NASA Ocean Color Research Team Meeting

Washington, D.C.

15 April, 2004

CLIVAR/CO_2 Repeat Survey & Underway pCO_2 On Ships of Opportunity

Richard A Feely

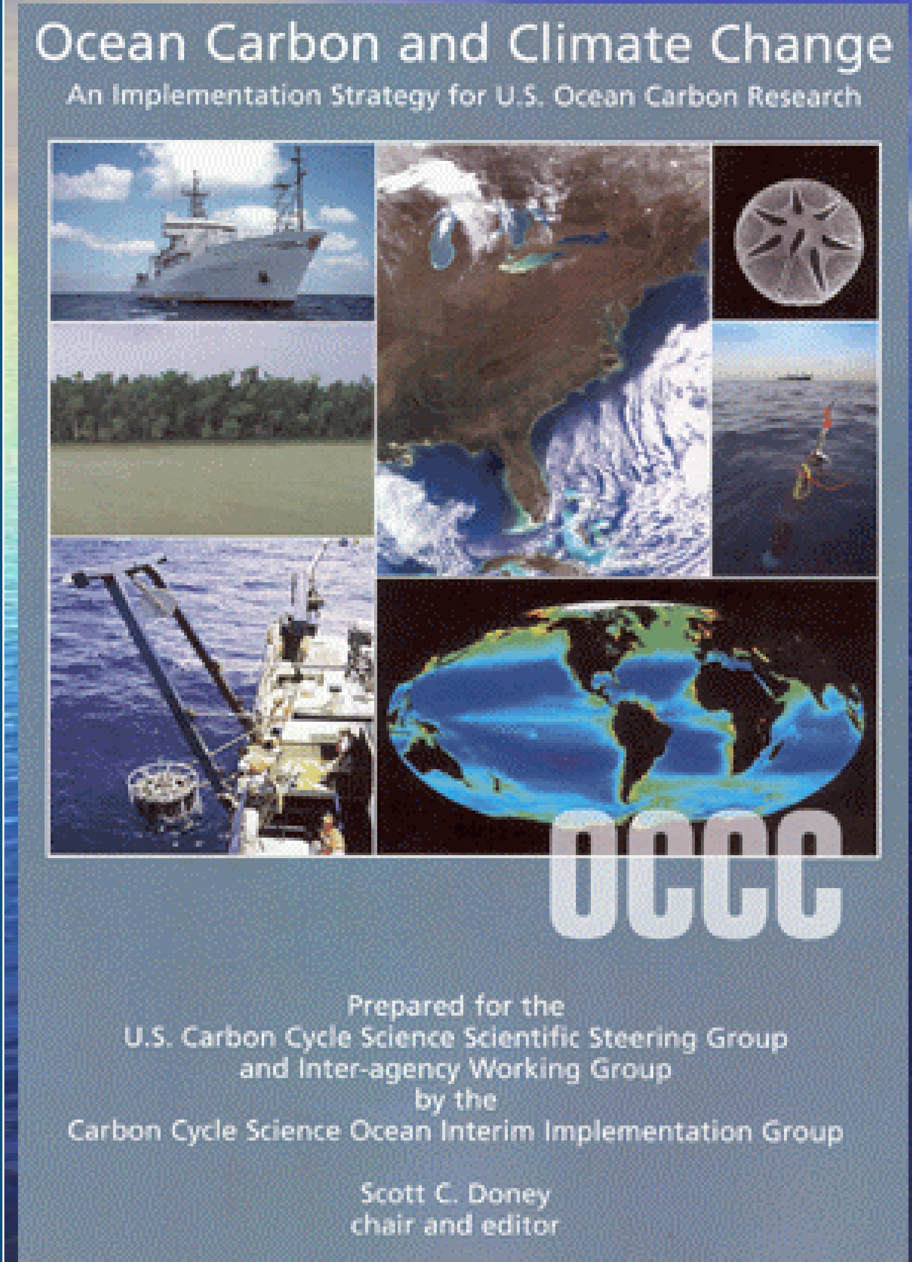
Pacific Marine Environmental Laboratory/NOAA

Acknowledgements: Rik Wanninkhof, Chris Sabine, Francisco Chavez, Chuck McClain, Dave Siegel

Conclusions

- Repeat Hydrography and VOS cruises offer excellent opportunities for calibration of sensors and validation of model results
- Remote sensing can be a powerful tool to monitor time and space variations of several parameters influencing CO_2 distribution and air-sea fluxes (wind speed, SSH, SST, Chl).
  - Remote sensing can help interpret and extend in space and time in situ measurements
  - Remote sensing can provide constraints for biogeochemical modelling

Fundamental Questions



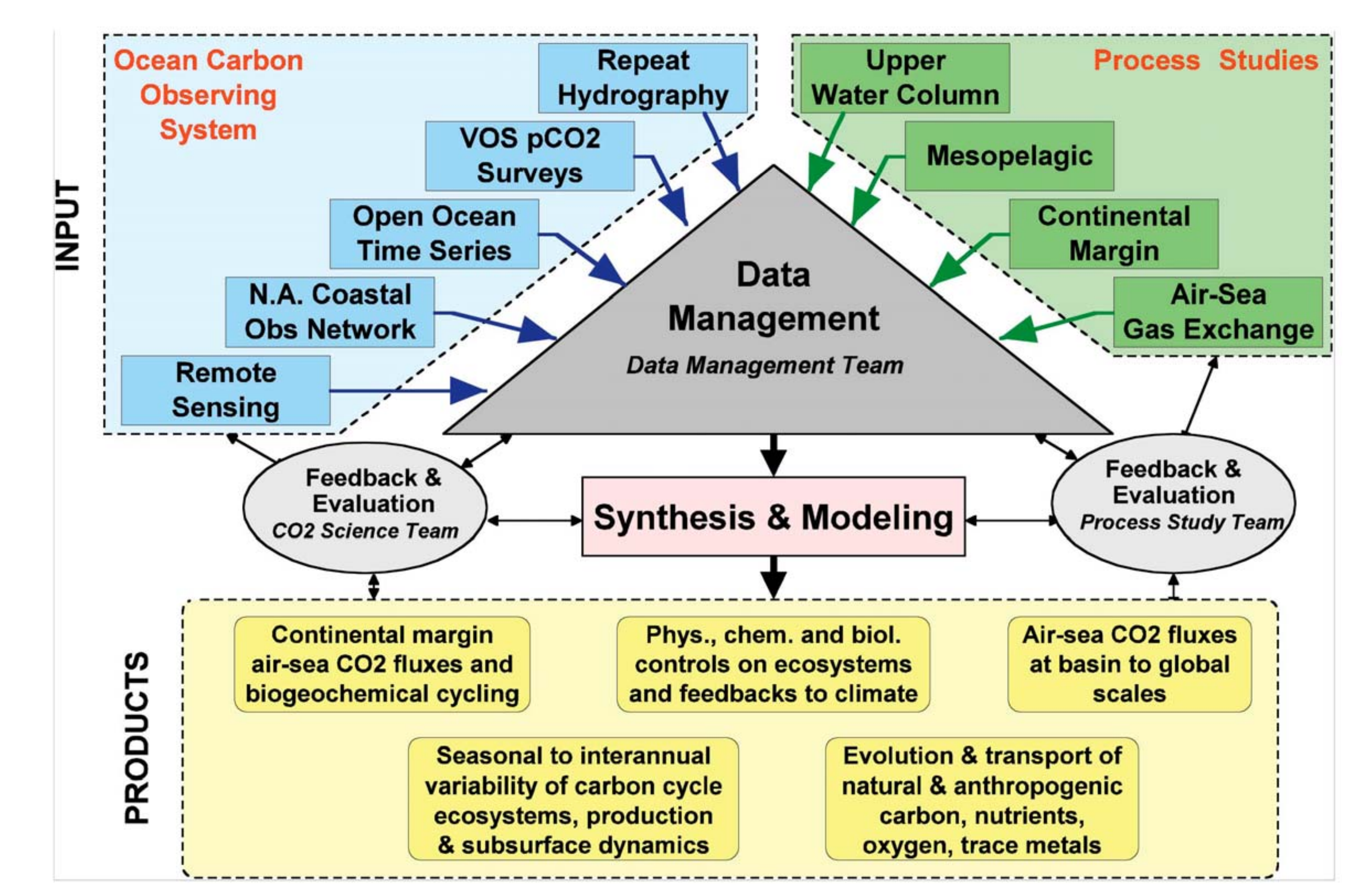
1. What are the global inventory, geographic distribution, and temporal evolution of anthropogenic CO_2 in the oceans?

2. What are the magnitude, spatial pattern, and variability of air-sea CO_2 flux?

3. What are the major physical, chemical, and biological feedback mechanisms and climate sensitivities for ocean organic and inorganic carbon?

4. What is the scientific basis for ocean carbon mitigation strategies?

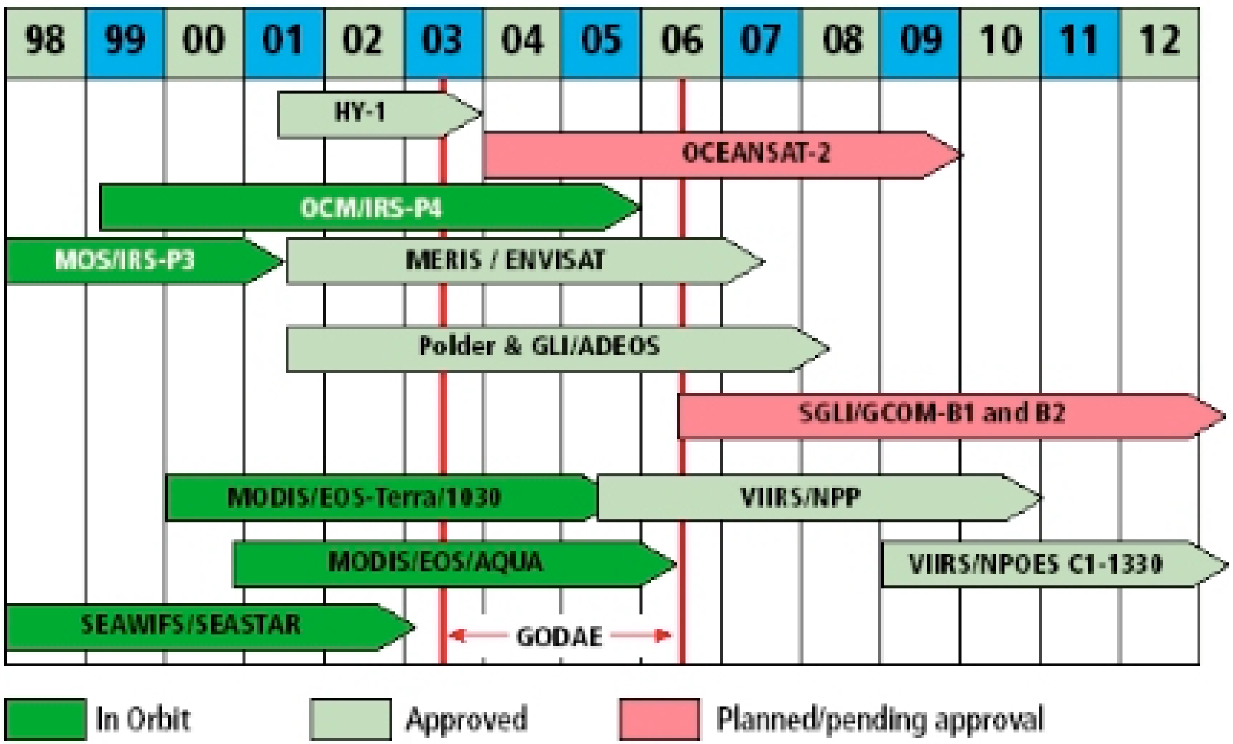
Ocean Carbon and Climate Change Observing System



U.S. Ocean Carbon and Climate Change Data Management System

Status of Current and Planned Observations

Remote Sensing / Ocean-Colour



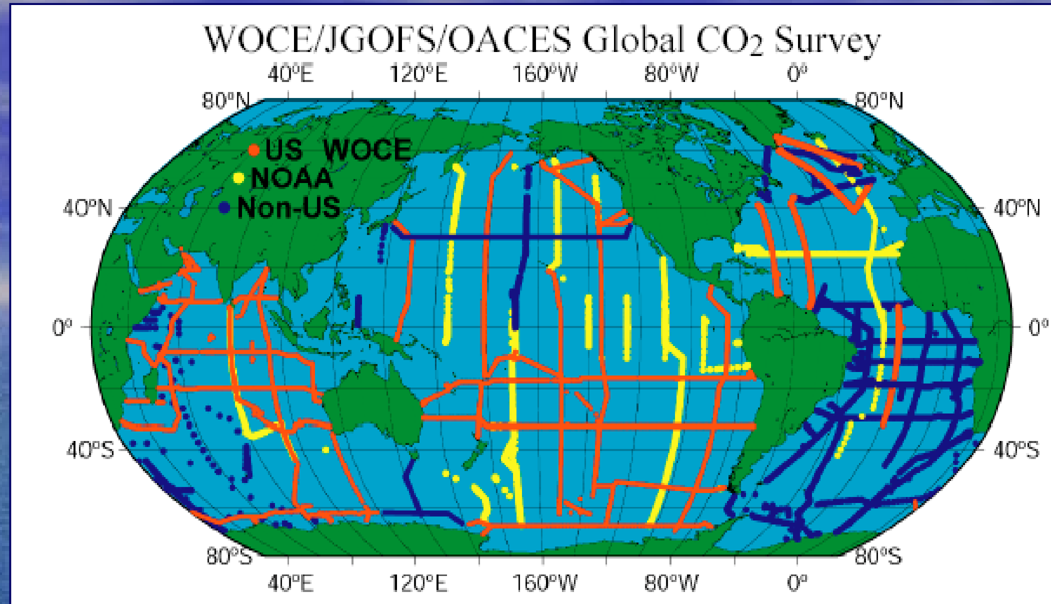
In Situ Water-Column

- -Chlorophyll-a
- -Phytoplankton
- -CDOM
- -Total suspended particles
- -Photosynthetic rates
- -phytoplankton and non-pigmented particle absorption spectra
- -DOC
- -Optical measurements
- -Fluorescence (in vivo)
- -pCO_2
- -Nutrients
- -Incoming solar radiation
- -Wind speed, direction
- -SST
- -Fast rep.-rate fluorometry

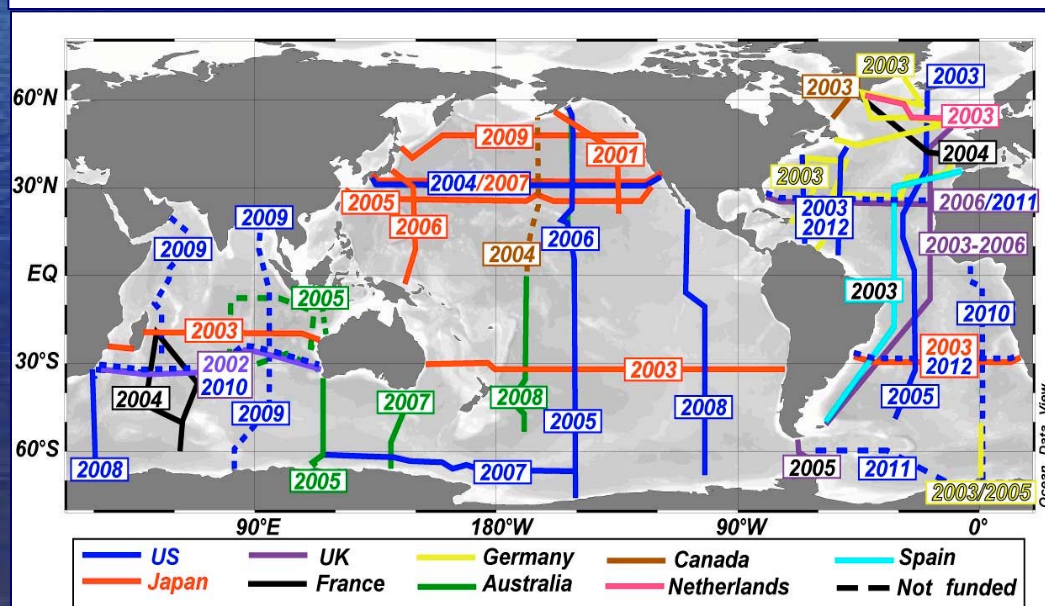
Existing System – Satellite missions adequate to meet requirements for the medium-term. In situ network must be enhanced through times series and VOS measurements.

Repeat Hydrographic Program (US CLIVAR and carbon programs)

1990 ~ 1998



2003 ~ 2012

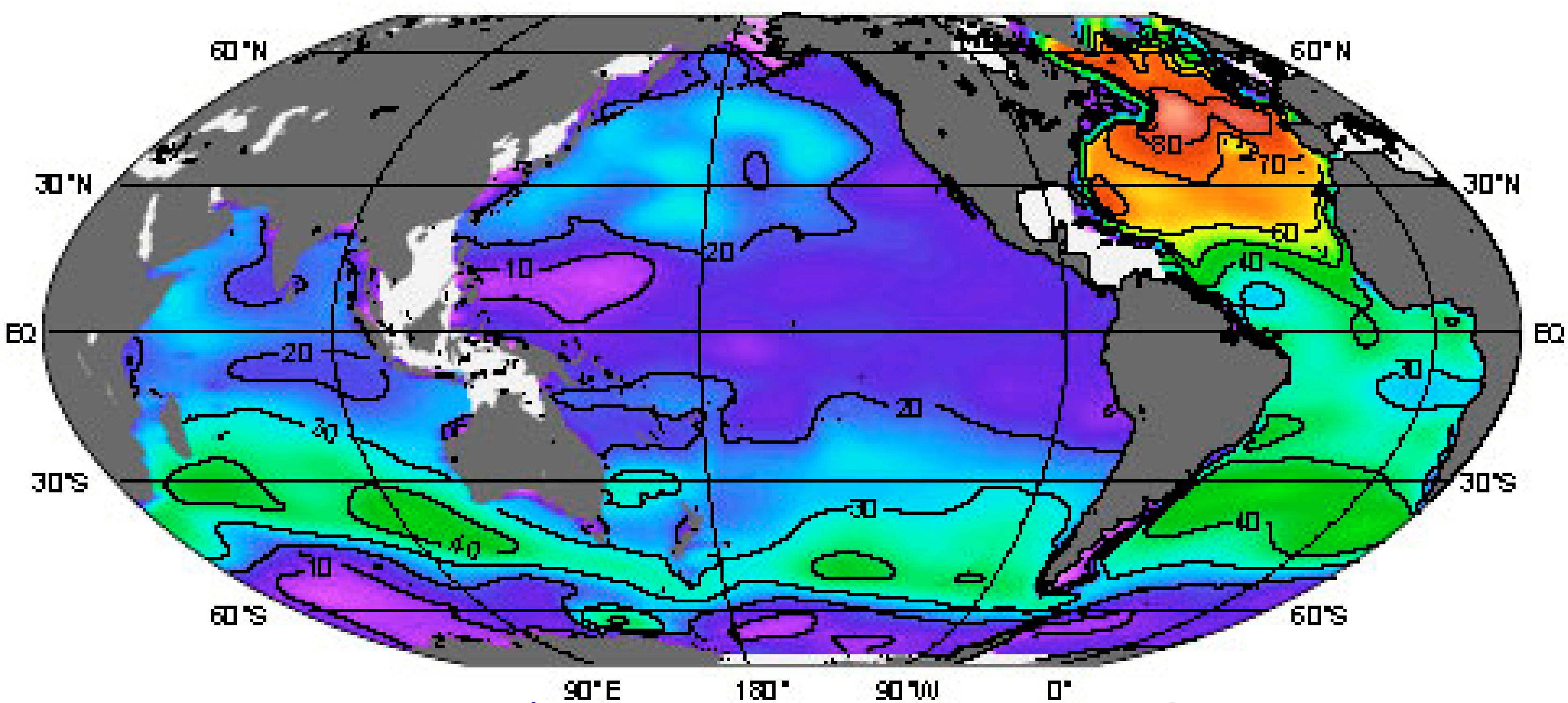


Conduct ongoing program in which 31 ocean sections planned spanning the global ocean are re-occupied every 10 years.

Objectives of the CLIVAR/CO_2 Repeat Hydrography Program

- Data for Model Calibration and Validation
- Carbon system studies
- Heat and freshwater storage and flux studies
- Deep and shallow water mass and ventilation studies
- Calibration of autonomous sensors

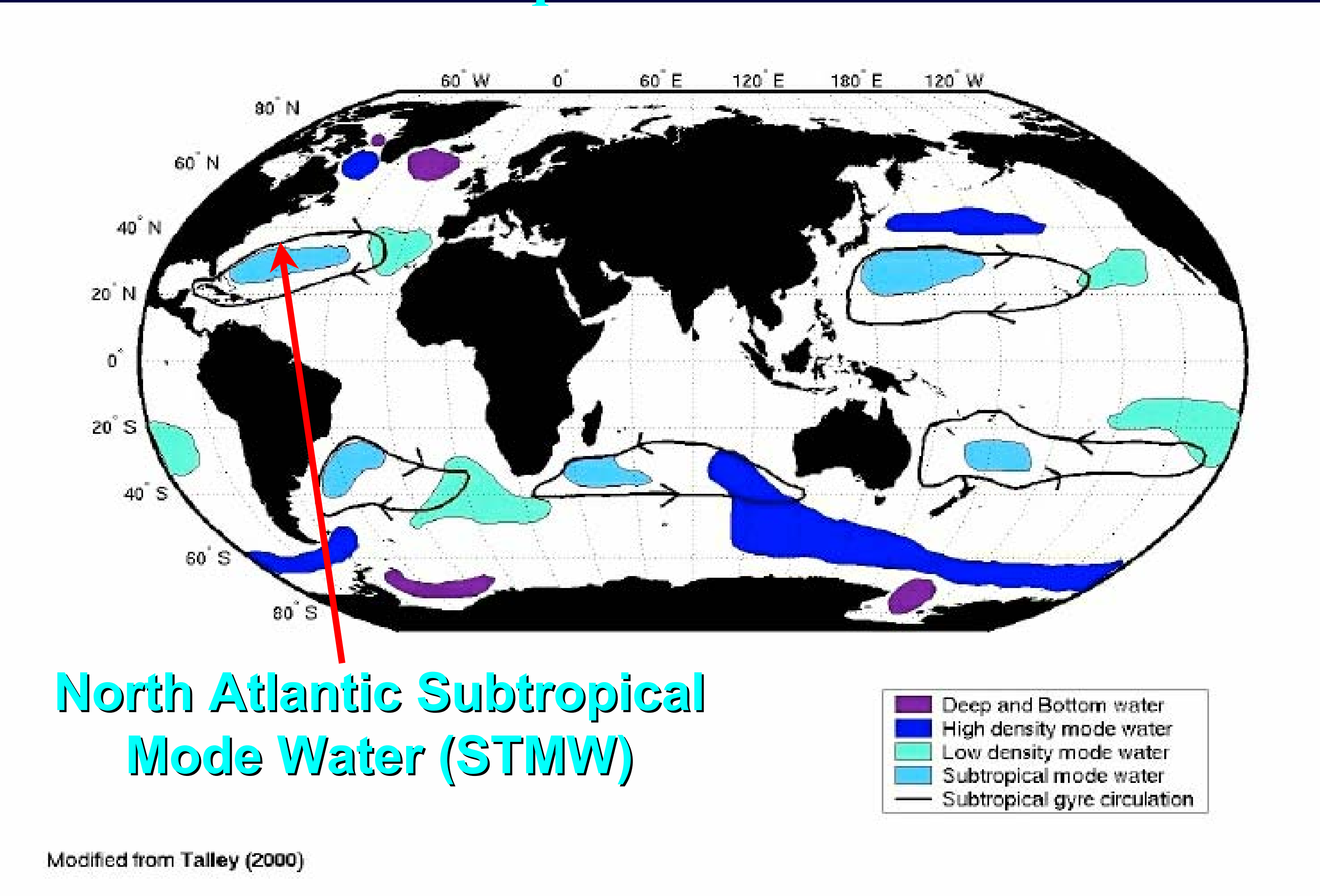
Column inventory of anthropogenic CO_2 that has accumulated in the ocean between 1800 and 1994 (mol m^{-2})



Mapped Inventory 106±17 Pg C
+ marginal seas 6± 6 Pg C
+ Arctic Ocean 6± 6 Pg C

Total Inventory 118±19 Pg C

The magnitude and interannual variability of uptake of carbon dioxide (CO_2) into mode waters are poorly quantified.

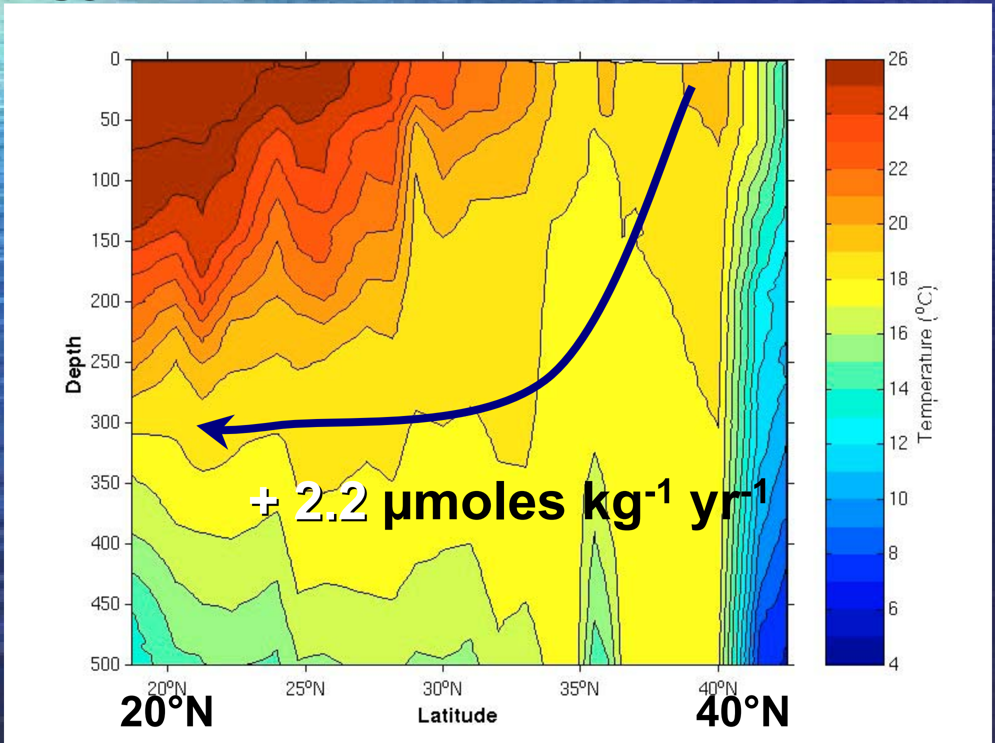


Source: Talley, 2000

Increased sink of CO_2 STMW?

• CO_2 gas flux at the site of STMW formation should increase STMW by 2-3 μmoles kg^{-1} yr^{-1}.

• CO_2 likely retained in STMW during recirculation since ~1987 due to lack of subsequent deep winter mixing associated with extensive STMW across the subtropical gyre.



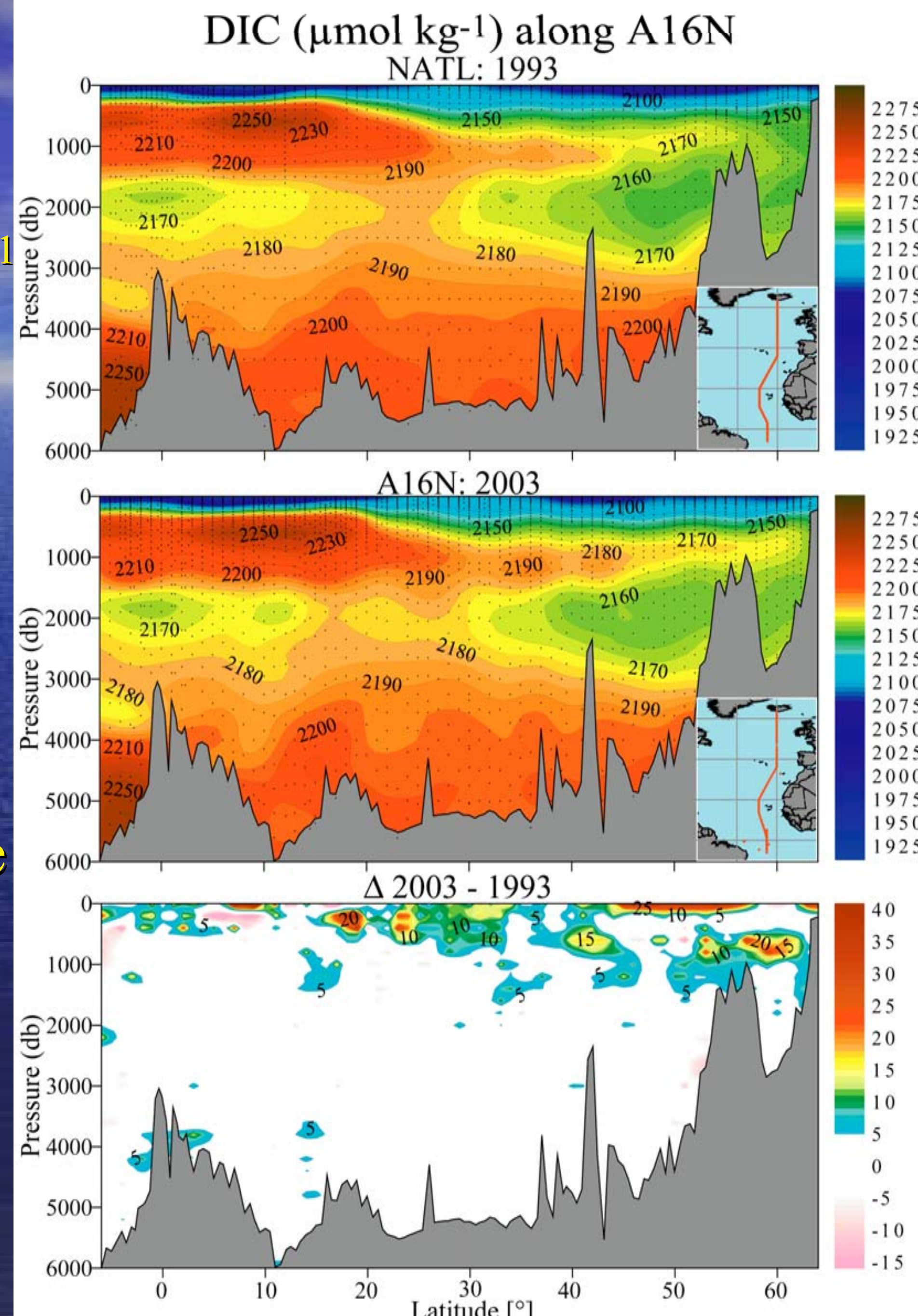
• Empirical and model studies report different annual formation rates of STMW, ranging from <u>5 to 23</u> Sv (Sv = 10^6 m^3 s^{-1}).

• •After STMW formation, the average time for a parcel of STMW water to be transported from the site of STMW to the western boundary current along the path of gyre recirculation has been reported at <u>6-10</u> years.

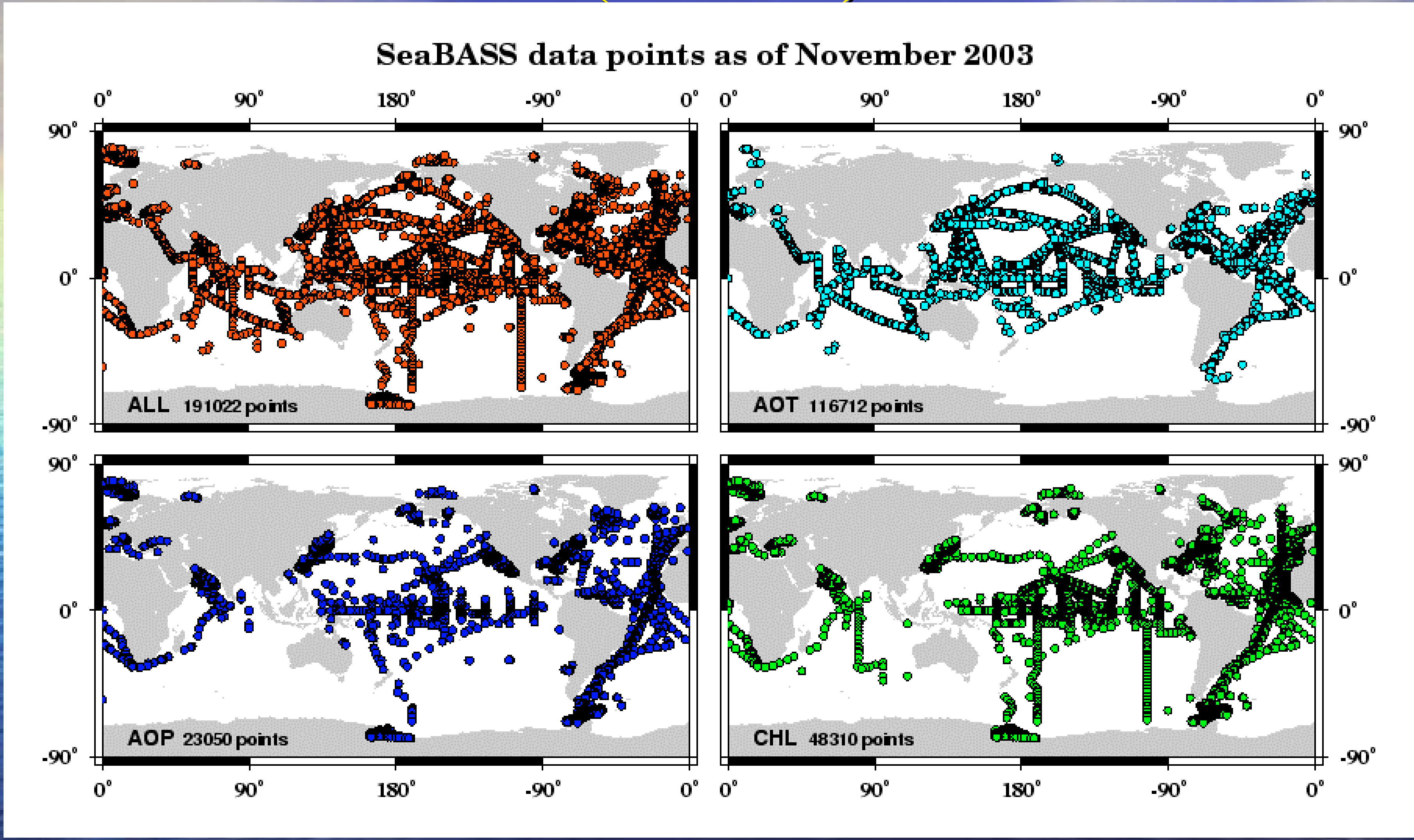
Source: Bates *et al.*, 2002

• Decadal increases at intermediate depths in DIC of ~ 5 – 22 μmol kg^{-1} north of ~ 20°N were observed

• These increases indicate that the upper and mid-thermocline waters in this region of the northern North Atlantic are rapidly accumulating anthropogenic CO_2 on decadal time scales.



SeaWiFS Bio-optical data Archive & Storage System (SeaBASS)



Data from over 1250 cruises

Apparent Optical Property (AOP); Chlorophyll-a (CHL); Aerosol Optical Thickness (AOT)

Chromophoric DOM: An Ignored Photoactive Tracer of Geochemical Process

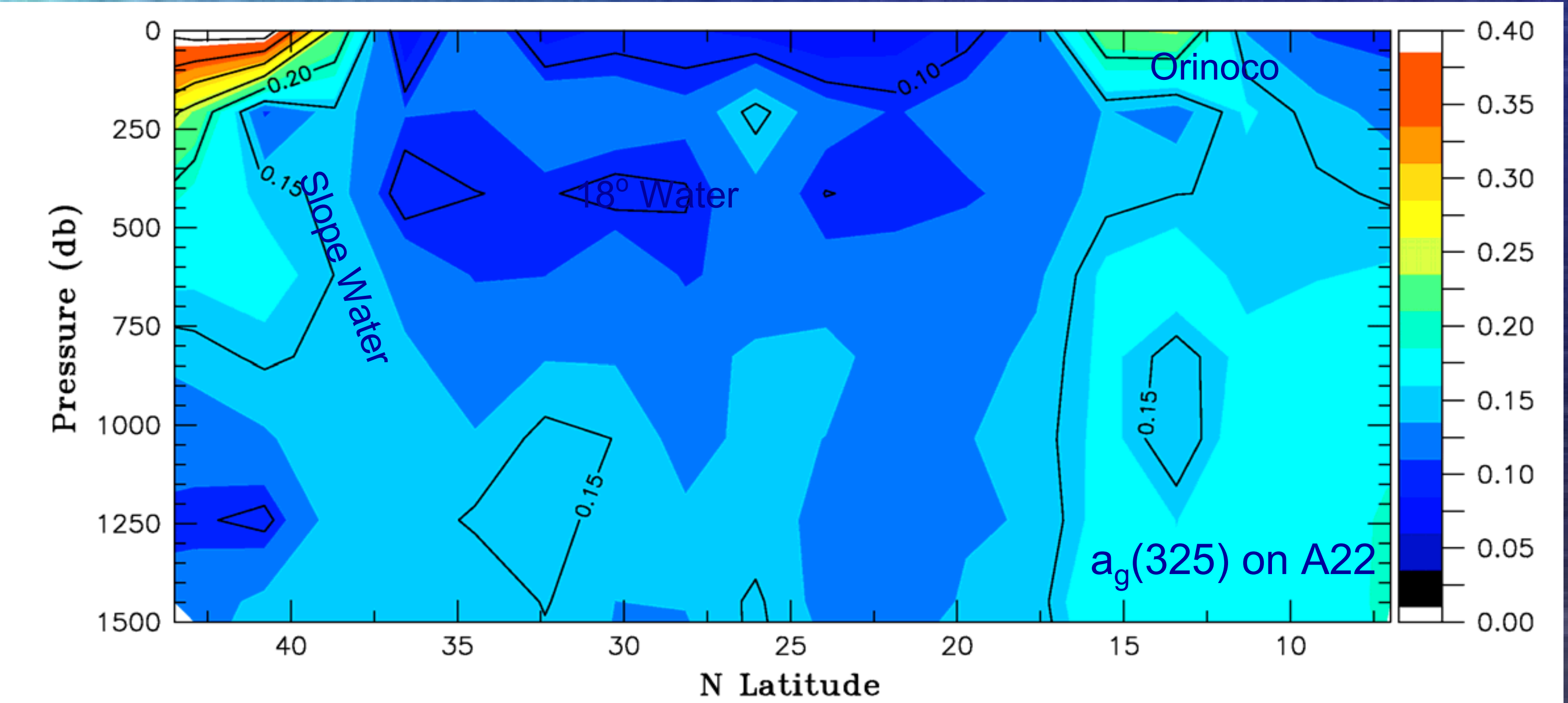
Siegel, Nelson & Carlson [UCSB] NSF/NASA Support

Working Hypotheses:

- CDOM is regulated by solar & microbial processes
- CDOM should act as a photoactive water mass tracer

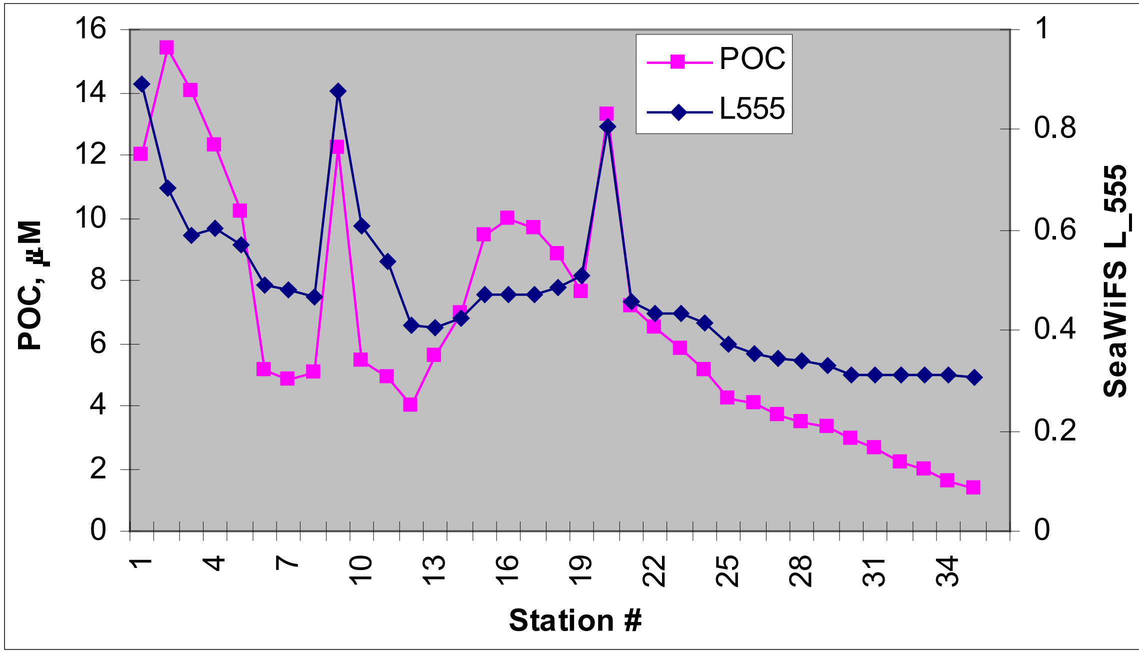
Work Plan:

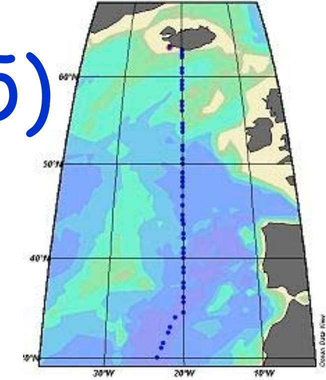
- Make CDOM & CDOM rate determinations on Repeat Hydrography cruises
- Develop & apply models of CDOM dynamics to test our hypotheses



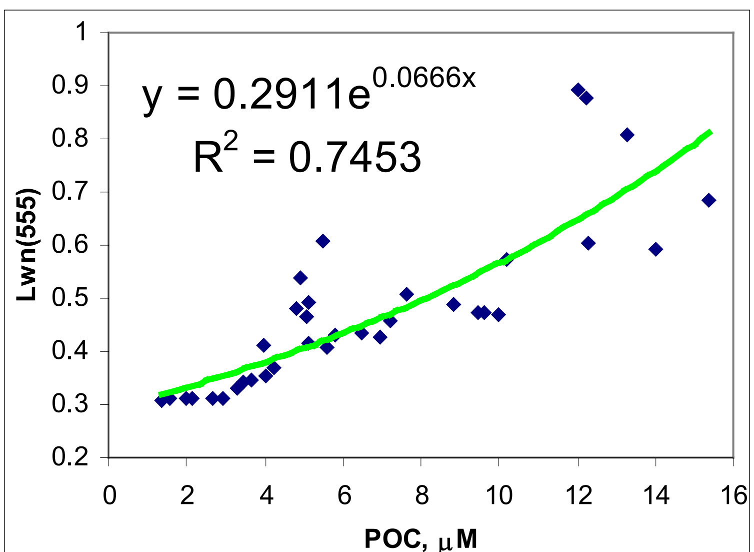
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

In-situ POC vs SeaWiFS $L_{NW}(555)$

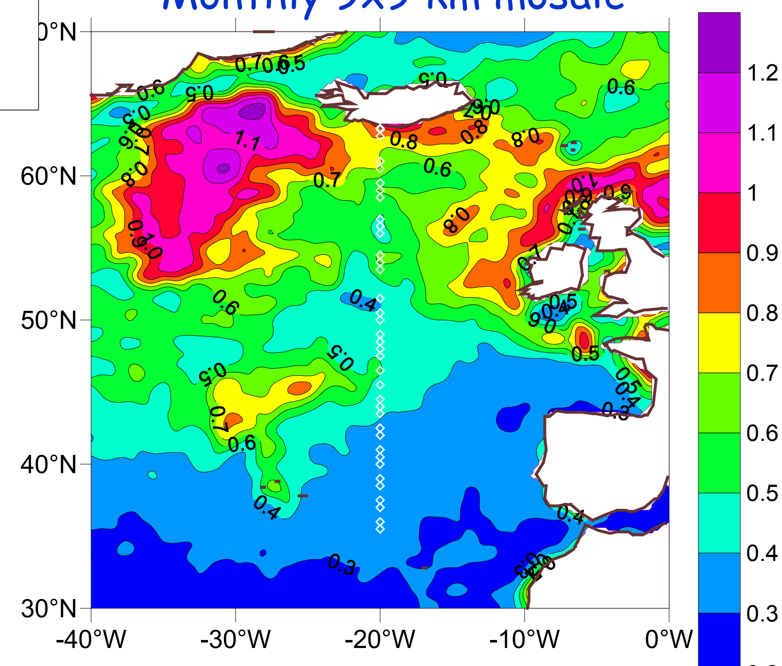




June 2003, A16N line
North Atlantic



Monthly 9x9 km mosaic

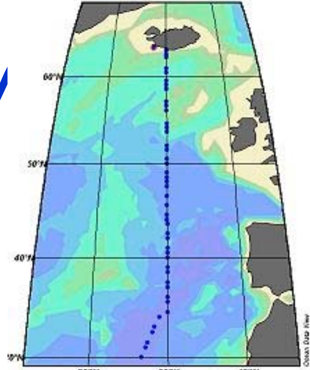


normalized water-leaving radiation @ 555nm

Gardner, Mishonov, Richardson, 2004; in prep.

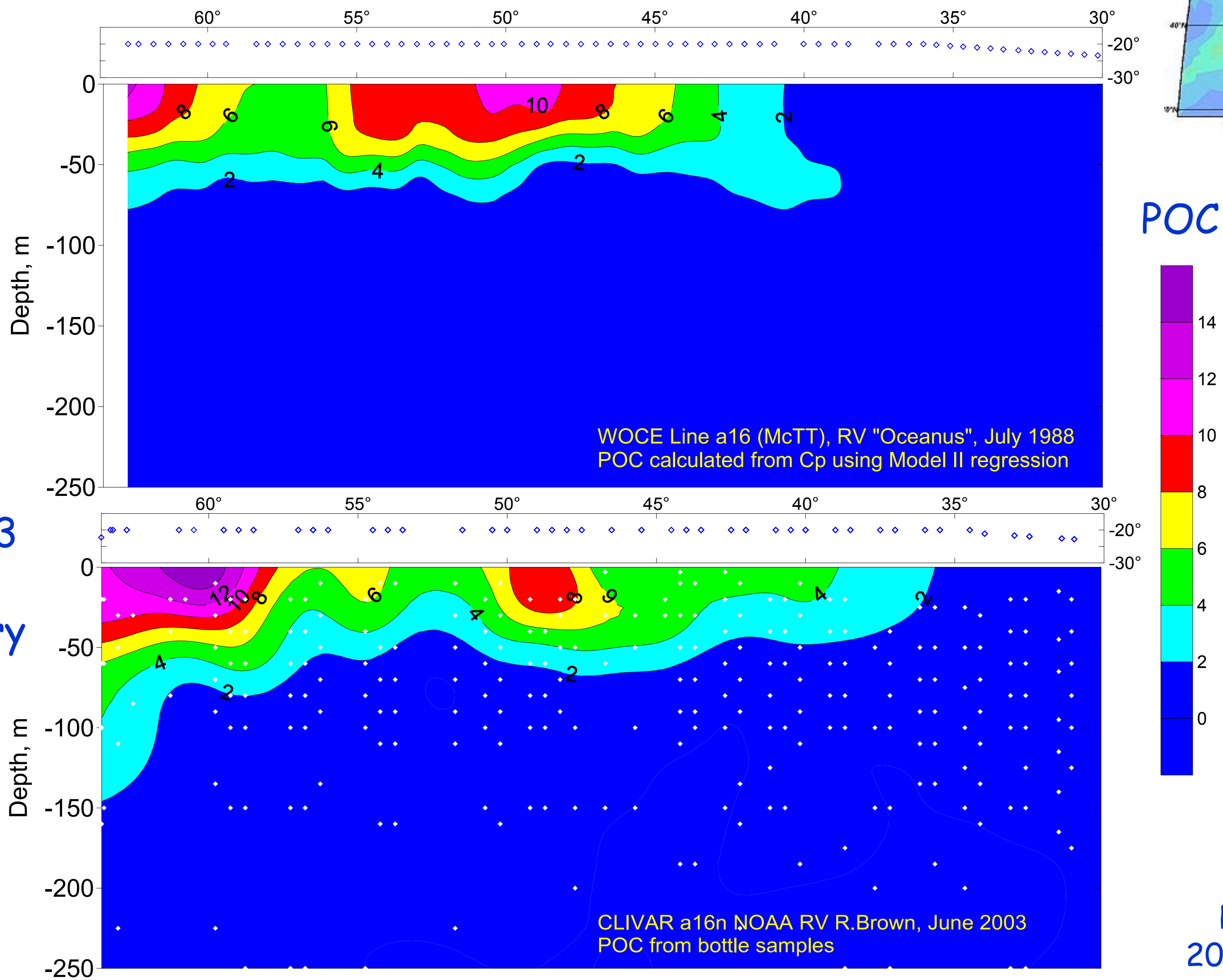
POC on CLIVAR/CO2 Repeat Hydrography

A16N line: North Atlantic



July 1988
WOCE
data

June 2003
CLIVAR
preliminary
data



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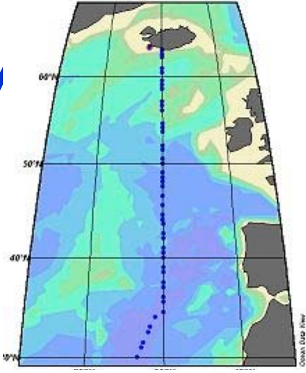
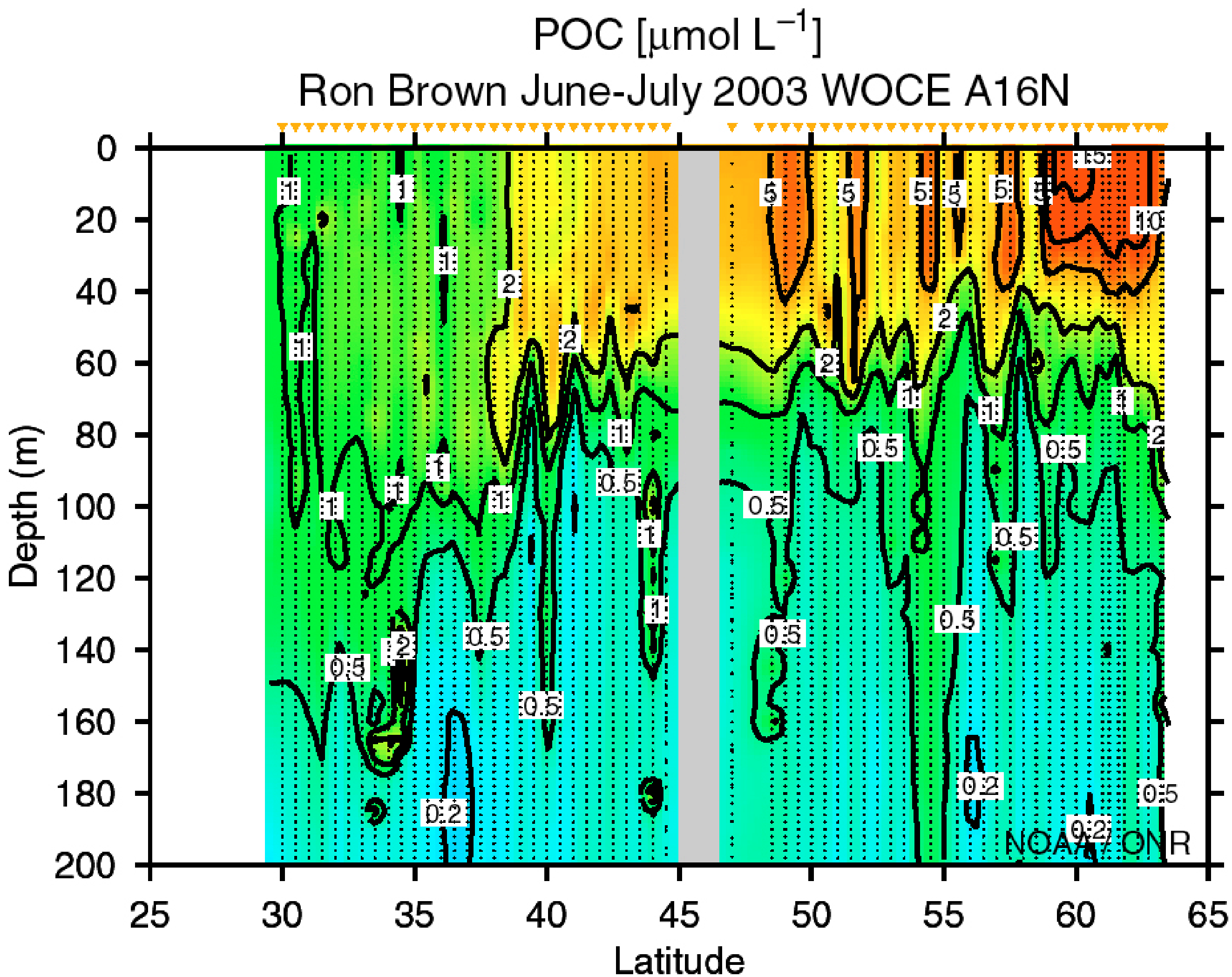


June 2003 CLIVAR preliminary data

Jim Bishop, LBNL, preliminary Data NOAA/ONR



Air-Sea CO_2 Flux

$$F_{av} = (k\ s\ ?\ pCO_2)_{av}$$

Gas transfer velocity

Function of:

Surface turbulence (wind speed)

Physical properties of gas and water

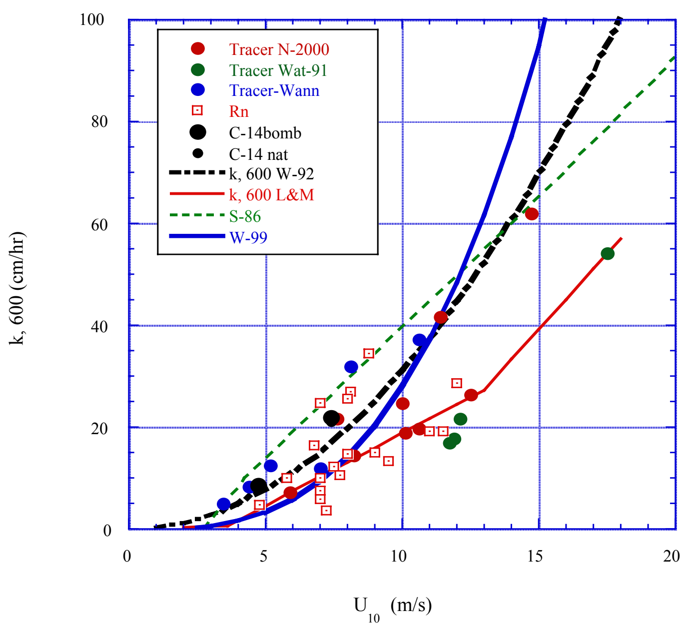
Thermodynamic component

Function of:

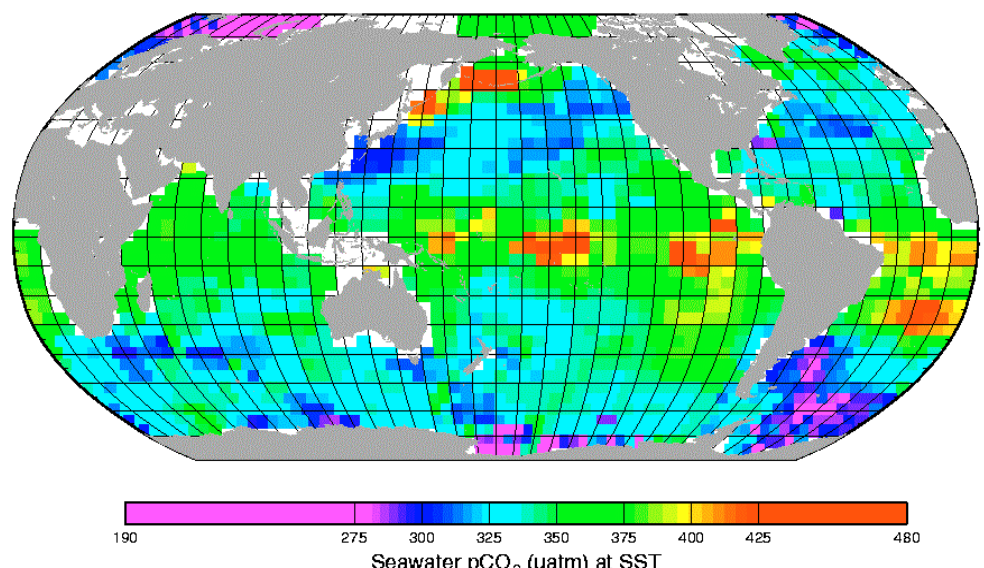
Temperature, Salinity, TCO_2

Biology (photosynthesis/respiration)

Transport (horizontal/vertical)

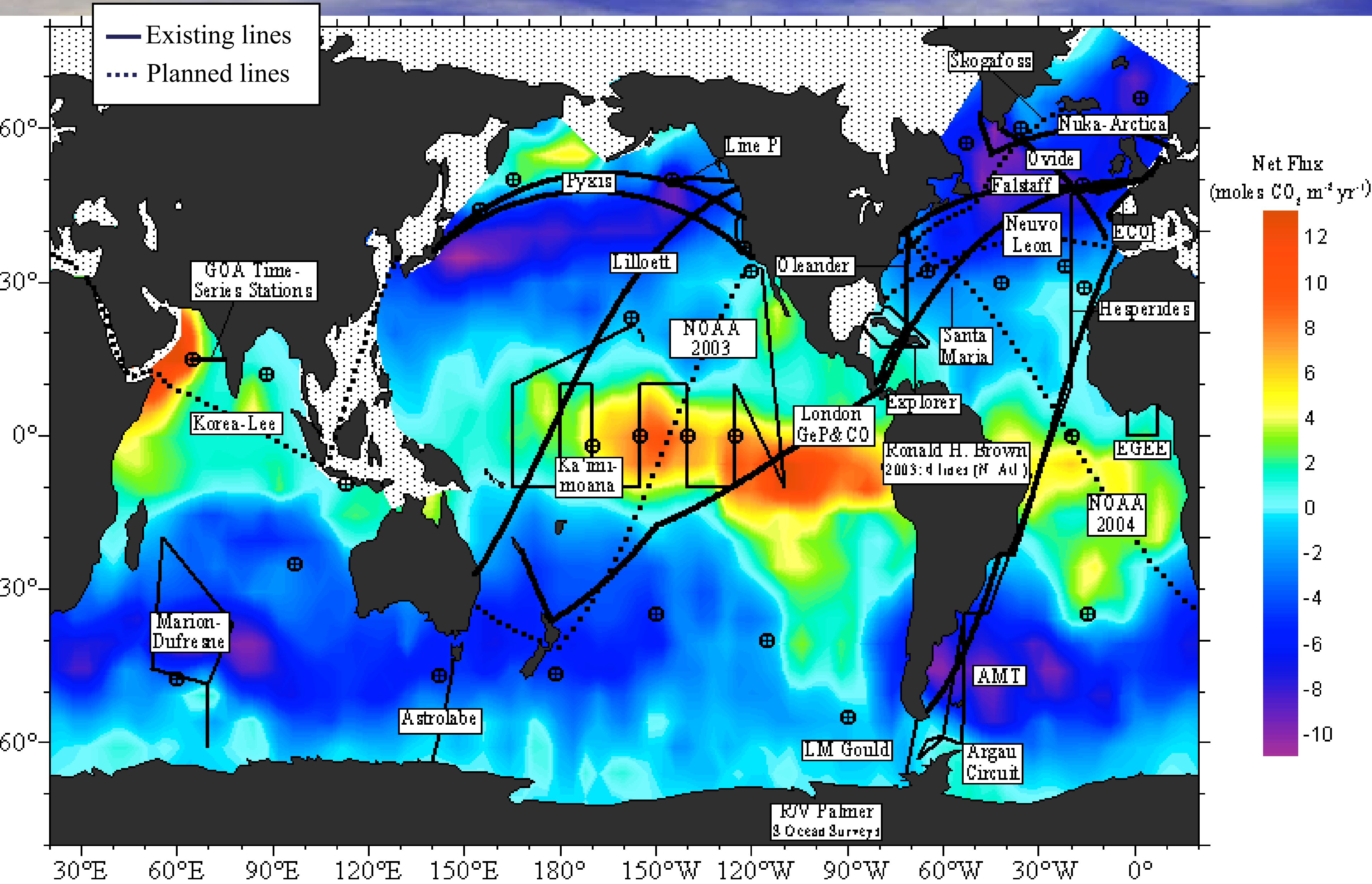


(B) Climatological pCO_2 in Surface Water for February 1995



Takahashi et al 2002

Global map of existing and planned near-surface pCO_2 measurements



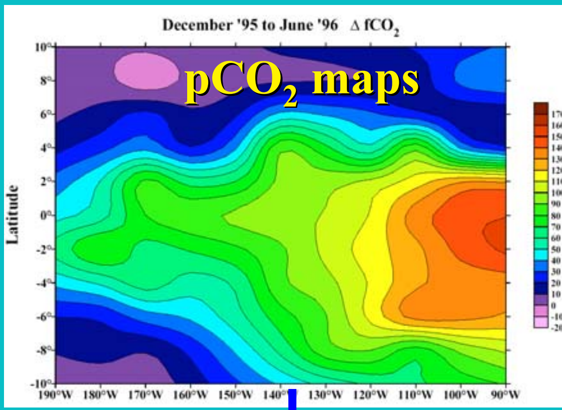
Producing Seasonal CO_2 Flux Maps

Shipboard sampling
pCO_2, SST, SSS, Chl

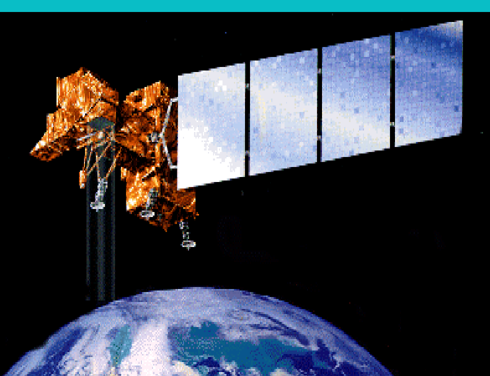
Algorithm development
pCO_2= f(SST, *color*)

Co-located satellite data

Apply algorithm to regional SST & *color* fields to obtain seasonal pCO_2maps



Flux = k s ? pCO_2

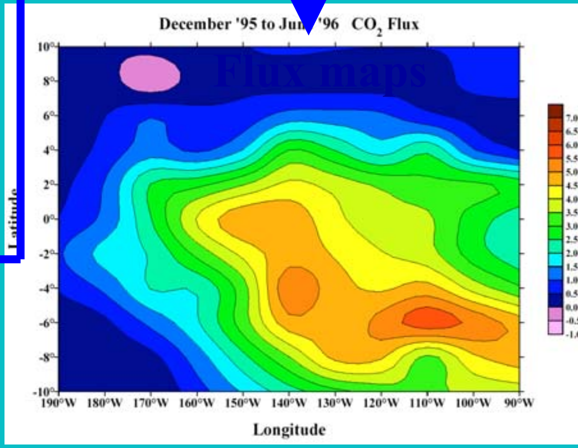


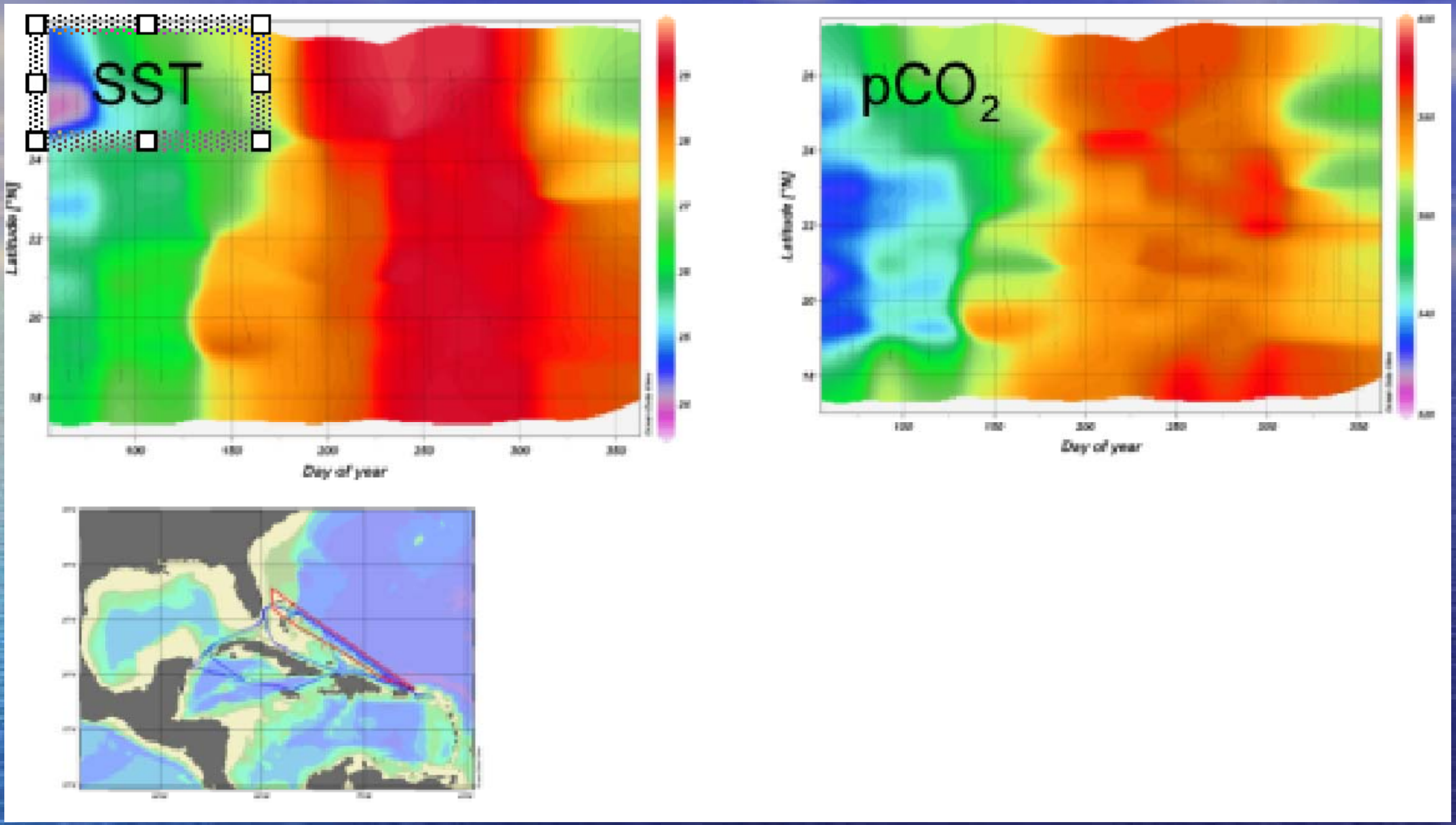
Regional satellite SST & color data

Wind data

Algorithm development Gas transfer, k = f (U_{10}, SST)

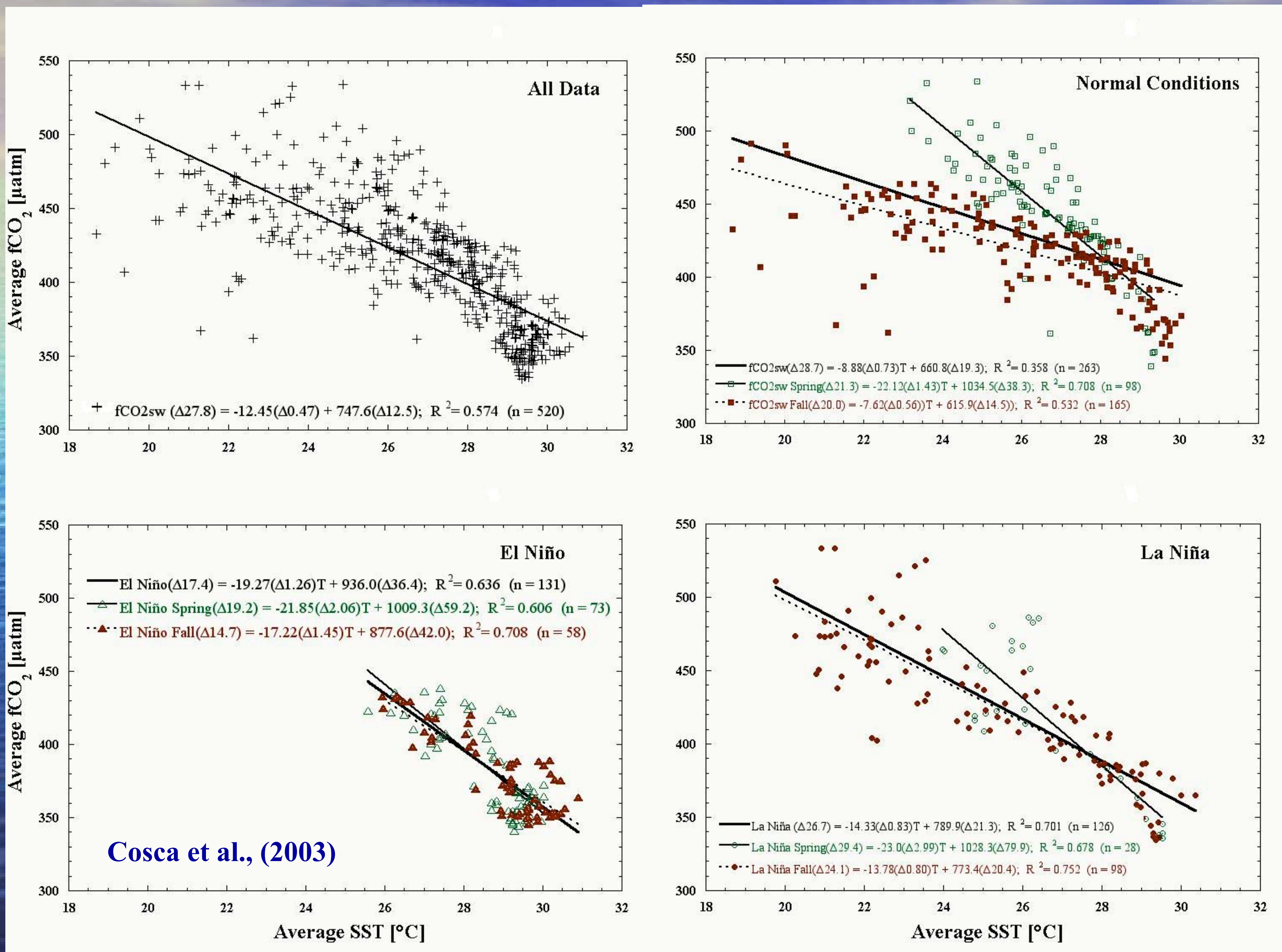
Remote sensing pCO_2, SST, color & wind

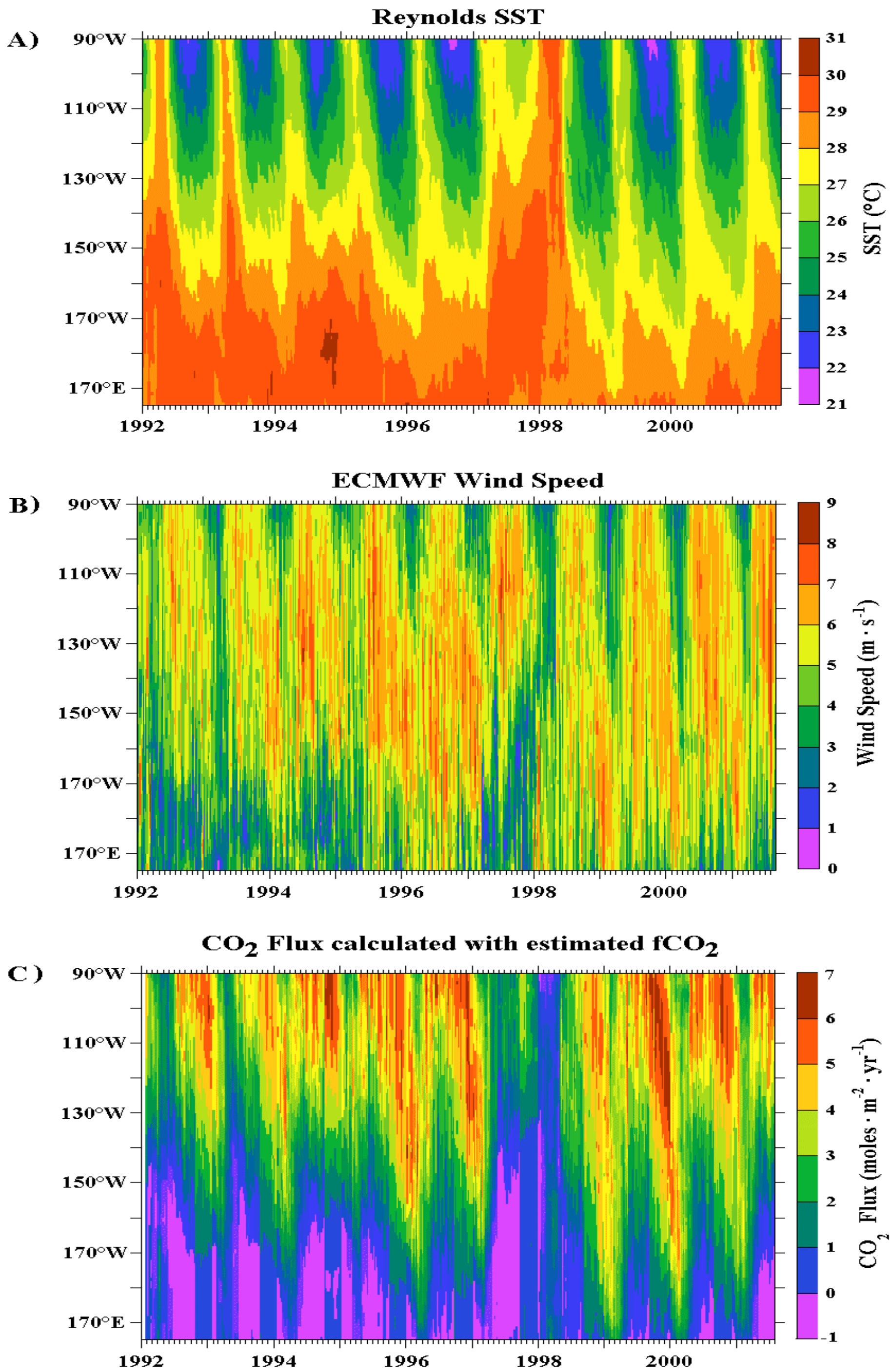




Production of pCO_2 maps in the Caribbean. Empirical algorithms are being developed with parameters that are measured at higher density/frequency (e.g. through remote sensing.). The close correspondence of temperature (left panel) trends and pCO_2 (right panel) along the cruise track (bottom) facilitates robust algorithms to extrapolate the pCO_2 to regional scales. From Olsen et al. (2004).

pCO_2 versus Temperature in the Equatorial Pacific
93 Data Sets Collected Between March 1992 and July 2001





Large-Scale Observational Results: 1992-2002

El Niño: 0.2-0.4 Pg C year^{-1}

Non El Niño: 0.7-0.9 Pg C year^{-1}

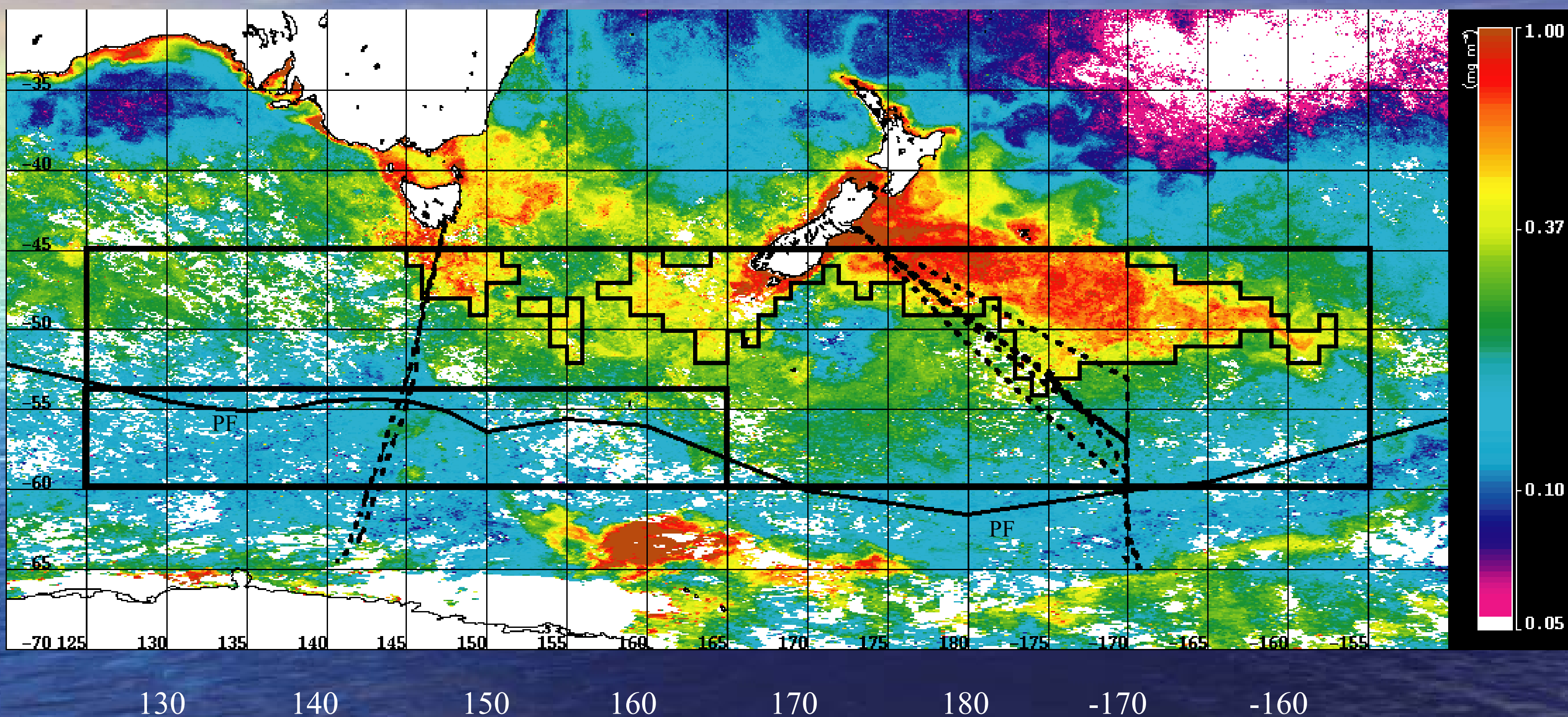
La Niña: 0.8-1.0 Pg C year^{-1}

Average: 0.6 ± 0.2 Pg C year^{-1}

from Feely et al. JGR (in press)

Influence of Chl and SST on pCO_2 observed during AESOPS and Astrolabe campaigns

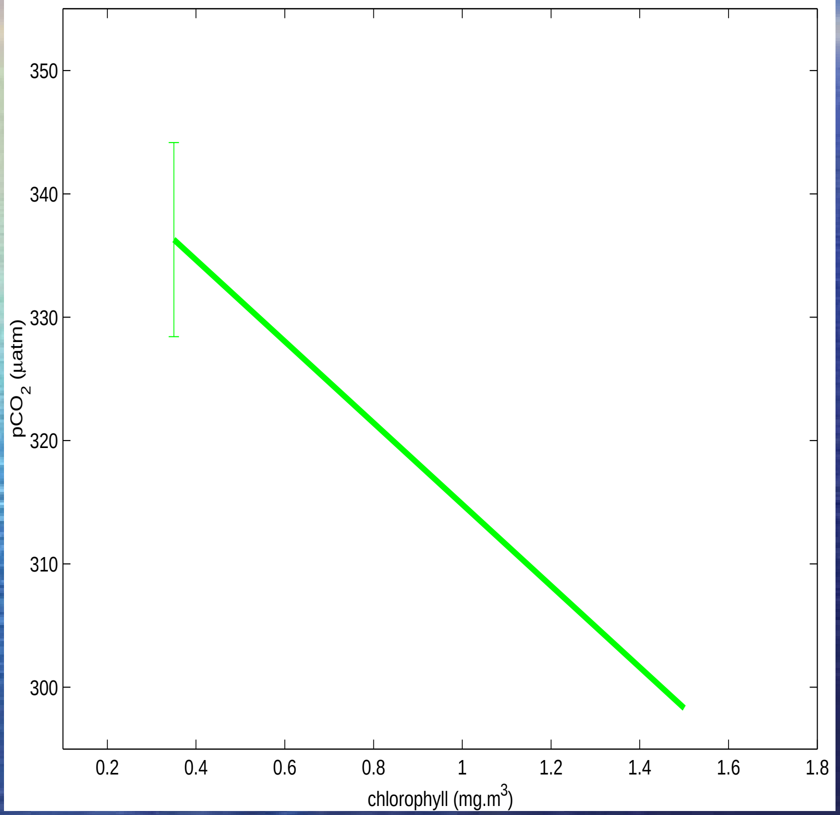
pCO2 campaigns (nov 97 to dec 99) - Seawifs chl a (mar 98)



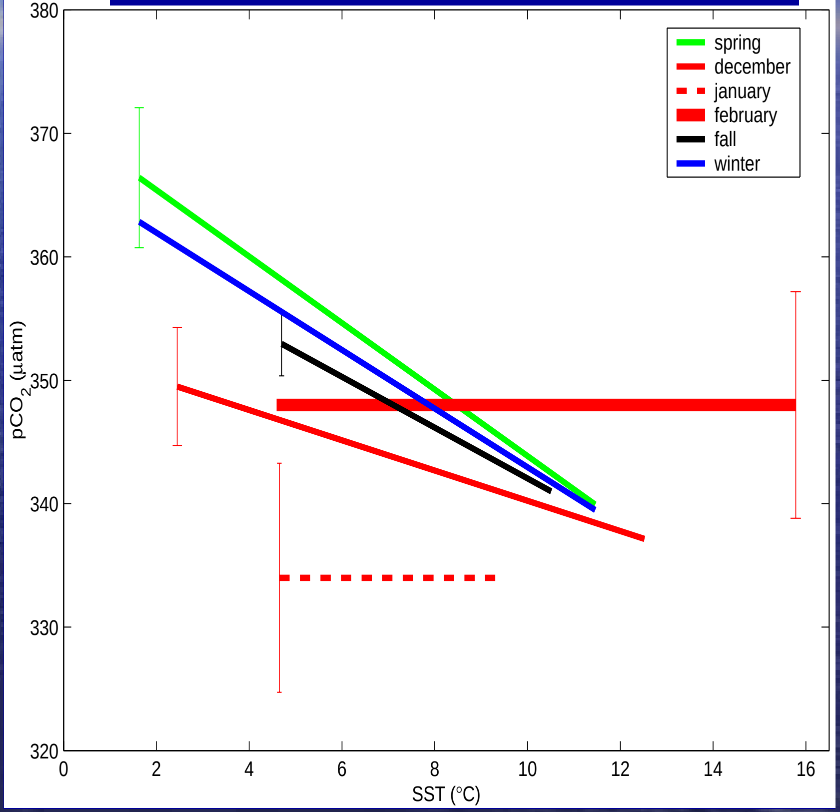
Boutin, Etcheto et al., JGOFS 2003

pCO_2 regressions South of Tasmania and New Zealand

pCO2 versus Chl in high Chl area



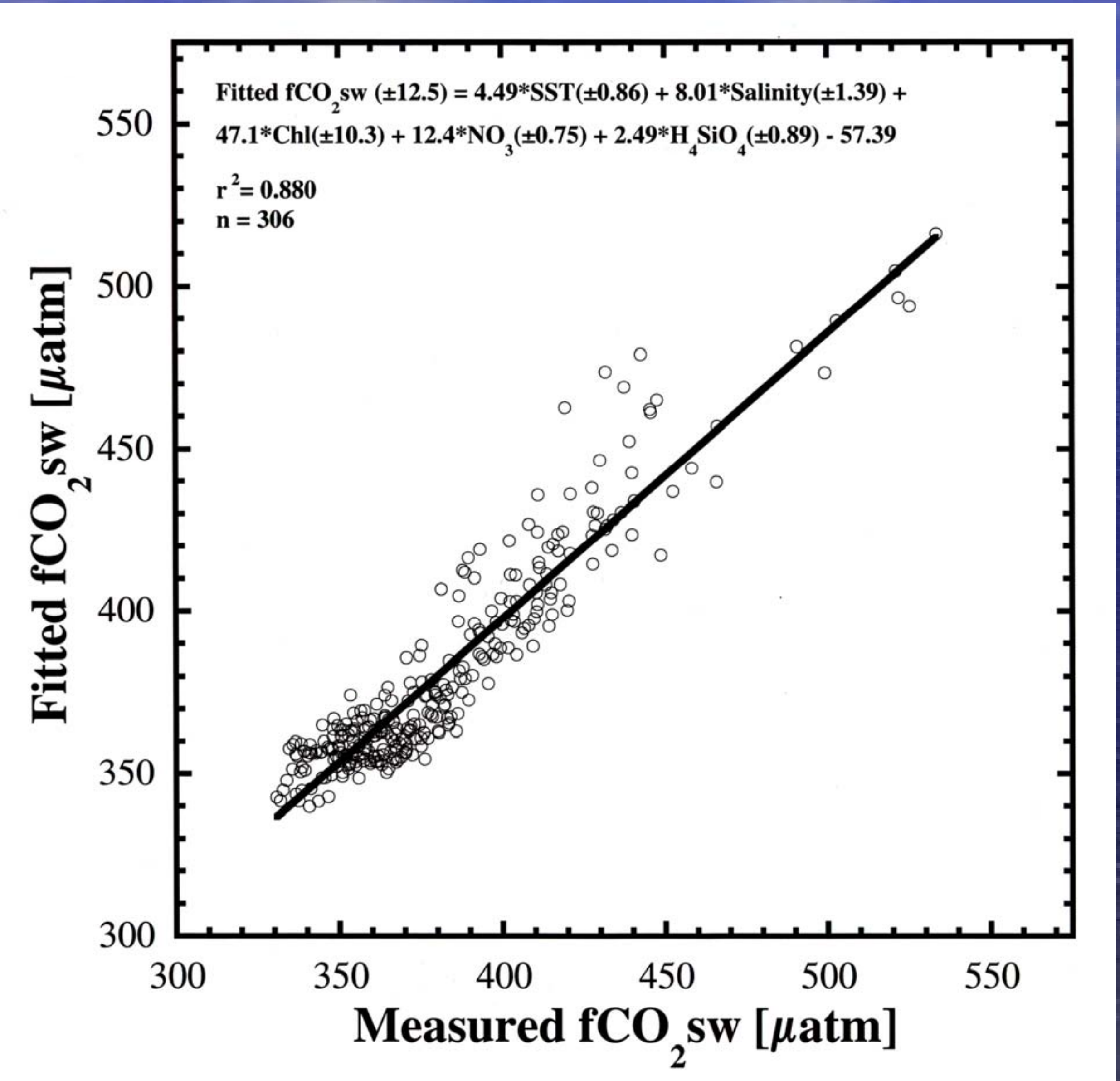
pCO2 versus SST in low Chl area by seasons

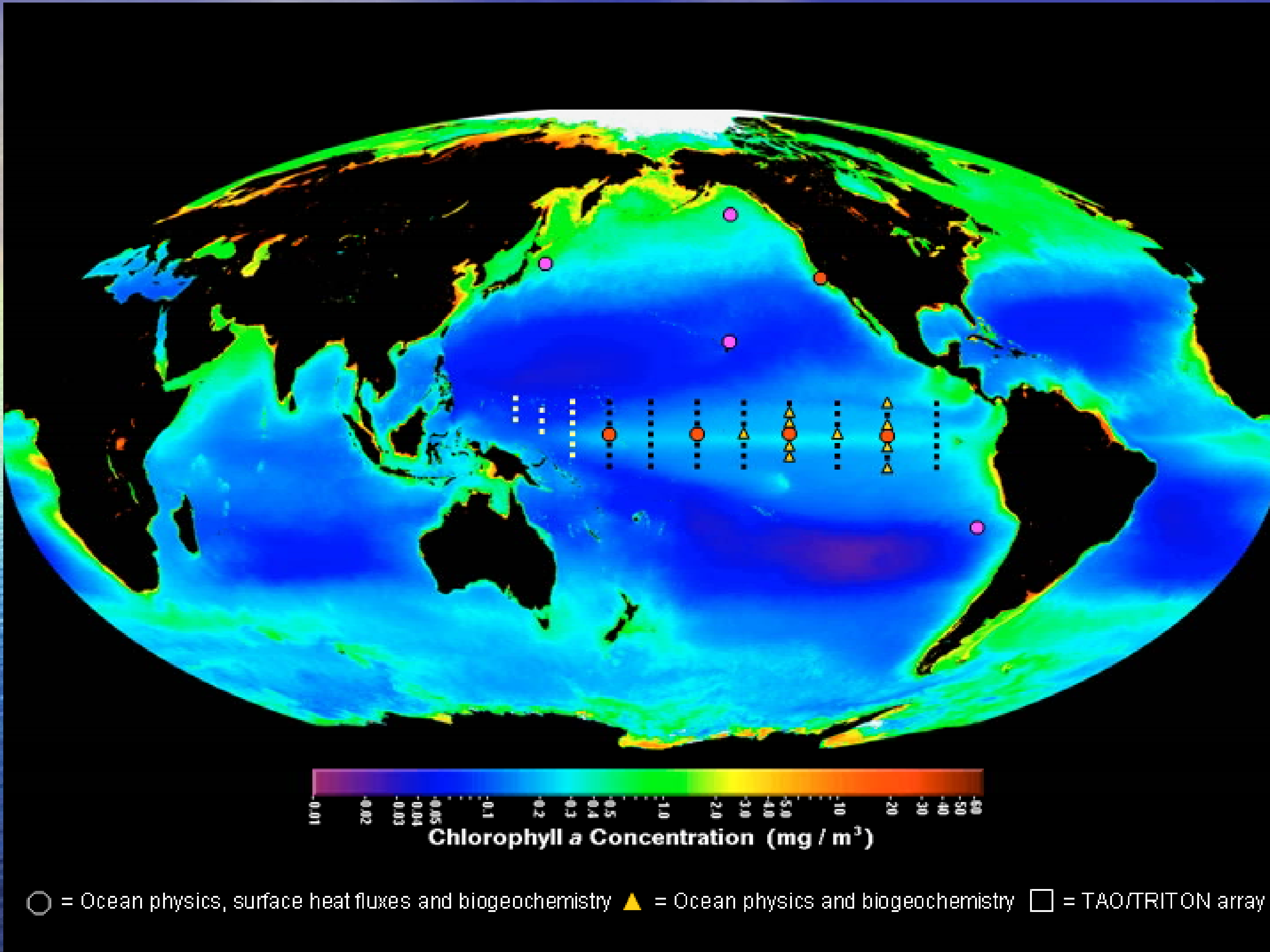


Boutin, Etcheto et al., JGOFS 2003

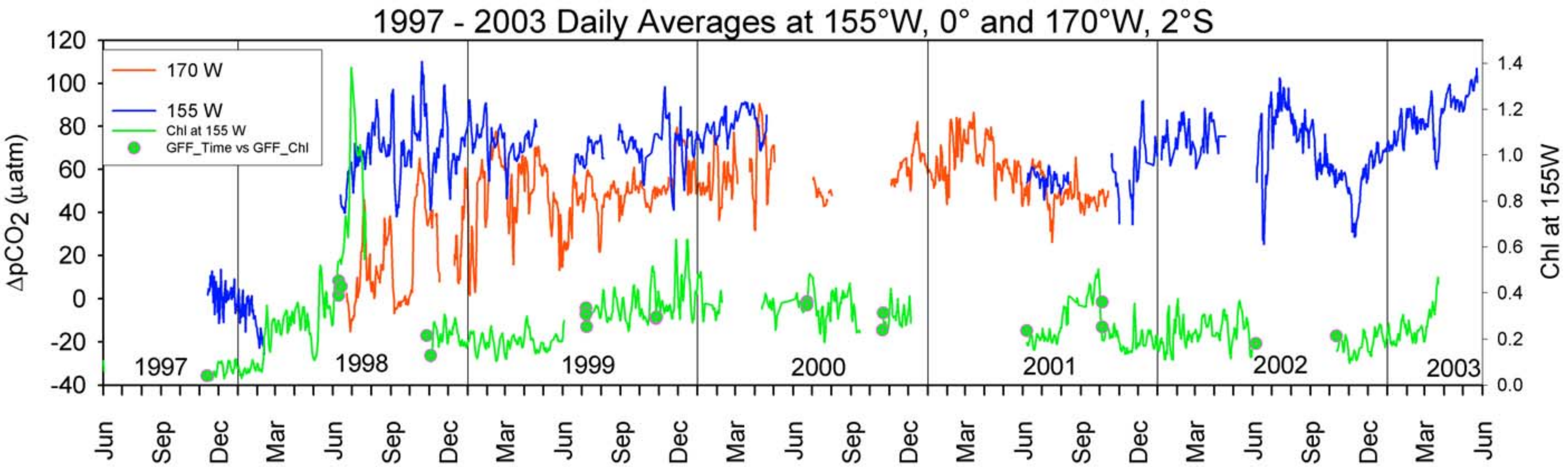
MLR Regression pCO_2 versus SST, SSS, Chla, NO3 and SiO4 in the Equatorial Pacific using 89 Data Sets Collected Between March 1992 and July 2001

Cosca et al. JGR, 2003)



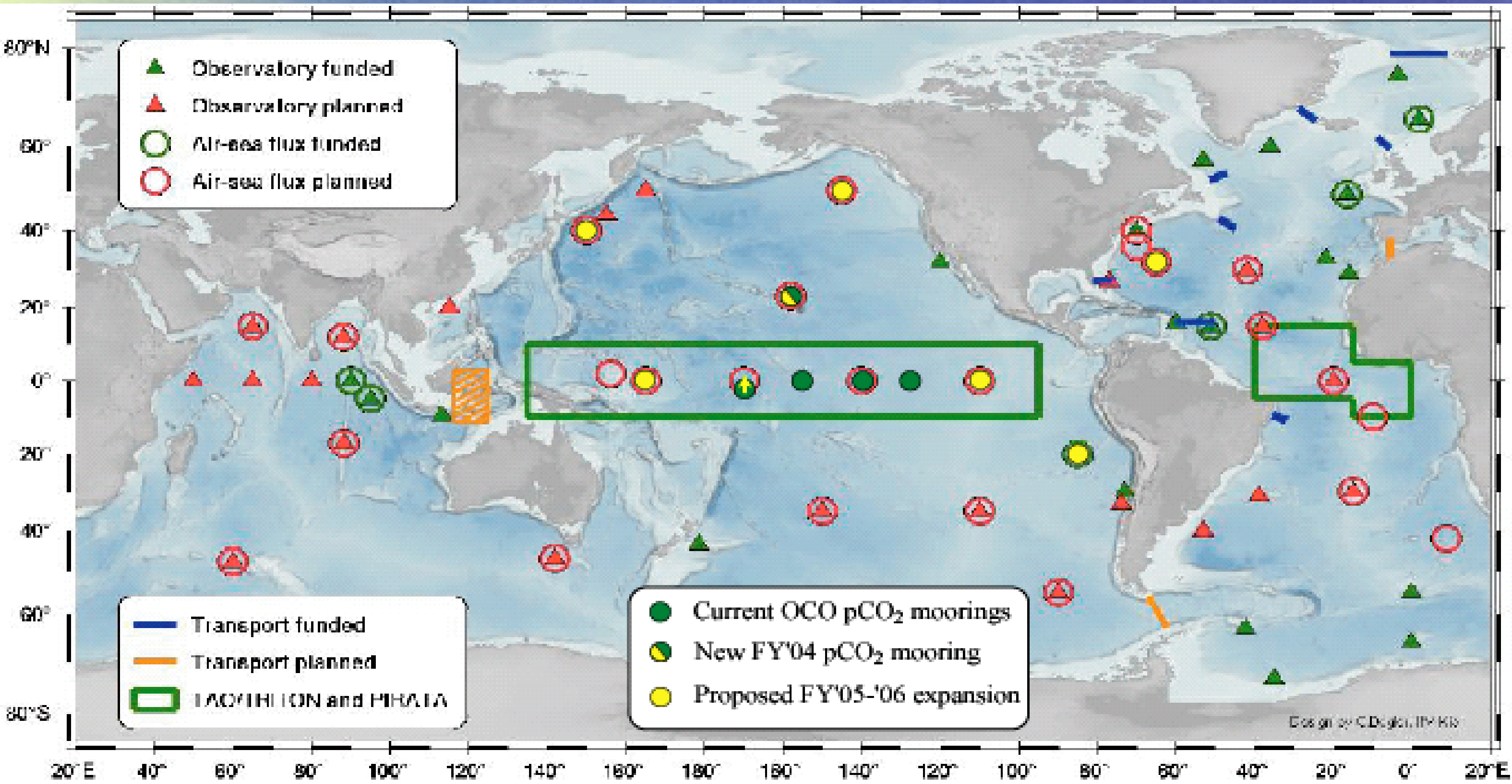


Francisco Chavez, MBARI


1997 - 2003 Daily Averages at 155°W, 0° and 170°W, 2°S
170 W
155 W
Chl at 155 W
GFF_Time vs GFF_Chl
ΔpCO2 (μatm)
Chl at 155W
1997
1998
1999
2000
2001
2002
2003
Jun
Sep
Dec
Mar

Moored pCO_2 Program

Goal: To determine the temporal variability in air-sea CO_2 fluxes by conducting high resolution time-series measurements of atmospheric boundary layer and surface ocean pCO_2.



Conclusions

- **Repeat Hydrography and VOS cruises offer excellent opportunities for calibration of sensors and validation of model results**
- **Remote sensing can be a powerful tool to monitor time and space variations of several parameters influencing CO_2 distribution and air-sea fluxes (wind speed, SSH, SST, Chl).**
  - **Remote sensing can help interpret and extend in space and time in situ measurements**
  - **Remote sensing can provide constraints for biogeochemical modelling**

Thank You

Repeat Hydrography Schedule and Measurements

Overall Coordinator: Jim Swift

Year of Project	Cruise	Days	Ports	Dates	Contact/ Chief Scientist	Level I Core Measurements: CTD/O_2/ Nuts	ADCP LADCP	Bottle Salinity	CFC	DIC	TAlk	Surface Underway T, S, pCO_2	He/Tr	TOC/ TON	Level II Core Measurements: pCO_2	pH	Trace Metals	C13 C14	AC9/ POC	CDOM
1	A16N	42	Reykjavik-Fortaleza	6/18/03-8/11/03	Bullister, PMEL	•	•	•	•	•	•	••	•		•	•	•	••	•	
2	A20	29	WHOI - Port of Spain	9/22/03-10/20/03	Toole, WHOI	•	•	•	•	•	•		•	•				••	•	•
2	A22	21	Port of Spain - WHOI	10/23/03-11/14/03	Joyce, WHOI	•	•	•	•	•	•		•	•				••	•	•
2	P2	72	Yokohama-Honolulu-San Diego	6/13/04-7/25/04	Swift/Robbins, SIO	•	•	•	•	•	•		•	•			•	•	•	
3	A16S	46	Punta Arenas-Natal	12/17/04-2/14/05	Wanninkhof, AOML	•	•	•	•	•	•	••	•	•	•	•	•	•	•	
3	P16S	40	Wellington-Tahiti	Austral summer 2005	Talley, SIO	•	•	•	•	•	•		•				•	•	•	•
4	P16N	57	Tahiti-Alaska	2006	Feely, PMEL	•	•	•	•	•	•	••	•		•	•	•	•	•	•
5	S4P/ P16S	25.5	Wellington-Perth	Austral summer 2007		•	•	•	•	•	•		•		•		•	•	•	
5	S4P/ P16S	25.5	Wellington-Perth	Austral summer 2007		•	•	•	•	•	•		•		•		•	•	•	
6	P18	32	Punta Arenas-Easter Island	2008	McCartney, WHOI	•	•	•	•	•	•	••	•		•	•	•	••	•	
6	P18	35	Easter Island-San Diego	2008		•	•	•	•	•	•	••	•			•	•	••	•	
6	I6S	42	Cape Town	2008		•	•	•	•	•	•		•					•	•	
7	I7N	47	Port Louis-Mascat	2009		•	•	•	•	•	•		•						•	
7	I8S	38	Perth-Perth	2009		•	•	•	•	•	•	••	•		•	•			•	
7	I9N	34	Perth-Calcutta	2009		•	•	•	•	•	•	••	•		•	•			•	
8	I5	43	Perth-Durban	2010		•	•	•	•	•	•		•					•	•	
8	I13.5	62	Abidjan- Cape Town	2010		•	•	•	•	•	•		•					•		
9	A5	30	Tenerife-Miami	2011		•	•	•	•	•	•		•					•	•	
9	A21/ S04A	42	Punta Arenas-Cape Town	2011		•	•	•	•	•	•		•					•		
10	A10	29	Rio de Janeiro-Cape Town	2012		•	•	•	•	•	•		•					••		
10	A20/22	29	Woods Hole-Port of Spain-Woods Hole	2012		•	•	•	•	•	•		•					••		

[1]PIC on A16N only
•• Surface only

Indicates Cruises Completed

Repeat Hydrography
in support of the US CLIVAR and CO_2 programs

Core Measurements of the CO_2/CLIVAR Repeat Hydrography Program

- Level I core measurements (mandatory on all cruises)
- Level II recommended measurements (highly desirable on subset of U.S. cruises)
- Level III ancillary measurements (on opportunity and space available basis)

Repeat Hydrography
in support of the US CLIVAR and CO_2 programs

Level I Core Measurements

- Dissolved Inorganic Carbon (DIC)
- Total Alkalinity (TAlk)
- CTD pressure, temperature, conductivity
- CTD oxygen (sensor)
- Bottle salinity
- Nutrients by standard autoanalyzer (NO_3/NO_2, PO_4, $Si(OH)_4$
- Dissolved oxygen (O_2)
- Chlorofluorocarbon tracers CFC-11, -12, -113
- Tritium - ^3He
- Total Organic Carbon (TOC)
- Total Organic Nitrogen (TON)
- Surface underway system: T, S, pCO_2
- ADCP shipboard
- ADCP lowered

Level II Core Measurements

- pH
- Discrete pCO_2
- CCl_4 and SF_6
- $\delta^{13}C$
- Fe/trace metals
- CTD transmissometer
- Surface underway system:
  (nutrients, O_2, Chlorophyll, DIC, and surface skin temperature)

Level III Core Measurements

- Chlorophyll
- Primary Production
- HPLC Pigments
- Experimental continuous analyzers
- $\delta^{15}N$ NO_3 (nutrient utilization)
- ^{32}Si
- ^{18}O of H_2O
- NH_4
- Low level nutrients
- Total Organic Phosphorus
- Upper ocean optical profile
- $\delta^{17}O$ of O_2
- Methyl halides
- DMS
- ADCP (Multibeam)

Repeat Hydrography
in support of the US CLIVAR and CO_2 programs

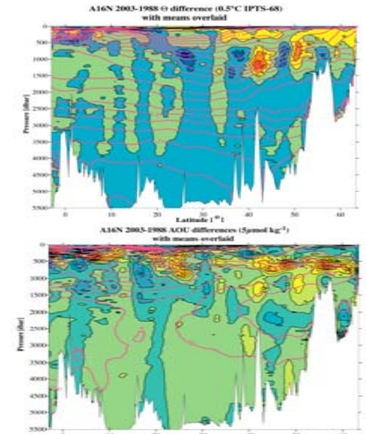
Schedule of US CO2/CLIVAR Hydrography Lines (as of 4/25/03)

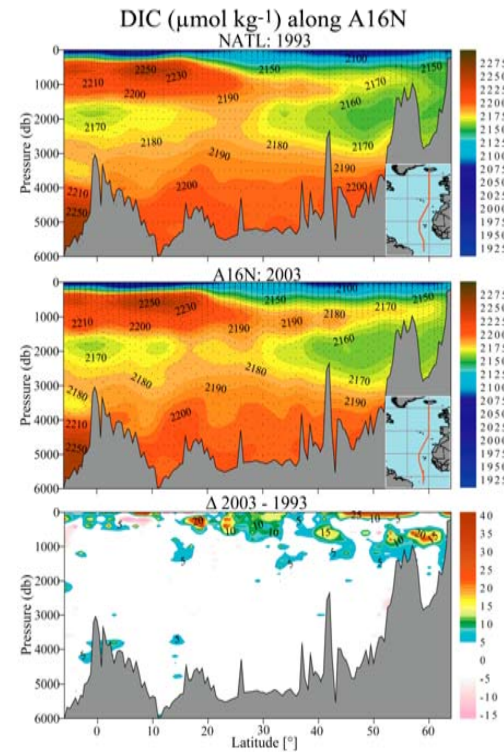
Dates	Cruise	Days	Ports	Year	Contact/Chief Scientist
					overall coordinator: Jim Swift, SIO
6/19/03-7/10/03	A16N, leg 1	22	Reykjavik-Madeira	1	Bullister, PMEL
7/15/03-8/11/03	A16N, leg 2	28	Madeira - Natal, Brazil	1	Bullister, PMEL
9/15/03-10/13/03	A20	29	WHOI - Port Of Spain	1	Toole, WHOI
10/16/03-11/07/03	A22	21	Port Of Spain - WHOI	1	Joyce, WHOI
summer 2004	P2 (two legs)	66	San Diego-Honolulu-Yokohama	2	Swift/Robbins, SIO
austral summer 05	A16S	44	Montevideo-Fortaleza Brazil	3	
austral summer 05	P16S	40	Wellington-Tahiti	3	
2006	P16N	57	Tahiti-Alaska	4	
austral summer 07	S4P/P16S	25.5	Wellington-Perth	5	
austral summer 07		25.5	Wellington-Perth	5	
2008	P18	32	Punta Arenas-Easter Island	6	
2008		35	Easter Island- San Diego	6	
2008	I6S	42	Cape Town	6	
2009	I7N	47	Port Louis/Muscat	7	future planning
2009	I8S	38	Perth- Perth	7	future planning
2009	I9N	34	Perth- Calcutta	7	future planning
2010	I5	43	Perth - Durban	8	future planning
2010	A13.5	62	Abidjan-Cape Town	8	future planning
2011	A5	30	Tenerife-Miami	9	future planning
2011	A21/S04A	42	Punta Arenas-Cape Town	9	future planning
2012	A10	29	Rio de Janeiro-Cape Town	10	future planning
2012	A20/A22	29	Woods Hole-Port of Spain-Woods Hole	10	future planning

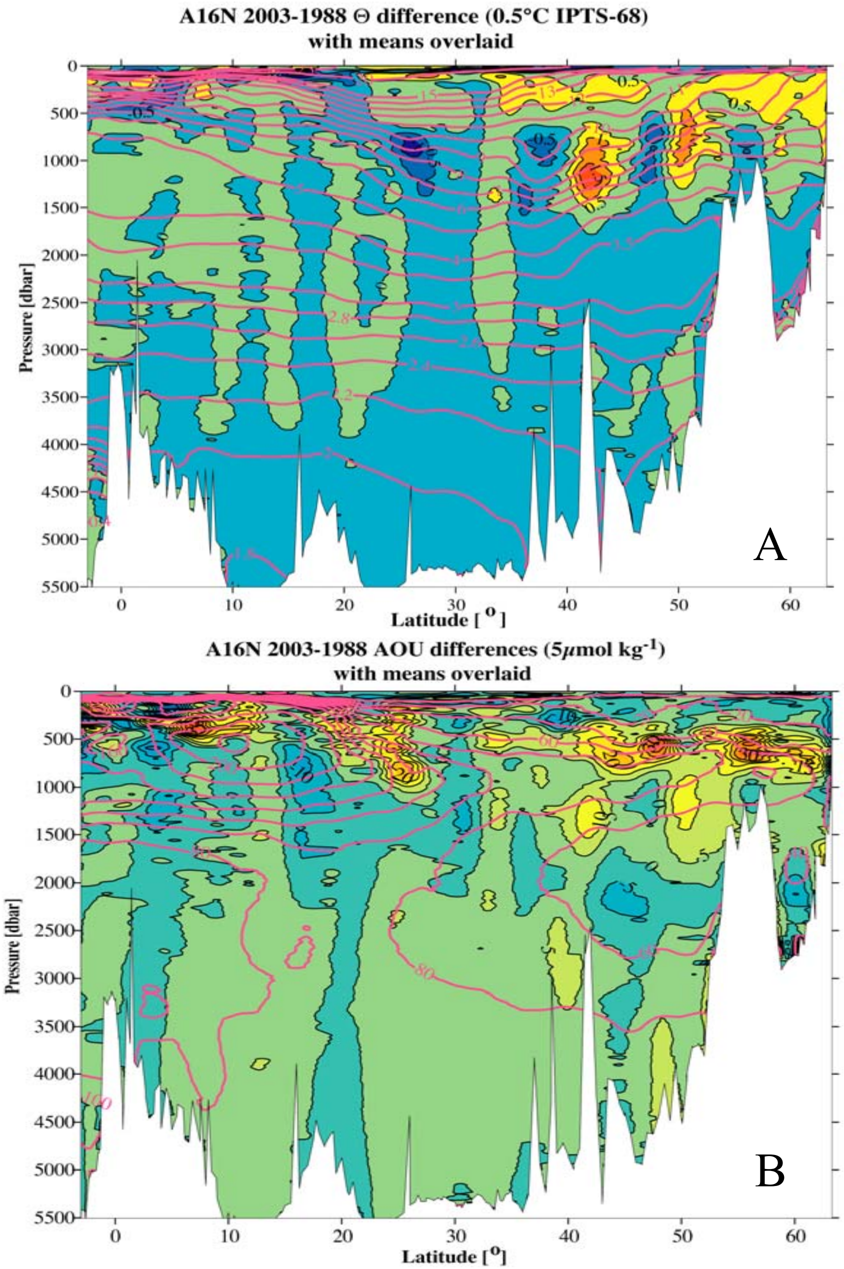
Years 1-6 are funded.

CLIVAR/CO_2 Repeat Hydrography Program - Can we see differences in the reoccupations?

- A16N (1988, 1993, 2003):
  - •Warming of ~ 0.5°C is evident between Iceland and 32°N from 100 – 700 dbar within the regional mode waters
  - •Over the same latitude range, but between 300 and 1000 dbar, the AOU has increased
  - •Decadal increases in DIC of ~ 5 – 22 µmol kg^{-1} at intermediate depths north of ~ 20°N indicate that the upper and mid-thermocline waters are rapidly accumulating anthropogenic CO_2
  - •Increases in CFC-12 indicate that the upper and mid depth waters are rapidly ventilated with atmospheric gases





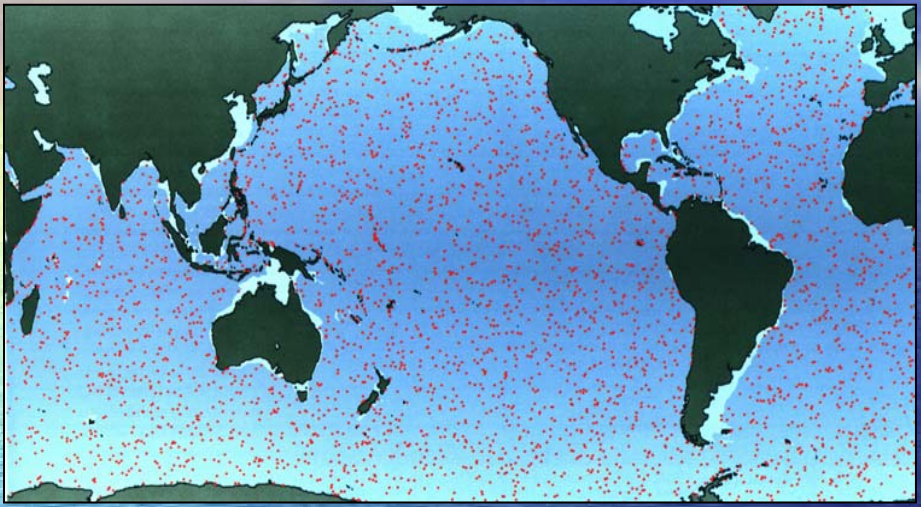


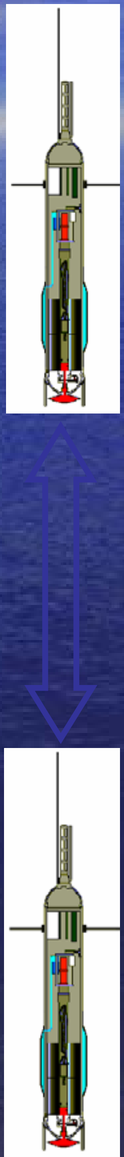
Note: Magenta contours are the means on each section.
Θ and AOU have been smoothed by 40 dbar vertically and 5° horizontally.

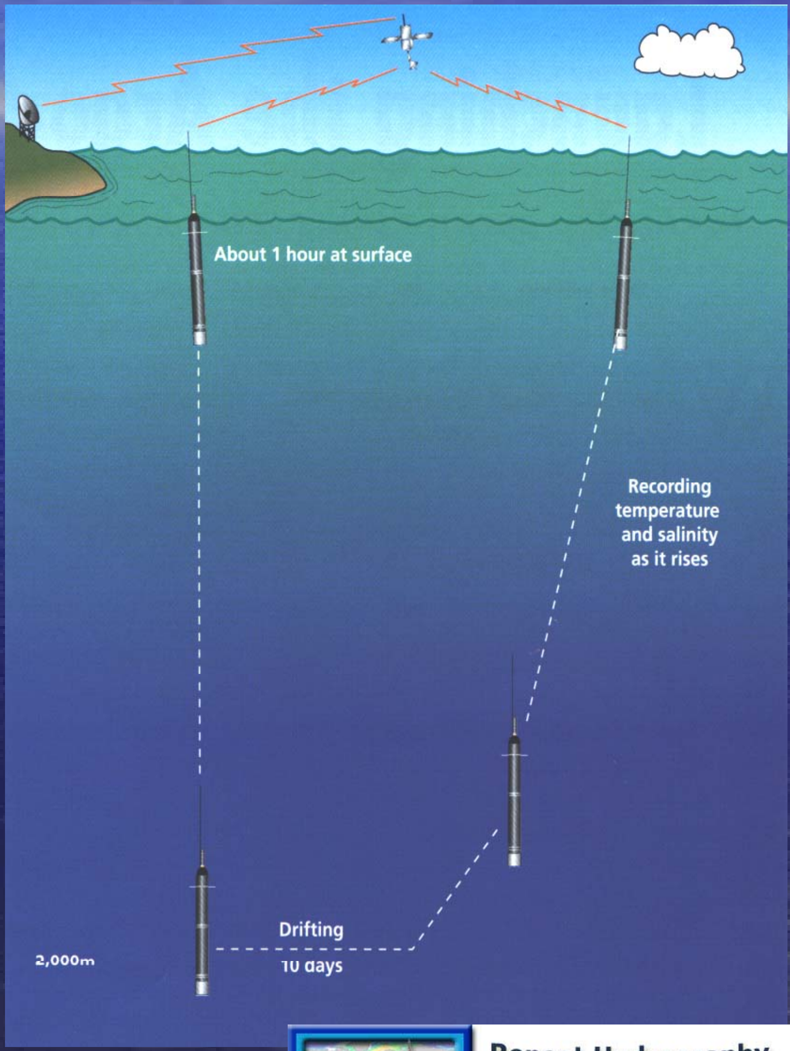
- Warming of ~ 0.5°C is evident between Iceland and 32°N from 100 and 700 dbar from within the regional mode waters (Fig A).

- Over the same latitude range, but between 300 and 1000 dbar, the AOU has increased (Fig. B).

Utilize emerging technologies and platforms (e.g. ARGO)





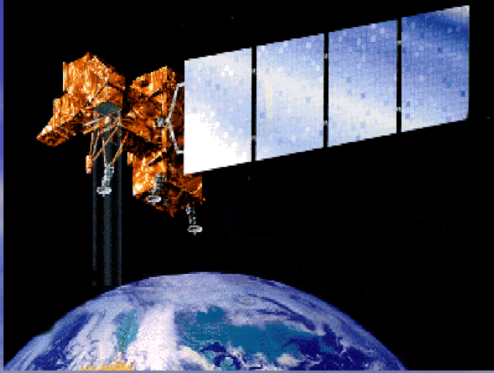


An ocean full of profiling floats and gliders ideal for measuring O_2 inventories

Can we adapt them for C O_2?

Repeat Hydrography
in support of the US CLIVAR and CO_2 programs

Current Satellite Sensors



Wind speed: (2 scatterometers in the air)

-Scatterometer: QSCAT 1999-TBD
Seawinds on ADEOS2 2003-TBD

Sea Surface Temperature:

-Visible/IR radiometer: AVHRR 1982-TBD
GOES -TBD
Meteosat 2nd generation 2002

-Microwave radiometer: TMI (40S-40N) 1997-TBD
AMSR-E on AQUA 2002-TBD
AMSR on ADEOS2 2002-TBD

Ocean Color: (6 radiometers in the air)

-Visible/IR radiometer: Seawifs 1997-2003
MODIS on Terra 2001-2005
MERIS on ENVISAT 2002-2007
MODIS on AQUA 2002 -2007
POLDER 2 & GLI on ADEOS2 2003-TBD

Sea Surface Height anomalies: (3 altimeters)

-Altimeter: Topex-Poseidon 1992 -TBD
Jason 1991-TBD
RA on ENVISAT 2002-TBD

Repeat Hydrography

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