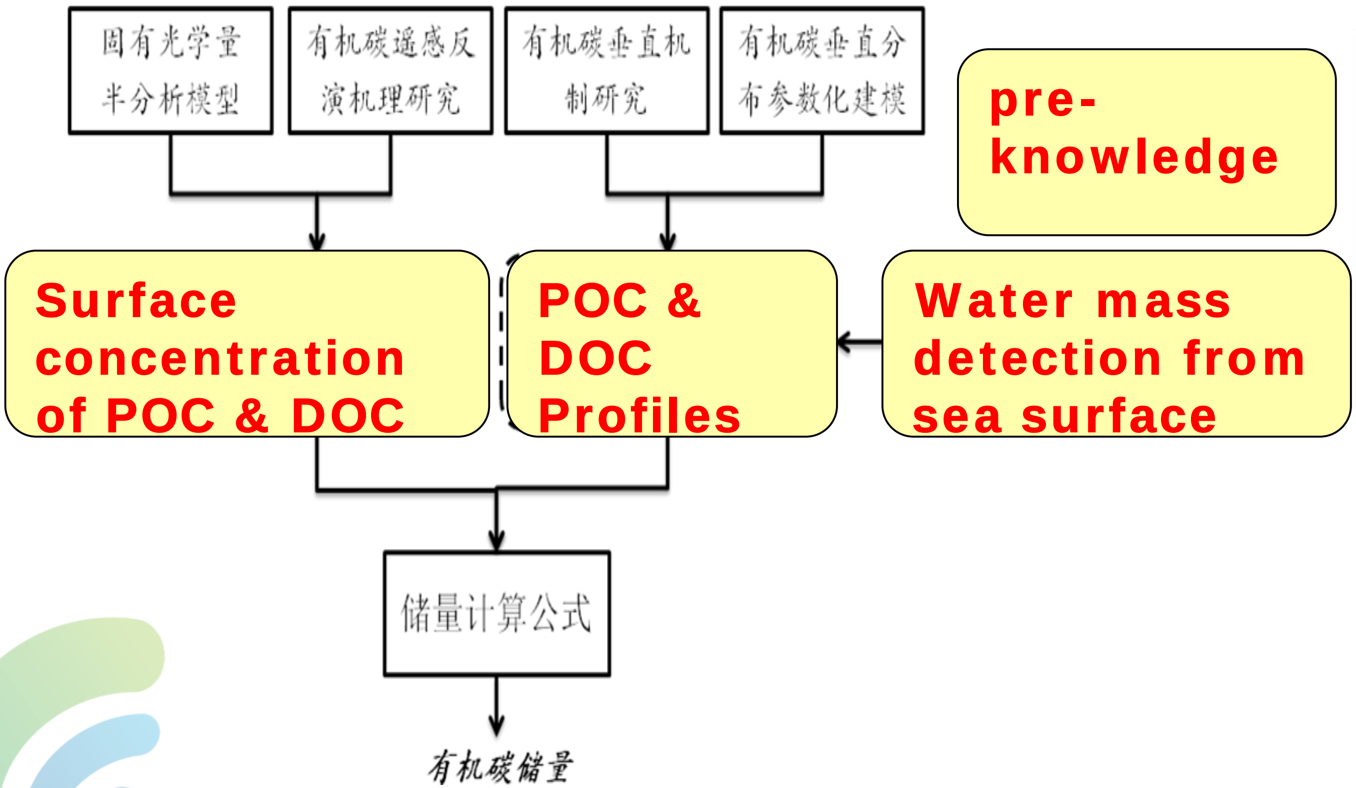
- Framework of satellite-based marine carbon research
- Inorganic Carbon : pCO_2
- Carbon flux estimation
- SatCO2-- Satellite-based marine carbon monitoring and analysis system

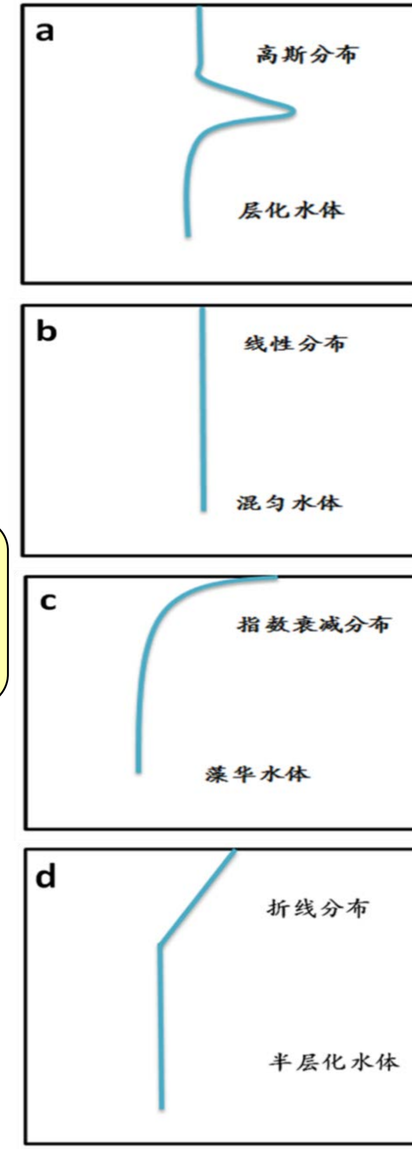
From surface to the water column

Estimation of POC inventory

$$OC_{reservior} = \int_{0}^{z_{eu}} OC_{surf} * f(z, L)dz$$

$$s_{poc} = \int_{0}^{z_m} c_{poc,s} f(z, \cdots) dz,$$





Pan et al., AOS, 2014

Water mass and models of DOC profile

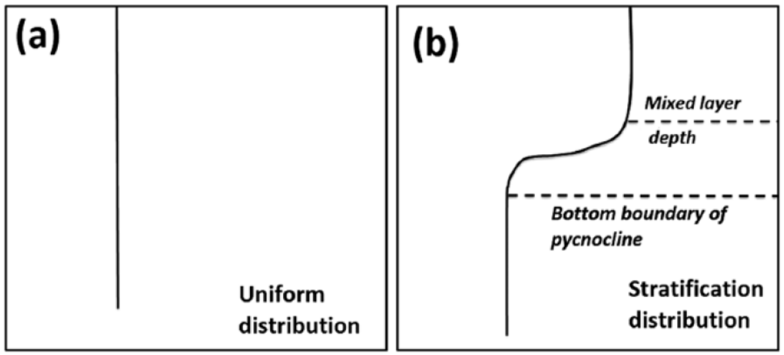
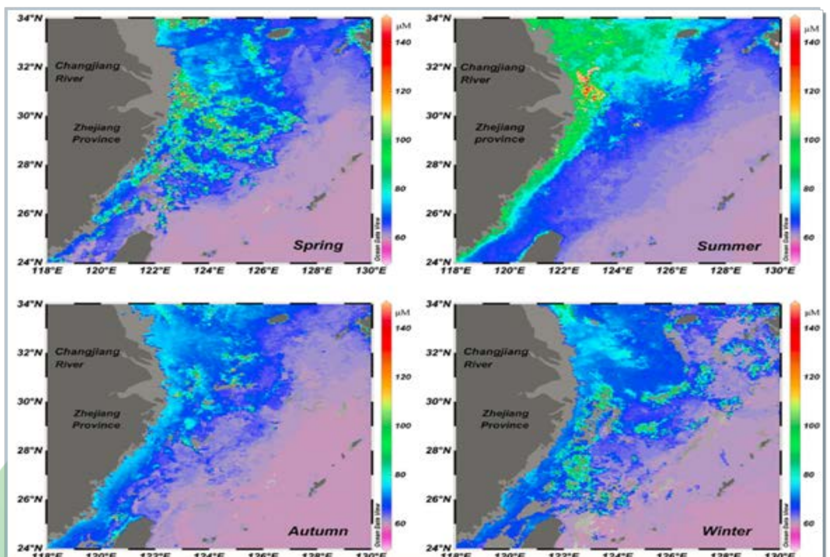
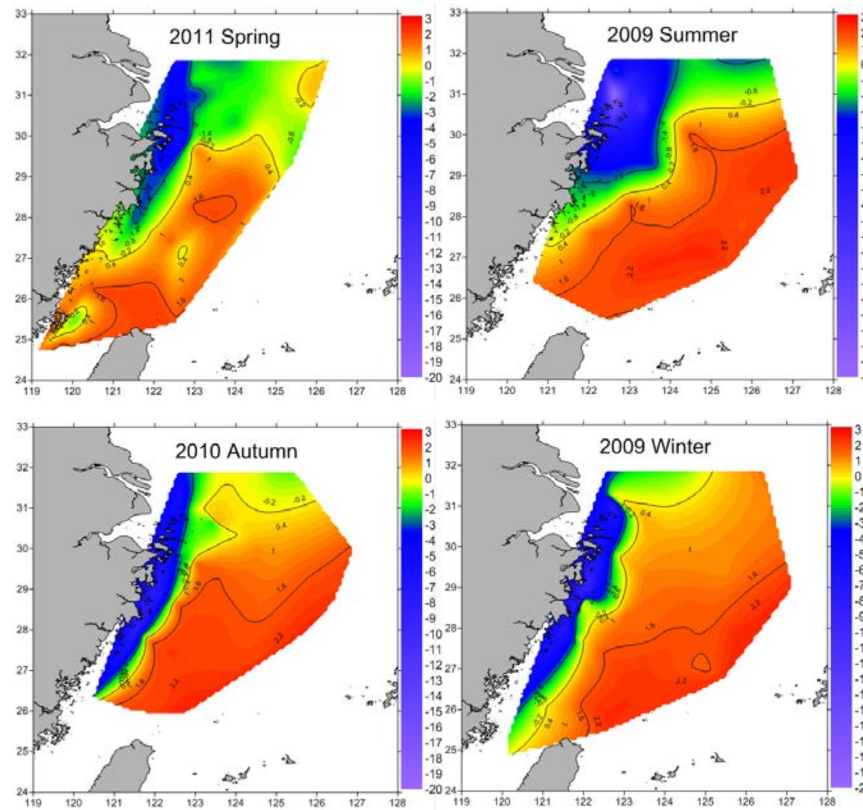


Figure 6. Two simplified models of the vertical DOC profile: (a) a uniform model and (b) a stratification model.



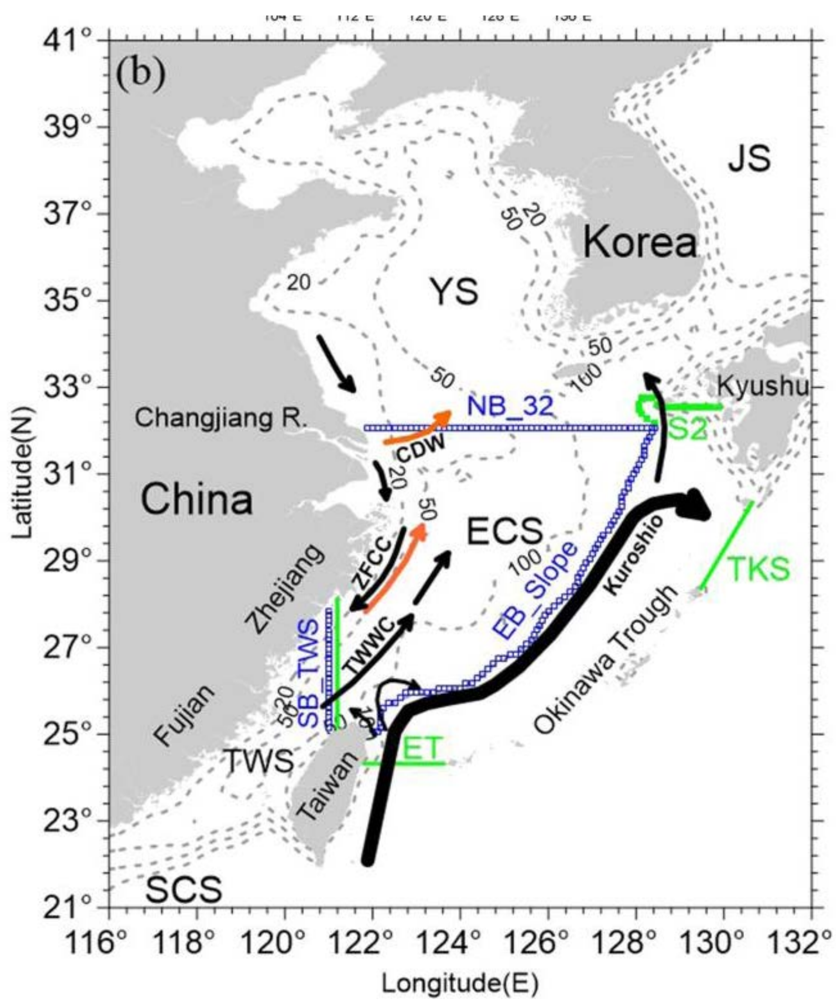
Liu et al., JGR-Oceans, 2014

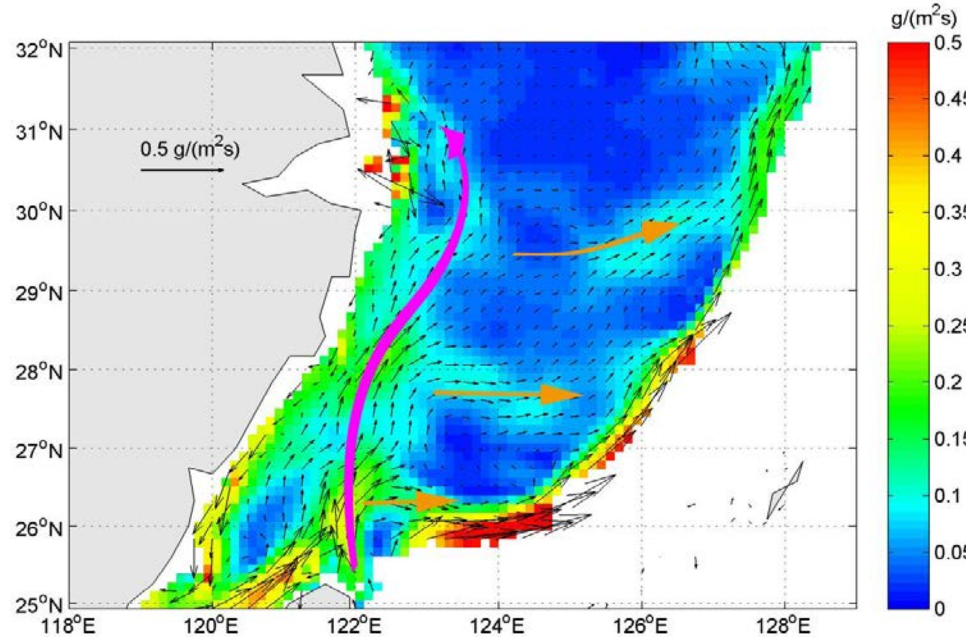


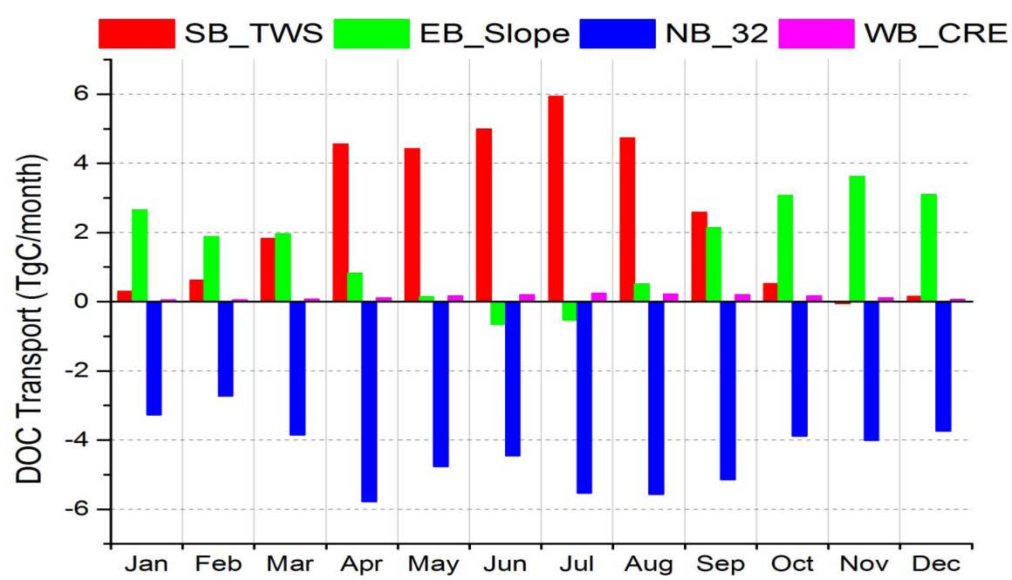
Spiciness index (Li et al., 2006)

$$\beta = \frac{(T - T')}{\Delta T} + \frac{(S - S')}{\Delta S}\alpha,$$

Estimation of lateral DOC transport in marginal sea based on remote sensing and numerical simulation



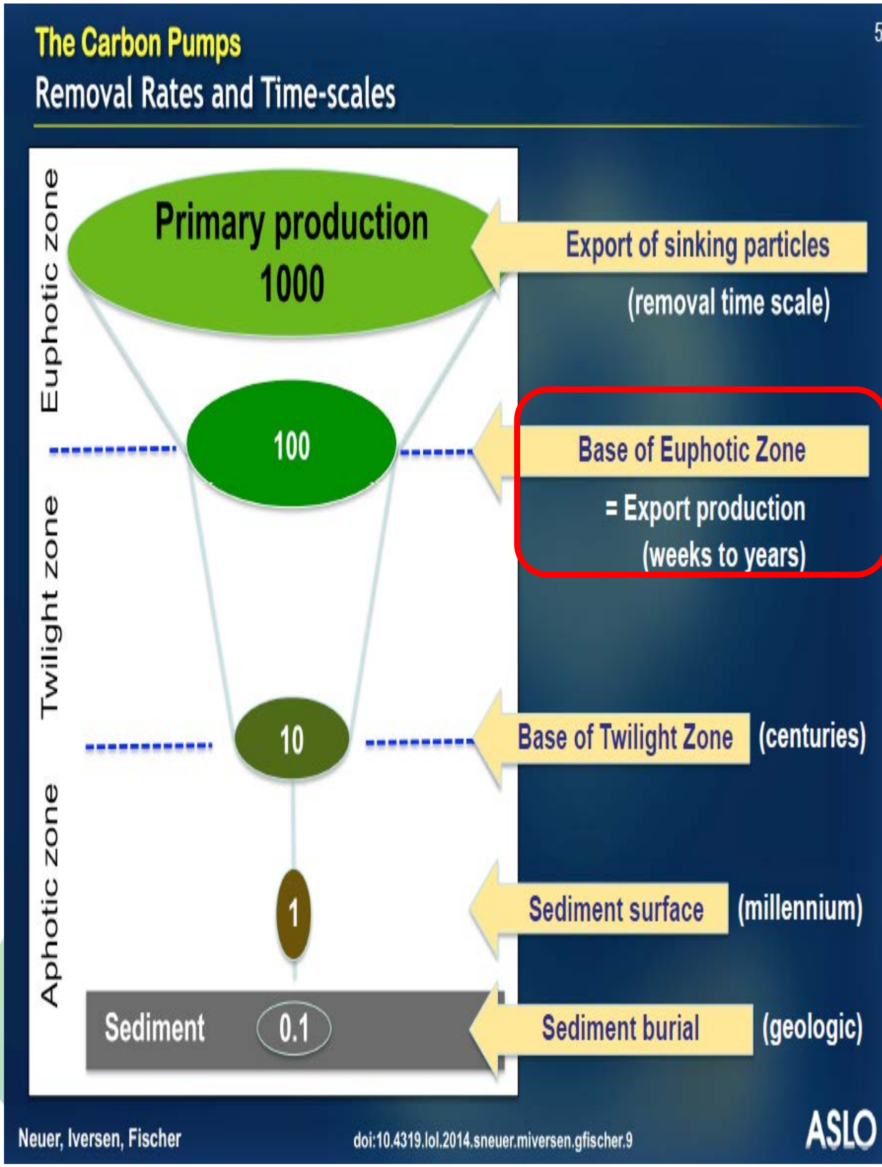


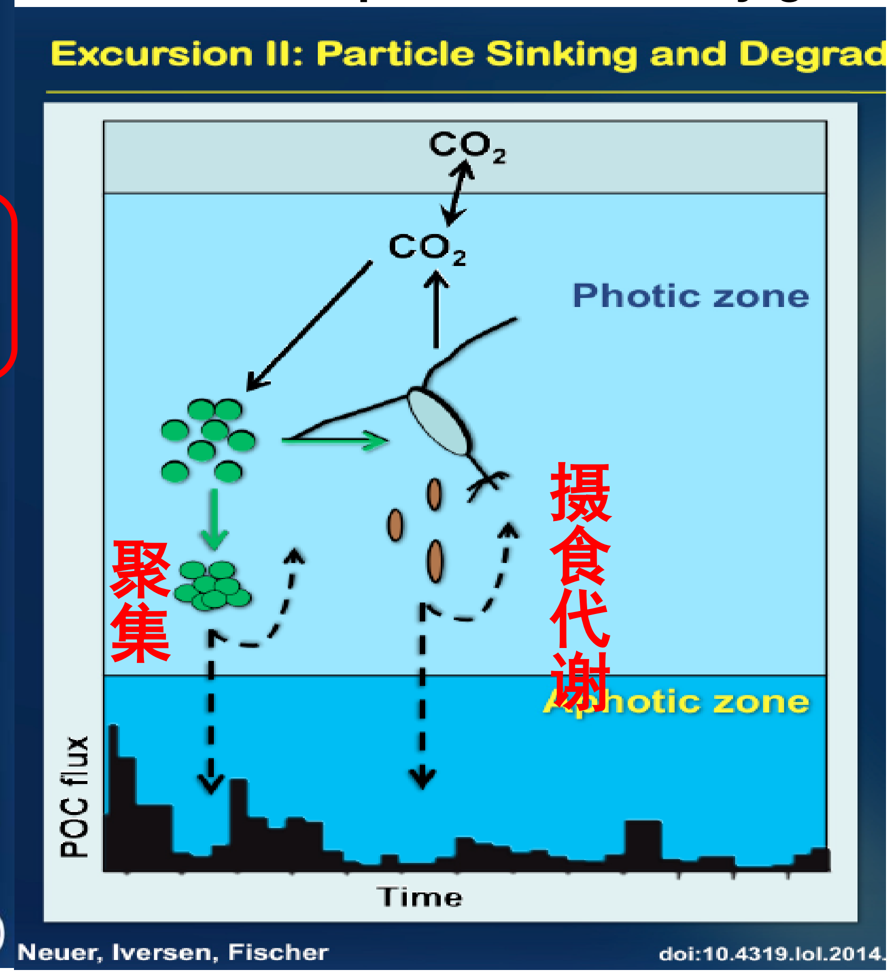


Cui, He*, et al., JGR, 2018

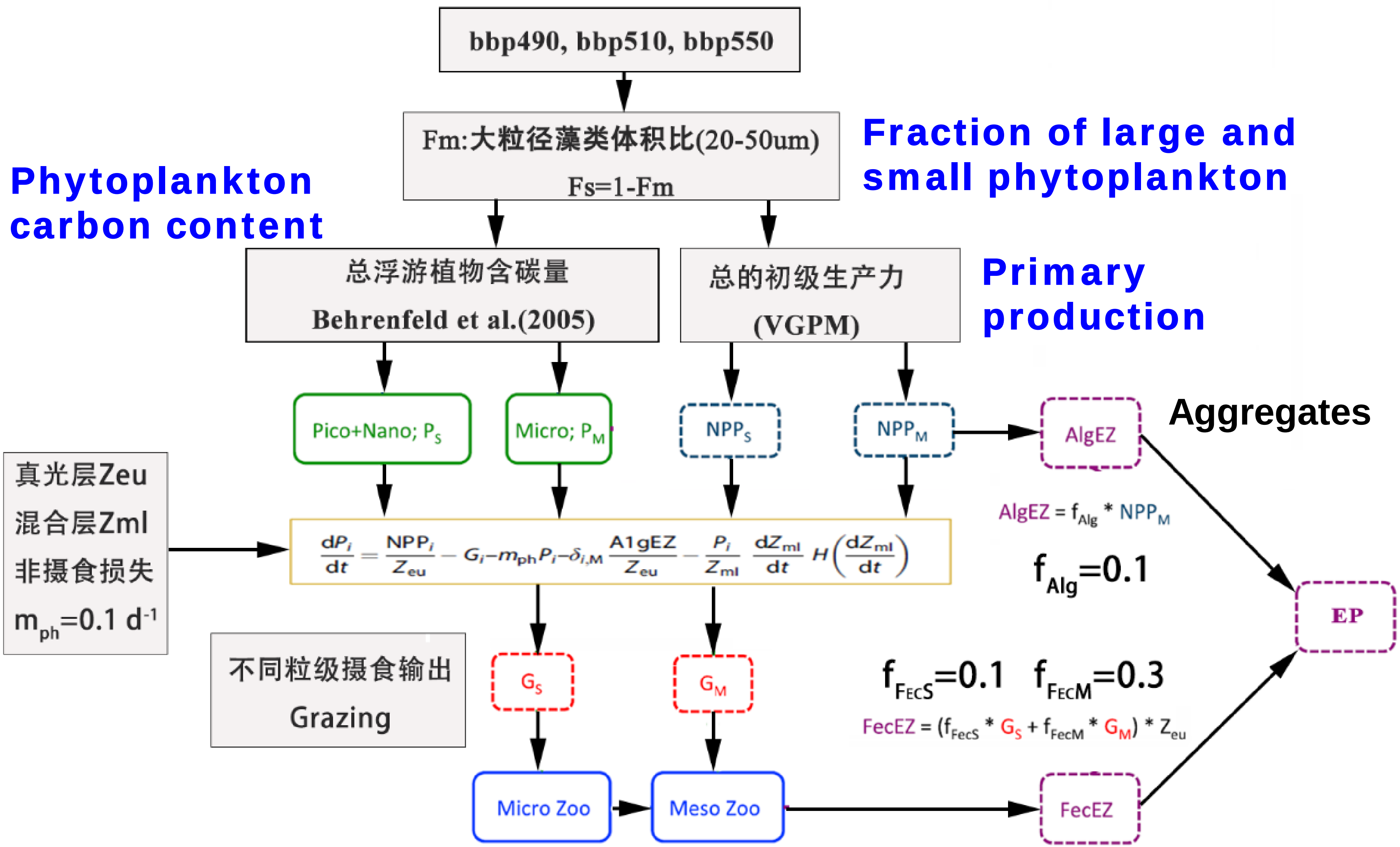
POC export flux (sequestration)

- **direct sinking flux of large phytoplankton and associated aggregates by gravity**
- **flux of zooplankton feces by grazing**





POC export flux estimated based on Food-web model

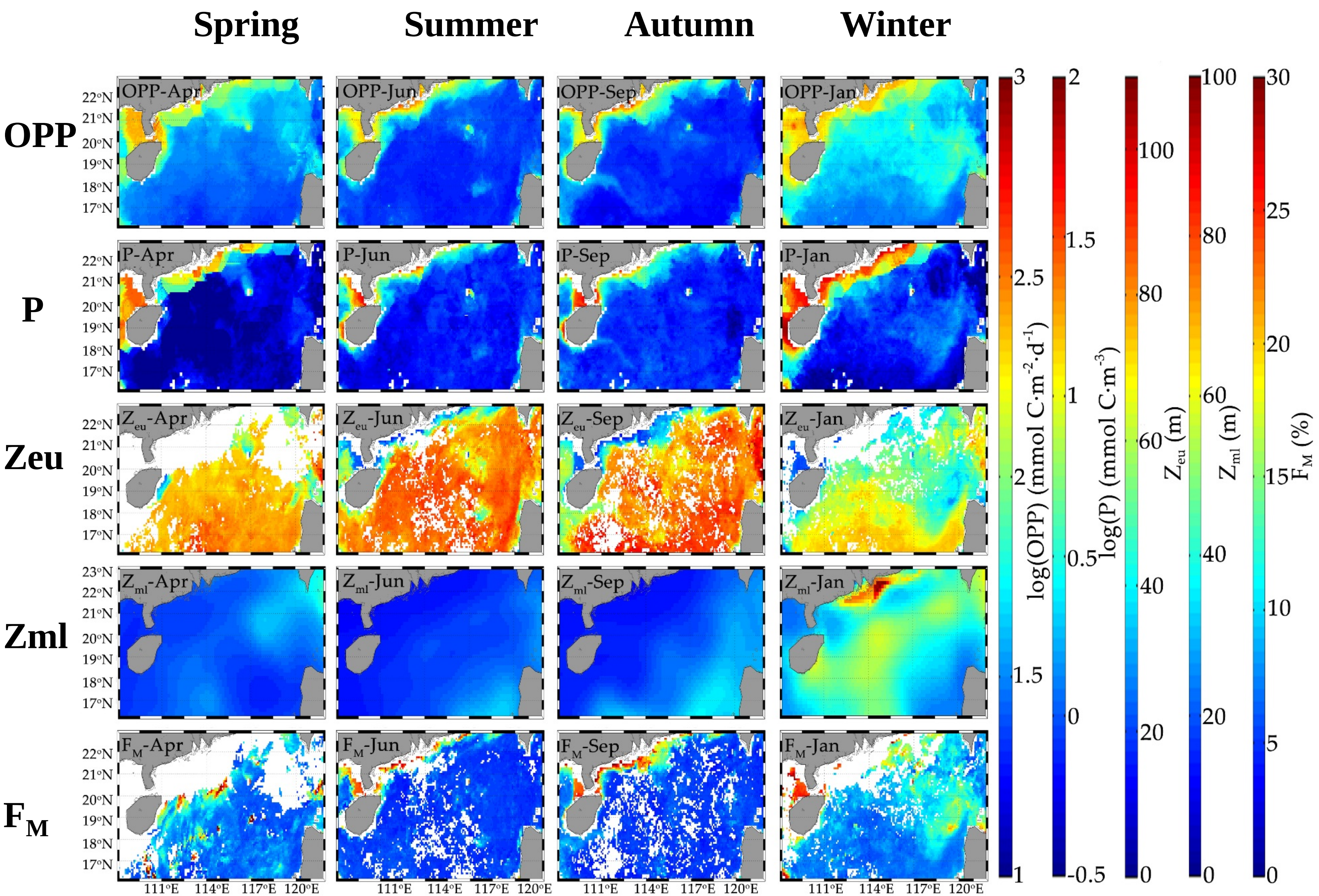


zooplankton feces by grazing

Siegel et al. 2014

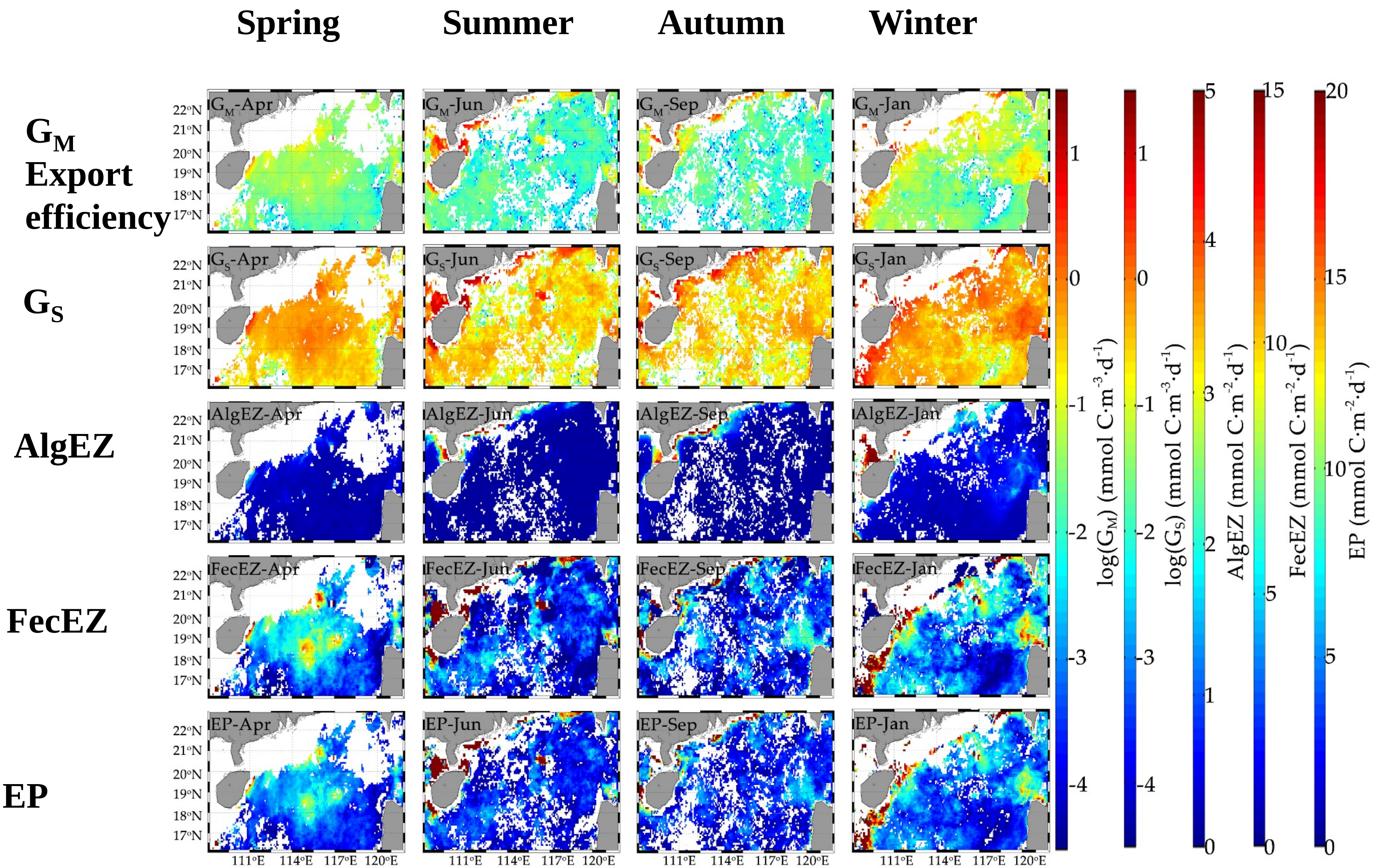
Model-input data

Li, Bai*, etc. 2018, JGR



Model results

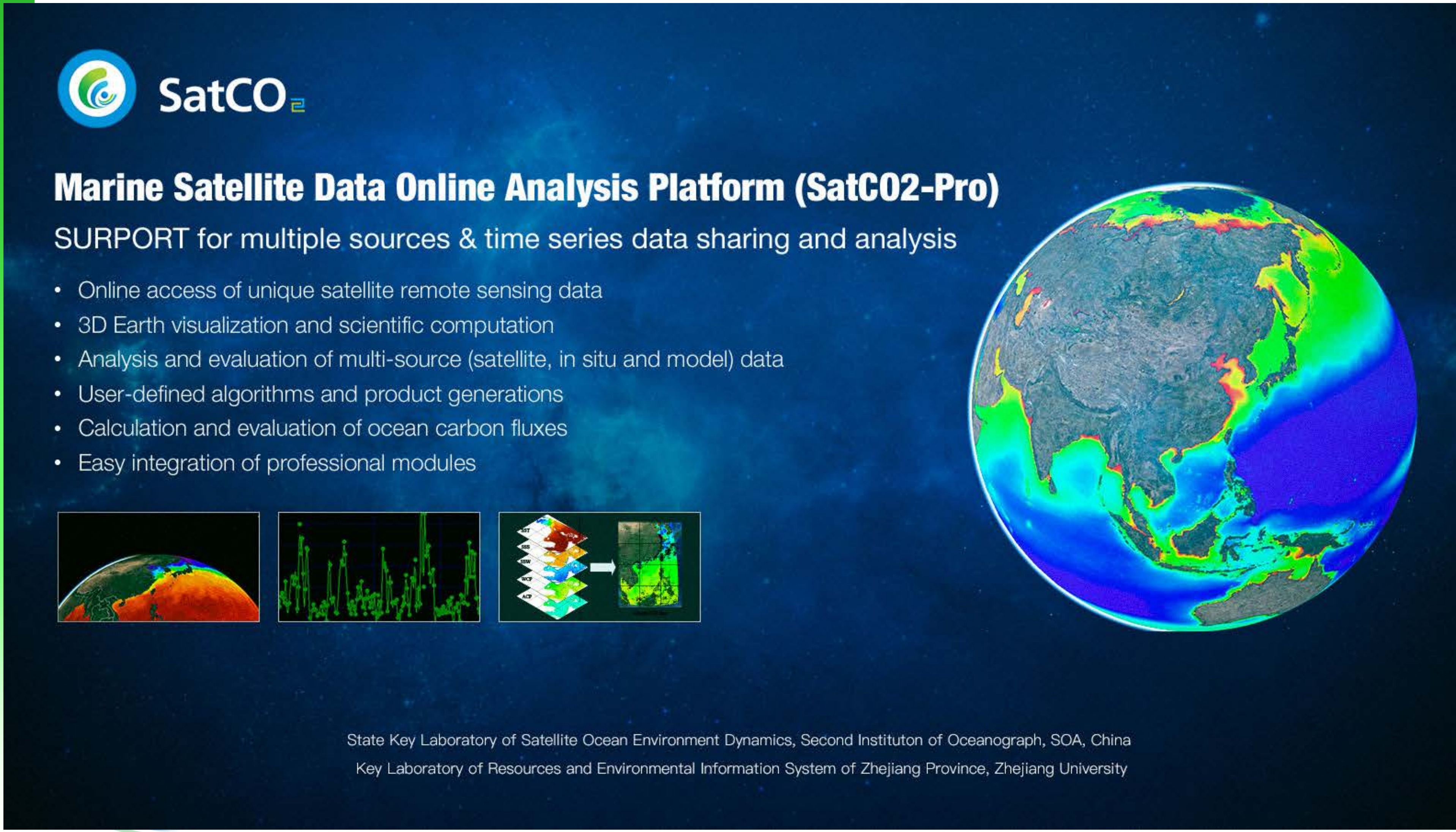
Li, Bai*, etc. 2018, JGR



Outline

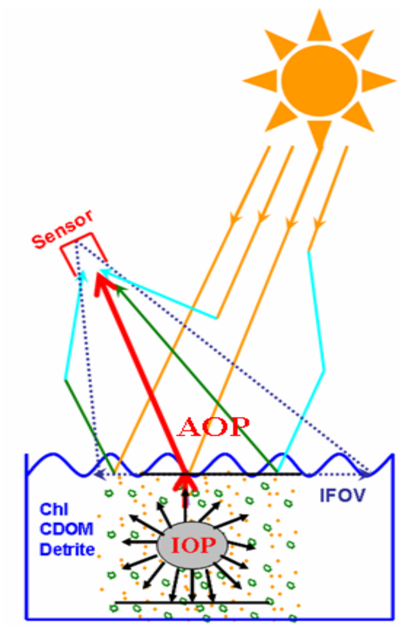
- Framework of satellite-based marine carbon research
- Example: $p\mathrm{CO_2}$ and POC export flux
- SatCO2-- Satellite-based marine carbon monitoring and analysis system

Satellite-based marine carbon monitoring and analysis system (SatCO2)

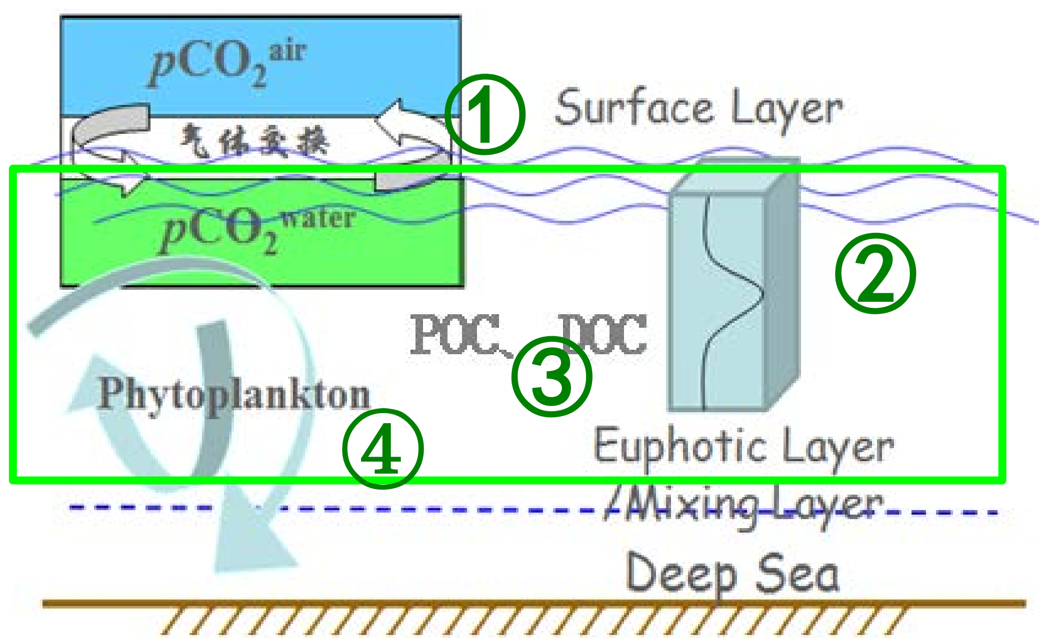


Concluding remarks

1. We want to develop an **integrated marine carbon monitoring and assessing system**, to better quantify, understand and predict the changing marine carbon system, especially in the highly dynamic marginal sea.
2. It need the **joint research on multi-disciplines and the collaboration**.



0.水光学遥感



Thank you for your attention！

SatCO$_2$

国家海洋局第二海洋研究所
SIO
SECOND INSTITUTE OF OCEANOGRAPHY SOA

SOED