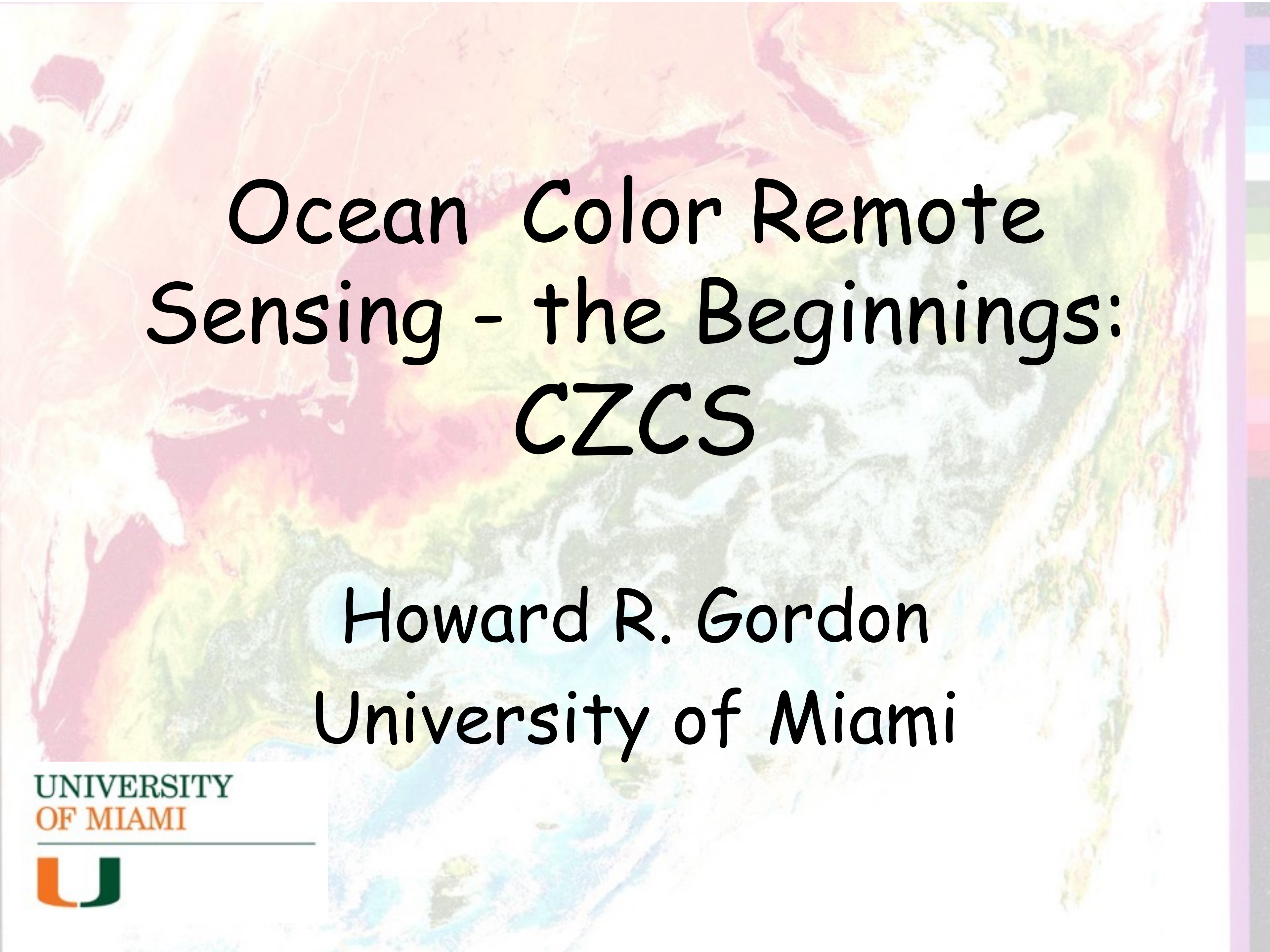


Ocean Color Remote Sensing - the Beginnings: CZCS

Howard R. Gordon

University of Miami

Outline

I was lucky enough to witness and participate in some of the early development of Ocean Color sensing.

In this talk I will

- describe some of these developments,
- provide (my own) historical retrospective, and
- maybe convey some of the excitement and frustration of those involved.

Only a few were thinking about ocean color in the early 60's e.g., C. Yentsch , DSR, 7, 1-9 (1960).

Conference "Oceanography from Space(?)" Woods Hole 1965: The suggested application of satellites to biology was mostly locating interesting areas for further study.

Jerlov's first book *Optical Oceanography* (1968) makes brief reference to it in a section near the end: "Discoloration of the Sea."

The most significant event: publication of

"Spectra of Backscattered Light from the Sea Obtained from Aircraft as a Measure of Chlorophyll Concentration." (Clarke et al. *Science*, **167**, 1119, 1970):

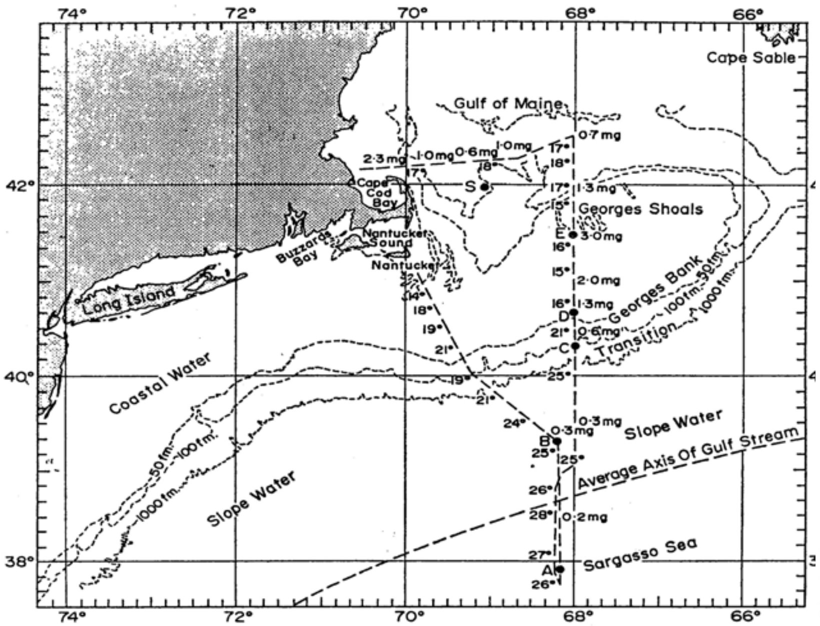


Fig. 1. Course of flight of 27 August 1968 and location of Stations A to
Surface water temperatures are shown to the left or below the flight pat
chlorophyll concentrations are shown to the right or above flight path (fro
Clarke *et al.*, 1970a).

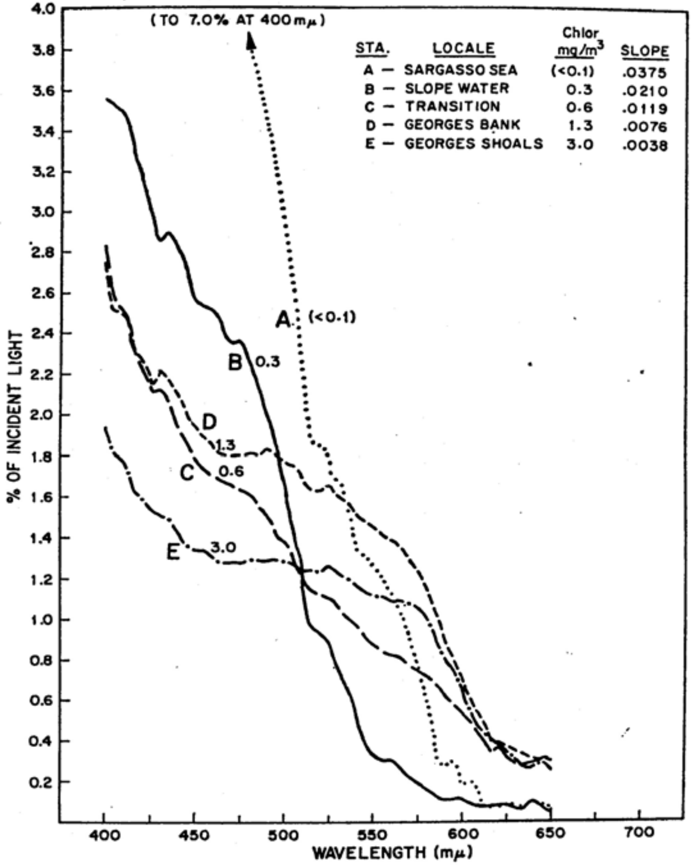


Fig. 2. Spectra of upwelling light obtained at 305 m on 27 August 1968 a
Stations A to E shown in Fig. 1 (from Clarke *et al.*, 1970a).

Variations in **Chlorophyll *a*** could be observed with an aircraft-based radiometer.

They did mention an interference with such measurements referred to as "air light": the increased radiance with an increase in altitude

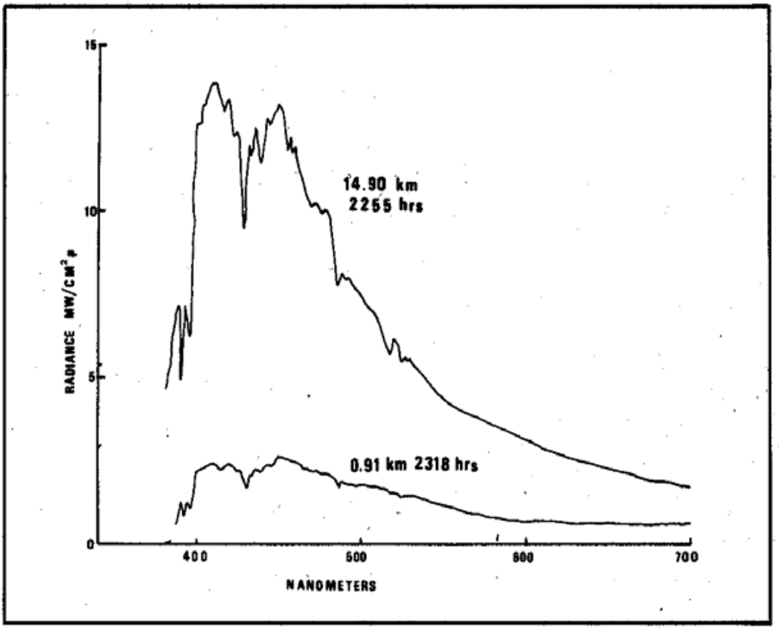


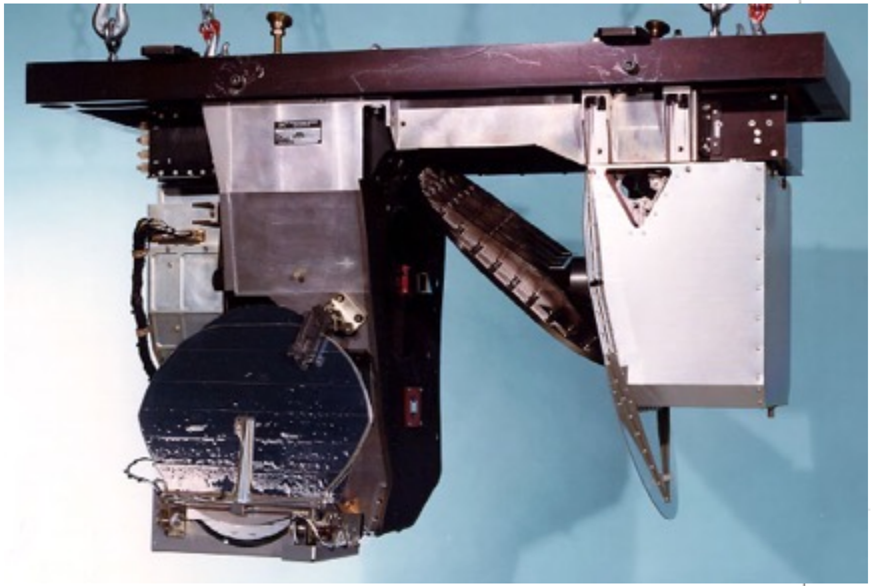
Figure 2. Upwelling Radiance over Catalina Channel at High and Low Altitude.

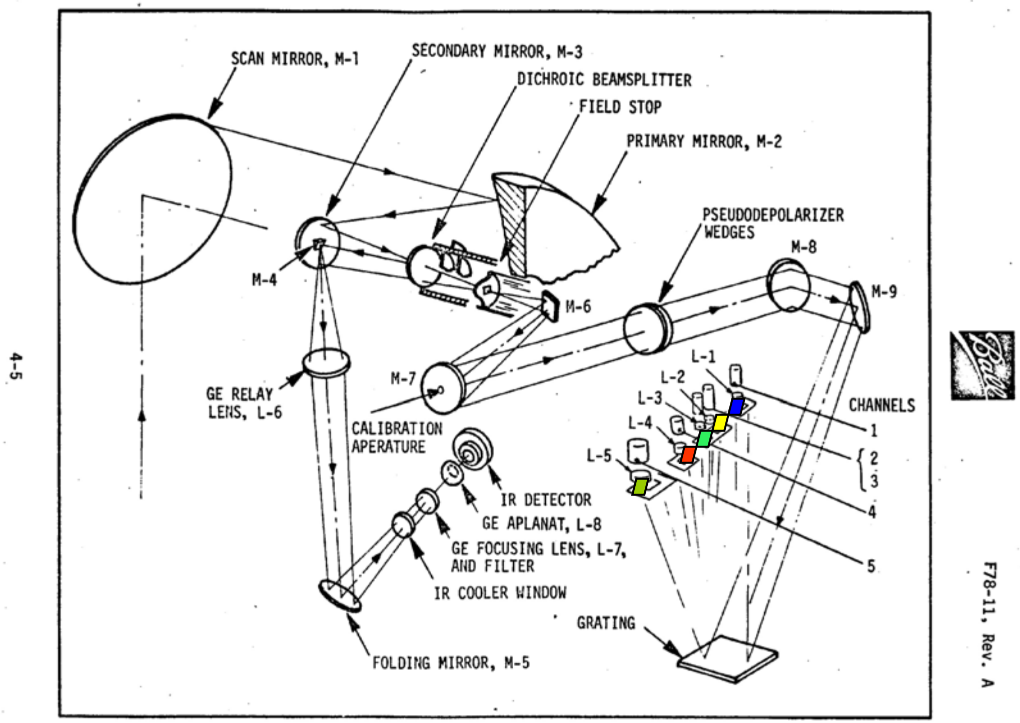
Hovis and Leung, Opt. Eng. (1977) -- Note work done in 1972

Still, these and other aircraft experiments led NASA to approve the Coastal Zone Color Scanner (CZCS) in 1973.

Ball Aerospace.

Yes, they also made canning jars.





At this point, no quantitative relationship existed between Chlorophyll a and the radiance exiting the water.

But it was clear that "something" of interest could be seen.

This vagueness led many to believe CZCS was a BOONDOGGLE!

A CZCS experiment team was formed by NASA in late 1975 to develop <u>quantitative</u> algorithms for deriving the concentration of Chlorophyll *a* from the CZCS imagery.

In other words, to make it work!

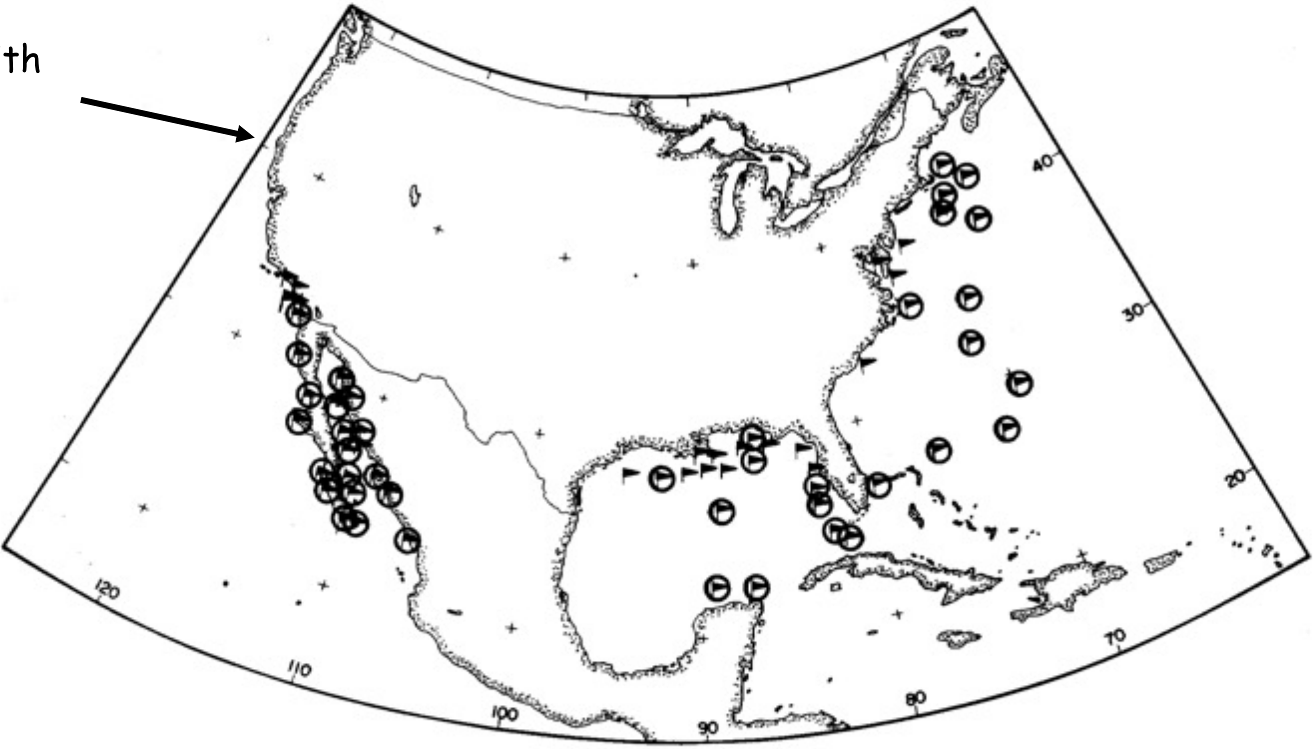
Note: At this time the construction of the CZCS was nearly complete --- modifications were out of the question.

No changes, make it work as is!

We needed data relating the spectral radiance exiting the water, $L_w(\lambda)$, and the chlorophyll *a* concentration.

Virtually none existed! Most earlier radiometry was of $E_u(\lambda)$ rather than $L_w(\lambda)$.

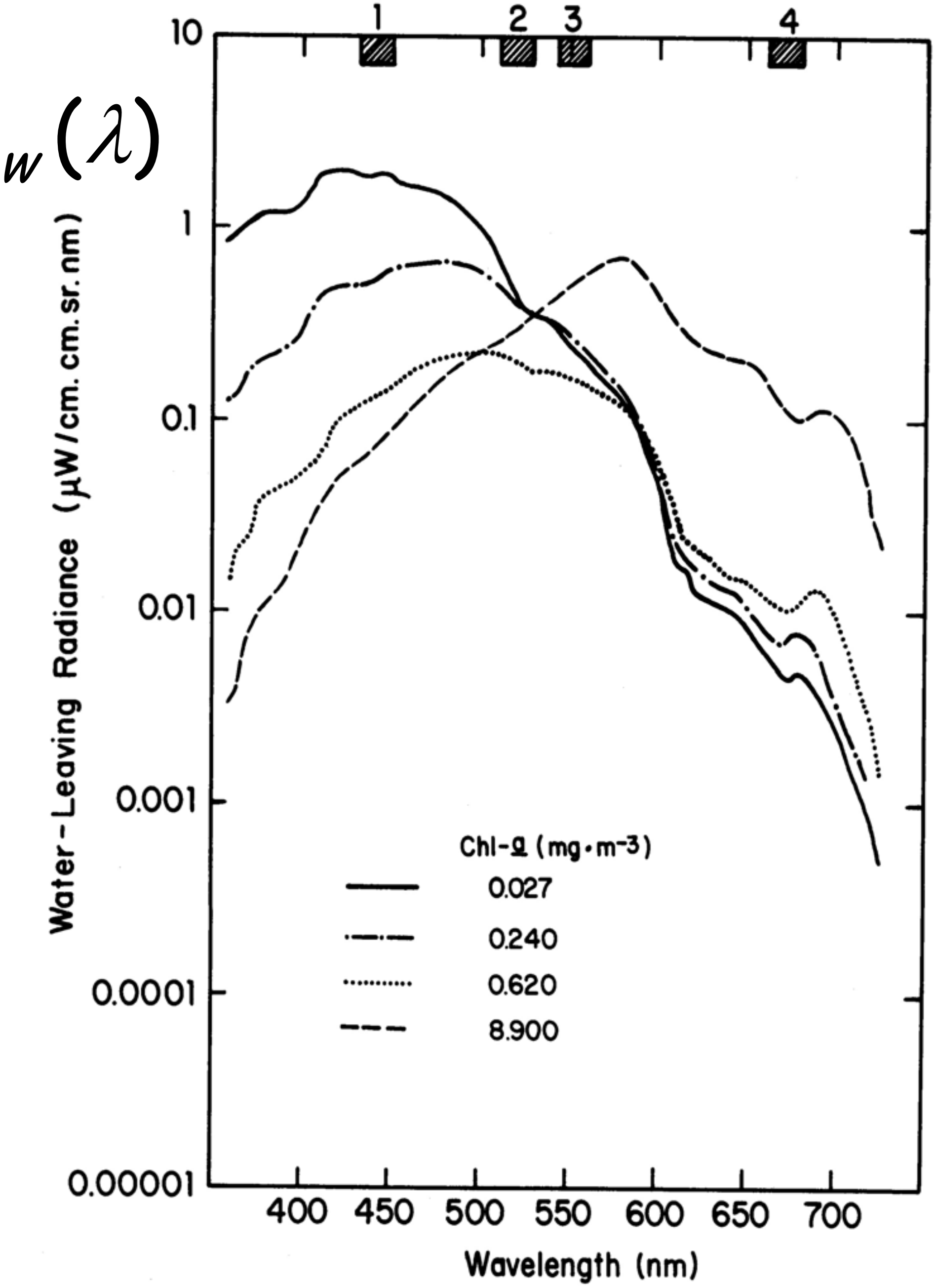
$E_u(\lambda)$ -> $L_w(\lambda)$ conversion varies by factor of 2.



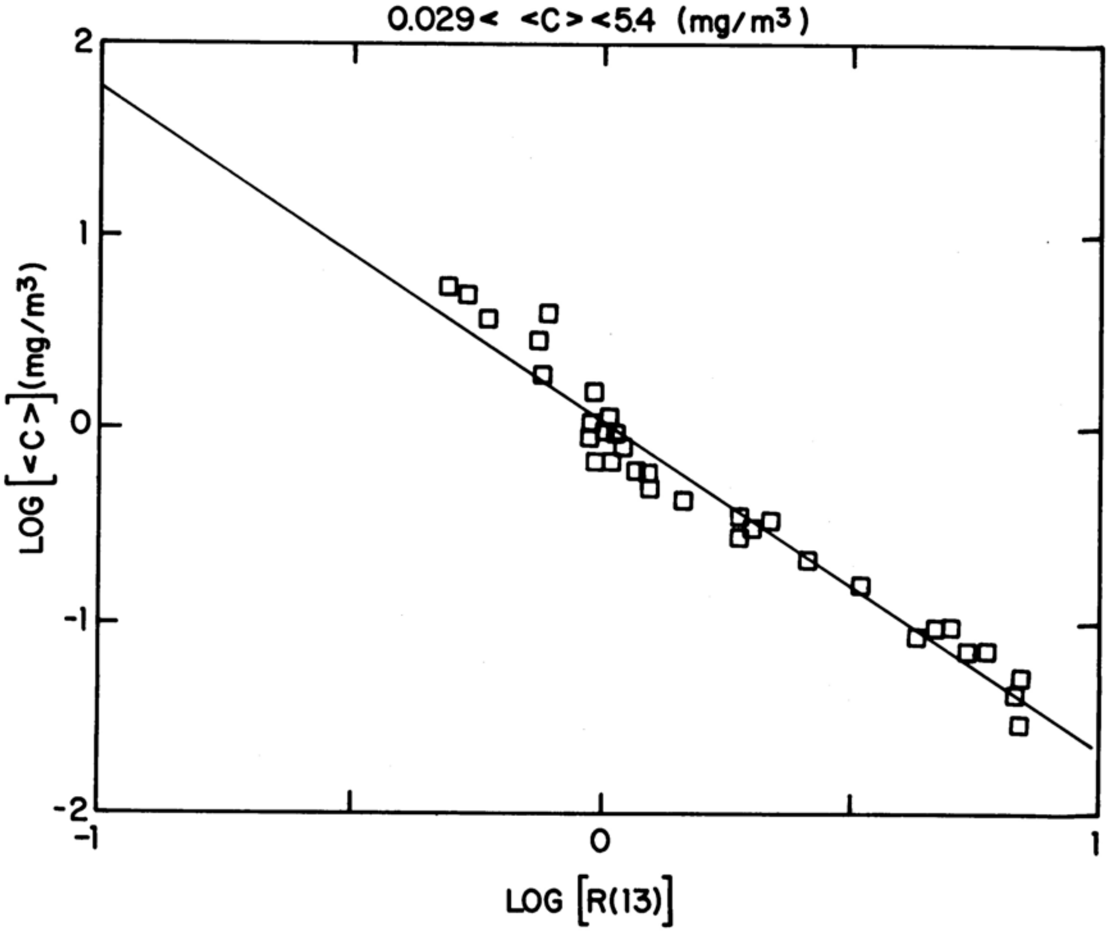
Ros Austin, Ray Smith and C. Yentsch: L_w

FIG. 3. Locations at which the *in situ* data described in the text were obtained. Circled locations are believed to meet the criteria for Morel's case 1 waters. Sites marked by unencircled flags are case 2. (From Gordon *et al.*, 1983a.)

$L_w(\lambda)$

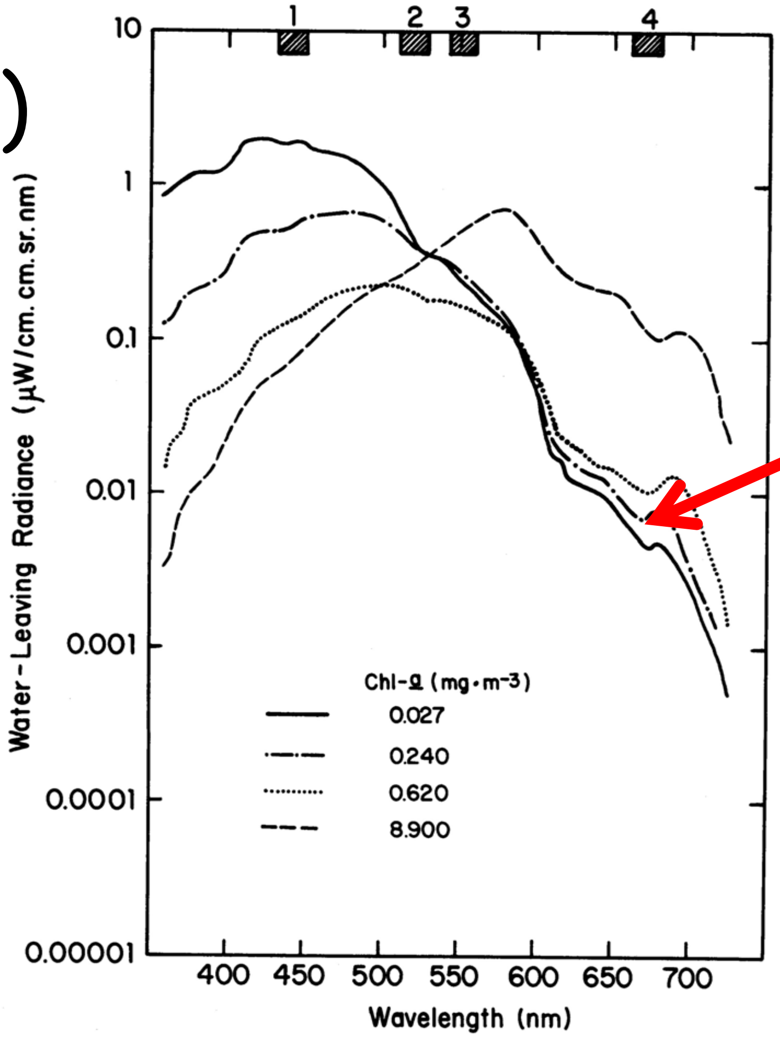

1
2
3
4
Water-Leaving Radiance (μW/cm. cm. sr. nm)
10
1
0.1
0.01
0.001
0.0001
0.00001
400
450
500
550
600
650
700
Wavelength (nm)
Chl-a (mg • m-3)
0.027
0.240
0.620
8.900

This work provided the empirical, but quantitative, algorithm linking $L_w(\lambda)$ and Chlorophyll a.



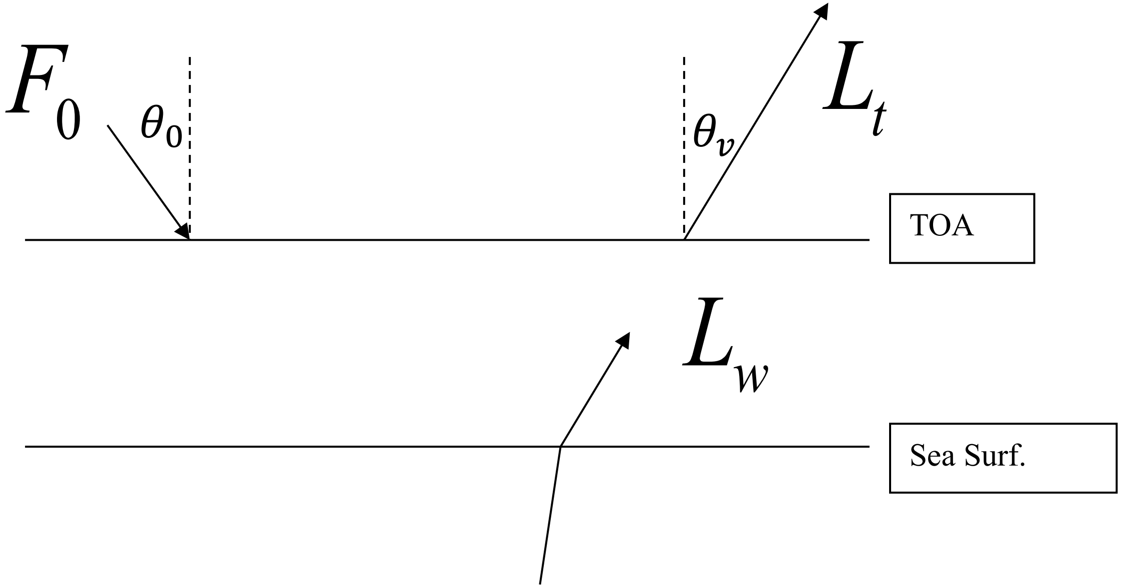
$$R(13) = L_w(443) \,/\, L_w(550)$$

$L_w(\lambda)$



Also: note L_w is very small in red!

"Air light" removal: ("Atmospheric Correction")



In single scattering: $L_t = L_r + L_a + tL_w$

Switch to "reflectance": $\rho = \dfrac{\pi L}{F_0 \cos\theta_0}$

Then $\rho_t = \rho_r + \rho_a + t\rho_w$

The Rayleigh term is easy to compute in single scattering:

$$\rho_r = \frac{\tau_r(\lambda) p_r(\theta_v, \varphi_v, \theta_0, \varphi_0; \lambda)}{4\ \cos\theta_0 \cos\theta_v}$$

$$p_r(\theta_v, \varphi_v; \theta_0, \varphi_0; \lambda_i) = P_r(\Theta_-, \lambda_i) + \left[r(\theta_v) + r(\theta_0) \right] P_r(\Theta_+, \lambda_i)$$

Similar formulas hold for (ρ_a); however, neither τ_a nor P_a are known!

Therefore, accounting for aerosols required some assumptions.

Aerosol Assumptions

1. Power-law particle size distribution:

=> $\tau_a(\lambda) \sim \lambda^{-\alpha}$
=> p_a independent of wavelength

2. Non-absorbing aerosol.

In addition: $L_w = 0$ in the red (670 nm)

Then the assumptions imply

$$\rho_a(\lambda_i) = (\lambda_i)^{-\alpha} \times Constant,$$

so, $$\rho_a(\lambda_i) = \left(\frac{\lambda_{Red}}{\lambda_i}\right)^{\alpha} \rho_a(\lambda_{Red}),$$

← Can be tested with aircraft data

where, $$\rho_a(\lambda_{Red}) = \rho_t(\lambda_{Red}) - \rho_r(\lambda_{Red})$$

Finally,

$$t\rho_w(\lambda_i) = \rho_t(\lambda_i) - \rho_r(\lambda_i) - \left(\frac{\lambda_{Red}}{\lambda_i}\right)^{\alpha} [\rho_t(\lambda_{Red}) - \rho_r(\lambda_{Red})]$$

$$t\rho_w(\lambda_i) = \rho_t(\lambda_i) - \rho_r(\lambda_i) - \left(\frac{\lambda_{Red}}{\lambda_i}\right)^{\alpha} [\rho_t(\lambda_{Red}) - \rho_r(\lambda_{Red})]$$

We attempted to test using a NASA "prototype" CZCS aircraft sensor, the OCS (Ocean Color Scanner)

Expected: $\rho_a \propto \lambda^{-\alpha}, 0 \leq \alpha \leq 2$

Found: $\alpha \sim 8$. Impossible!

Problem: Very poor radiometric calibration of OCS

Stopped trying to validate the algorithm with real data.

Concentrated on simulations.

Underscores importance of calibration

Atmospheric correction was not validated with real data prior to launch!

Approximately four months before launch we had

1. an empirical, but fairly accurate, phytoplankton pigment algorithm: (L_w -> Chl).

2. a candidate atmospheric correction algorithm that was never validated with real data: (L_t->L_w).

June 1978: a meeting in Victoria B.C. "Passive Radiometry of the Ocean" included many interested in ocean color

We all knew the problems faced with CZCS but, perhaps with some measure of audacity, developed specs for a follow-on sensor.

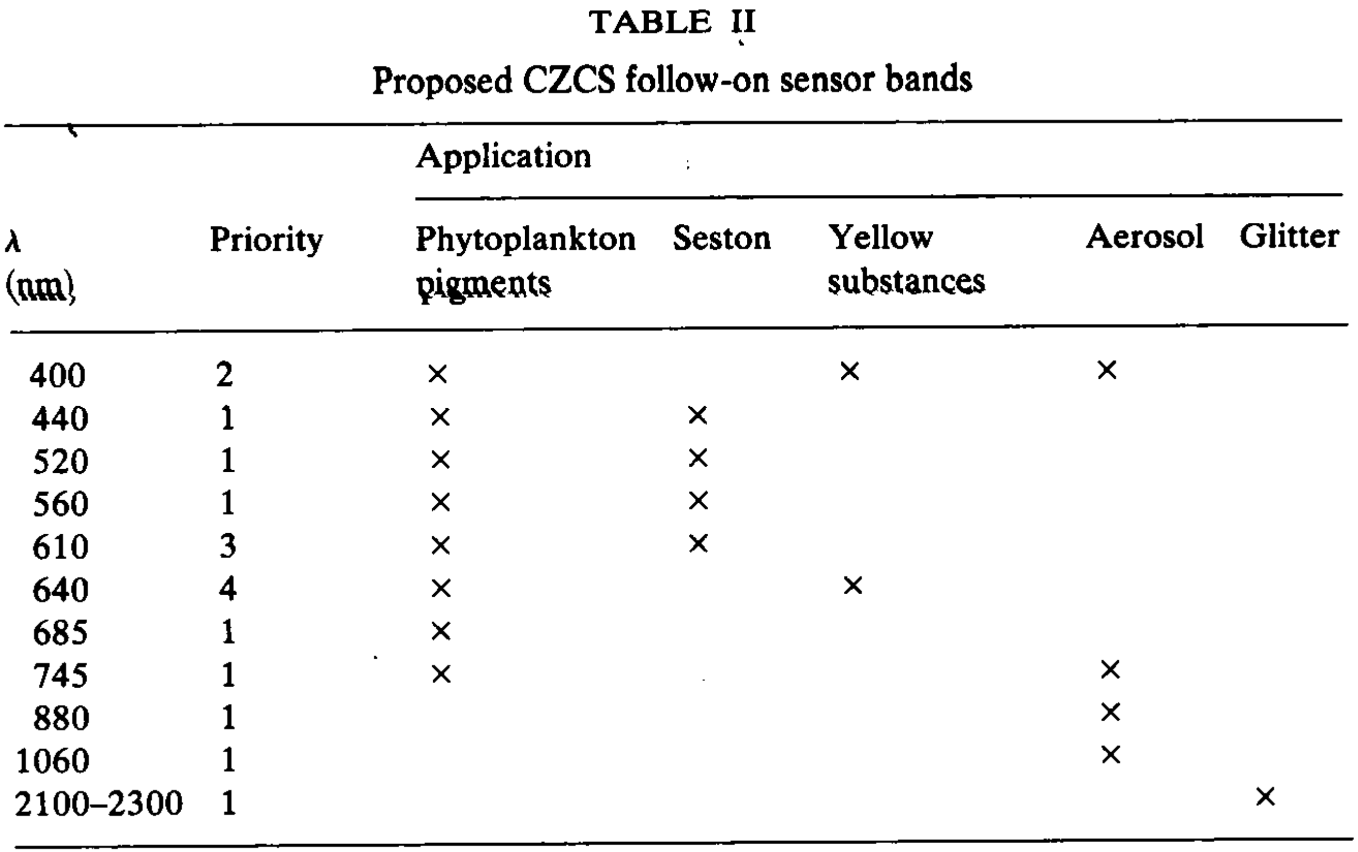


TABLE II

Proposed CZCS follow-on sensor bands

λ (nm)	Priority	Application				
		Phytoplankton pigments	Seston	Yellow substances	Aerosol	Glitter
400	2	×		×	×	
440	1	×	×			
520	1	×	×			
560	1	×	×			
610	3	×	×			
640	4	×		×		
685	1	×				
745	1	×			×	
880	1				×	
1060	1				×	
2100–2300	1					×

Note the similarity to SeaWiFS and MODIS!

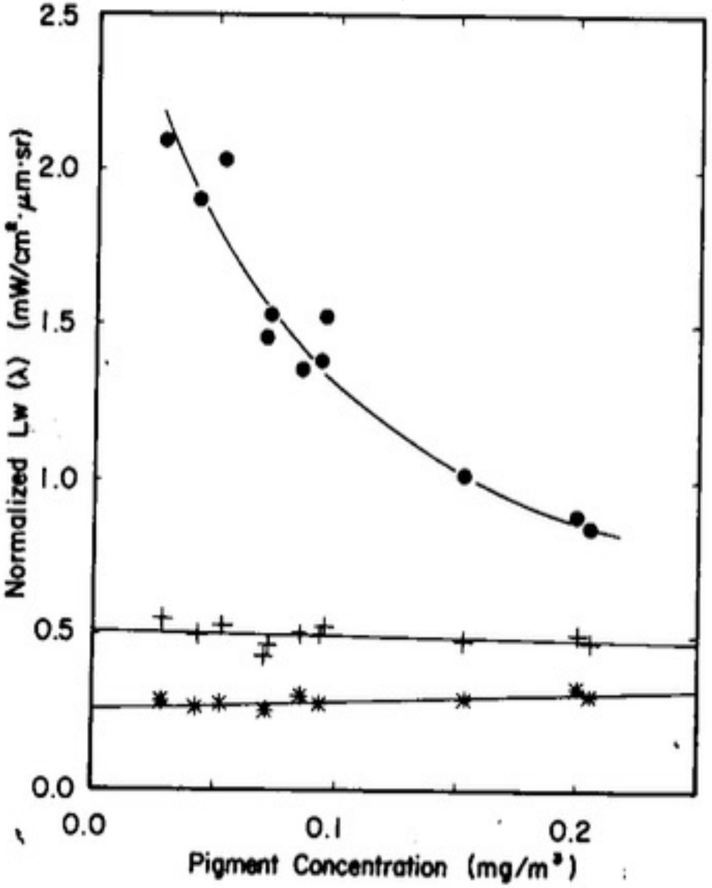
At the meeting Dennis Clark and I examined the accuracy with which pigments could be estimated for a given accuracy in α.

The results were favorable, assuming the correction algorithm worked as planned.

But how do we find α?

The "Clear-Water Radiance" concept:

$$\frac{L_w}{\cos\theta_0} \quad e^{+\tau_r/\cos\theta_0}$$



Gordon & Clark, A.O. **20** 4175 (1981)

$$\rho_t = \rho_r + \rho_a + t\rho_w$$

This provided $\rho_a(520)$ and $\rho_a(550)$ and thus α.

Use this α for the whole image!

Did it work?

First image ever processed:

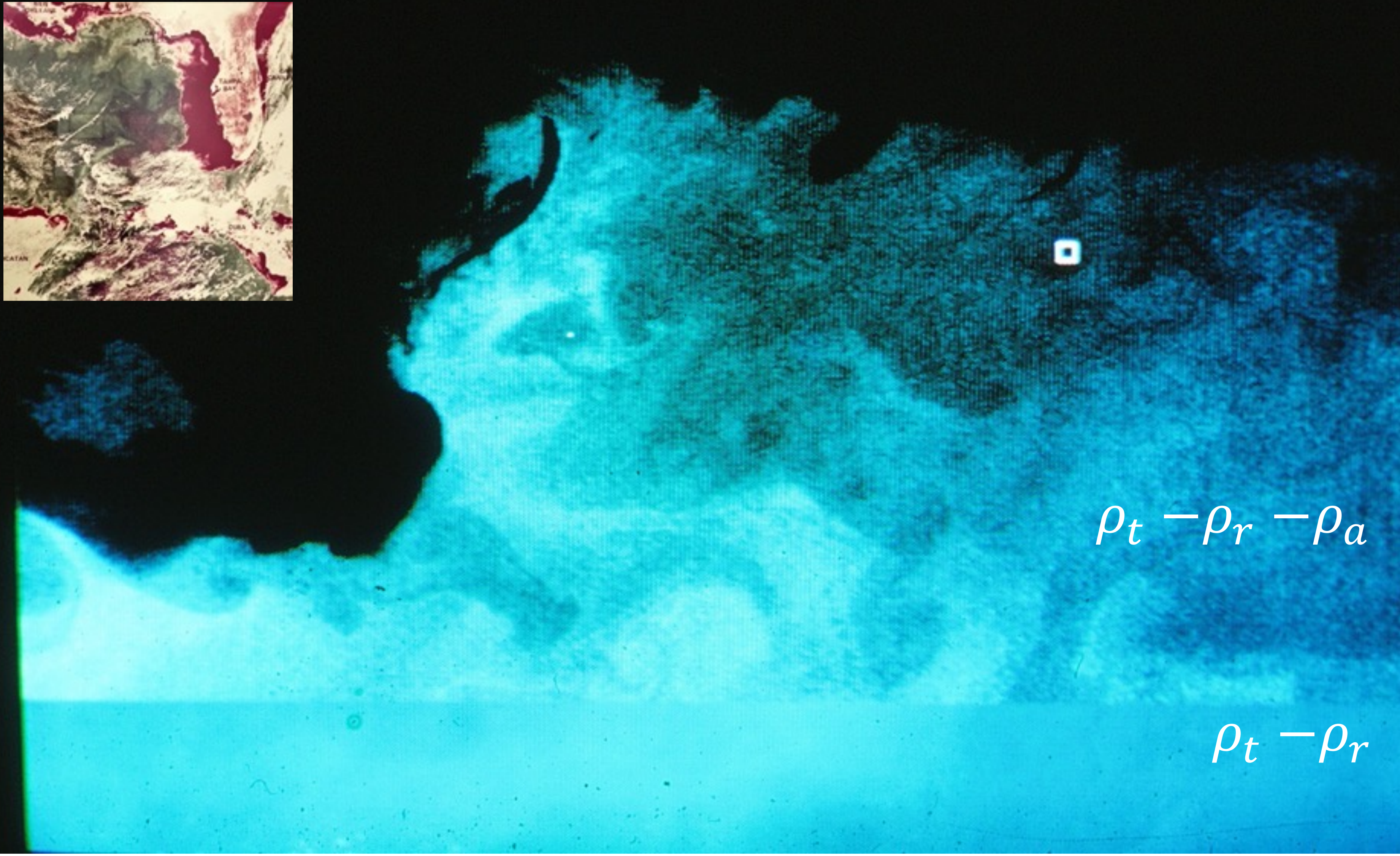
$$t\rho_w(\lambda_i) = \rho_t(\lambda_i) - \rho_r(\lambda_i) - \left(\frac{\lambda_{Red}}{\lambda_i}\right)^{\alpha} [\rho_t(\lambda_{Red}) - \rho_r(\lambda_{Red})]$$

I computed ρ_r in line# - pixel# coordinates for each band using a Univac 1106 mainframe computer.

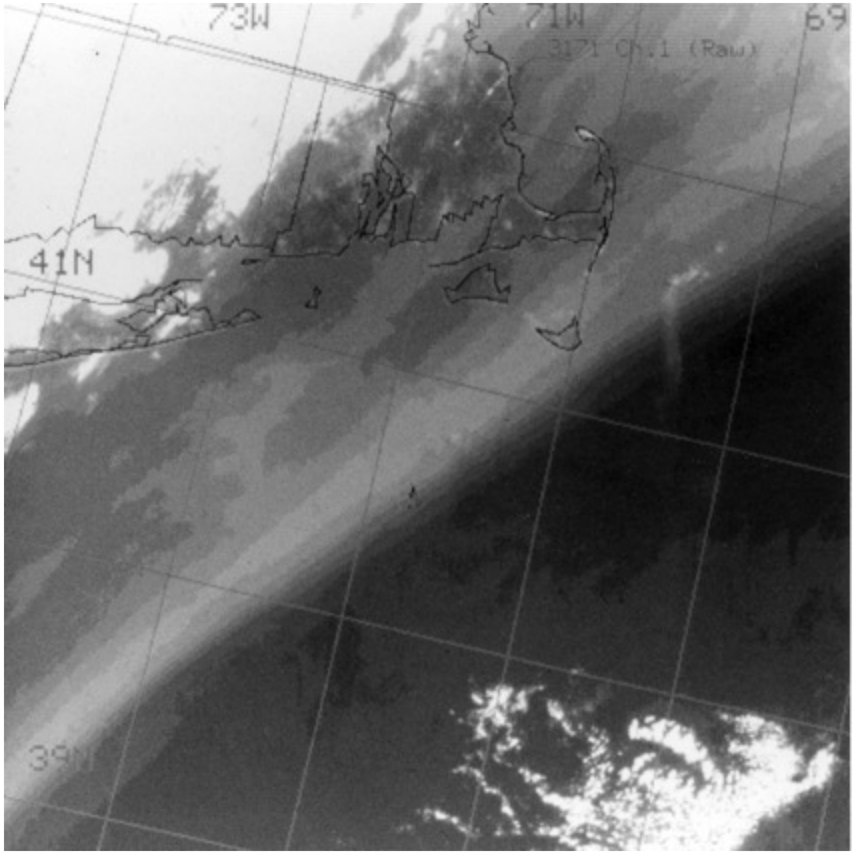
ρ_r was taken to GFSC and placed on an image processing system (AOIPS – DEC PDP 11/55). It could perform simple arithmetic manipulation on images in line# - pixel# coordinates, e.g., subtract one image from another, etc.

The whole algorithm was applied to a CZCS sub-image using AOIPS, and I photographed the monitor as atmospheric correction proceeded.

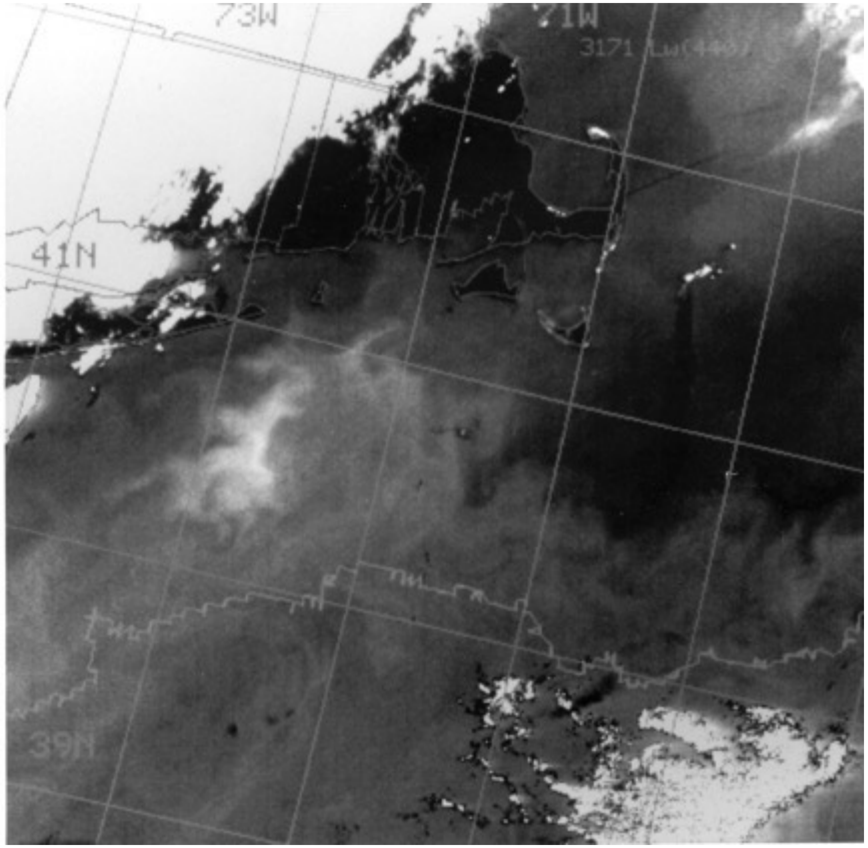
Atmospheric Correction in Progress: Orbit 130, Gulf of Mexico @443 nm



Later, we could effect all of this in an image processing environment.

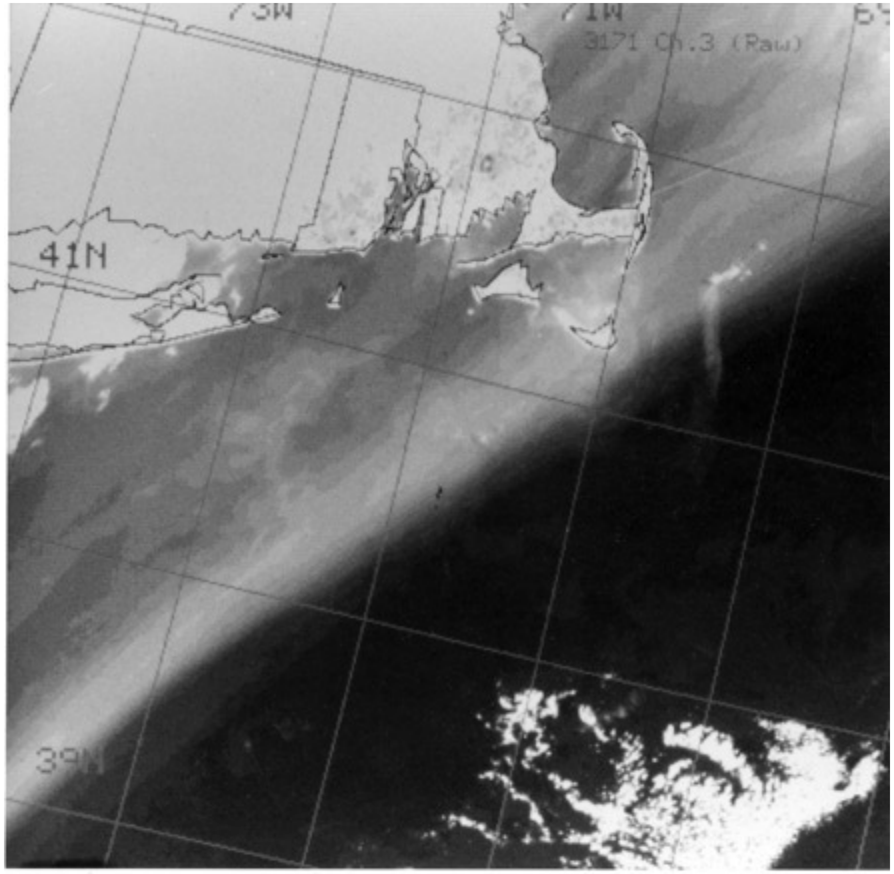


$L_t(443)$

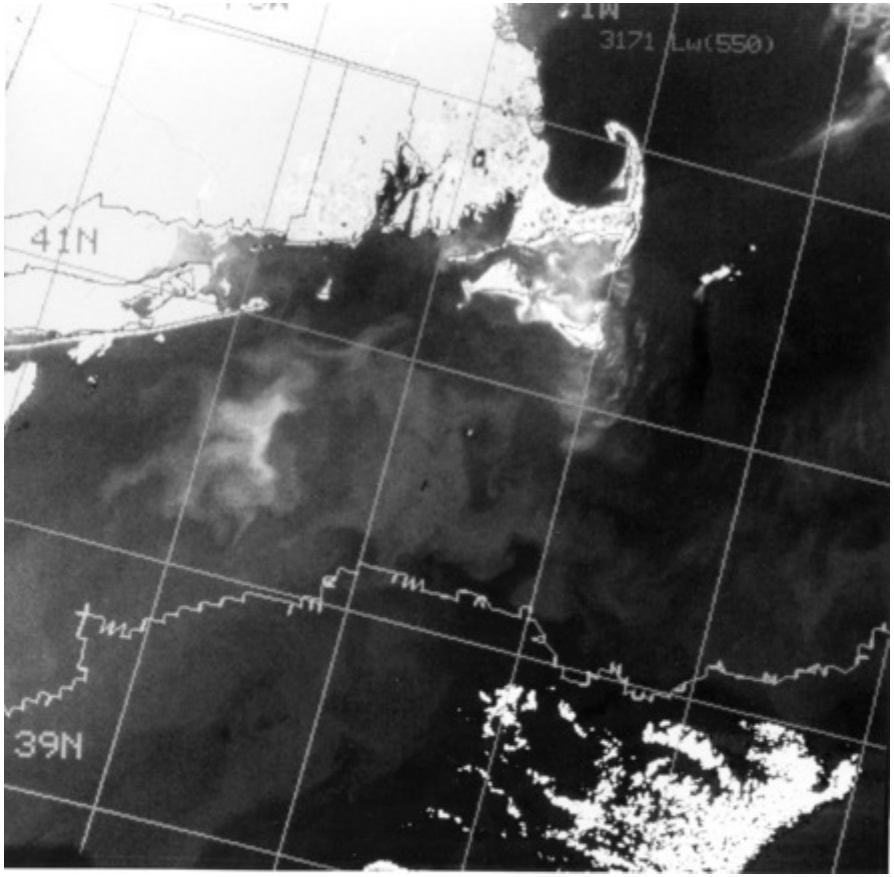


$L_w(443)$

Gordon et al., Appl. Opt. **22**, 20 (1983)



$L_t(550)$

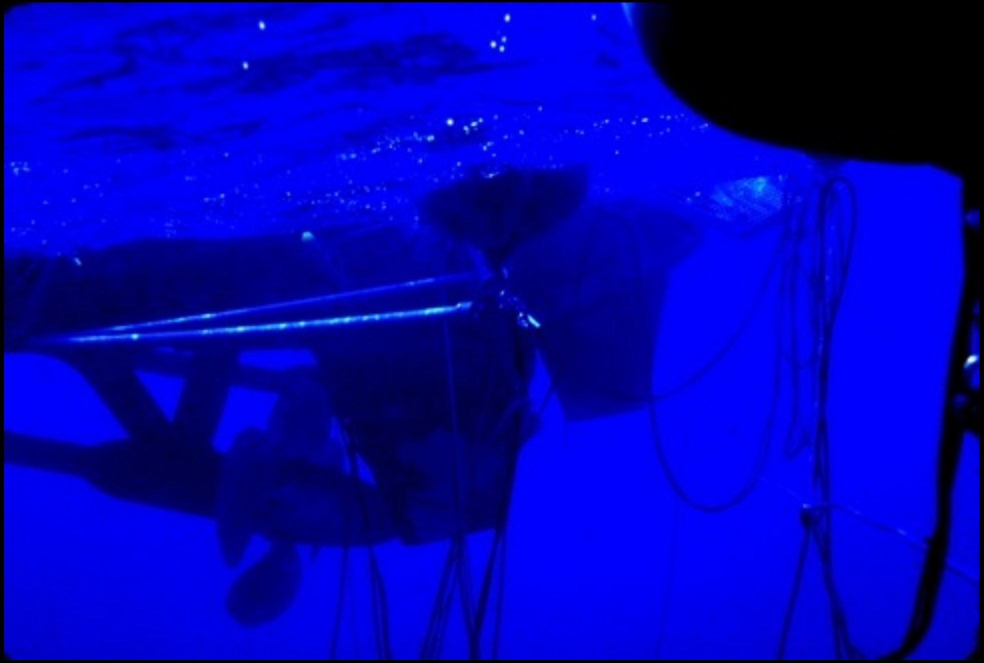


$L_w(550)$

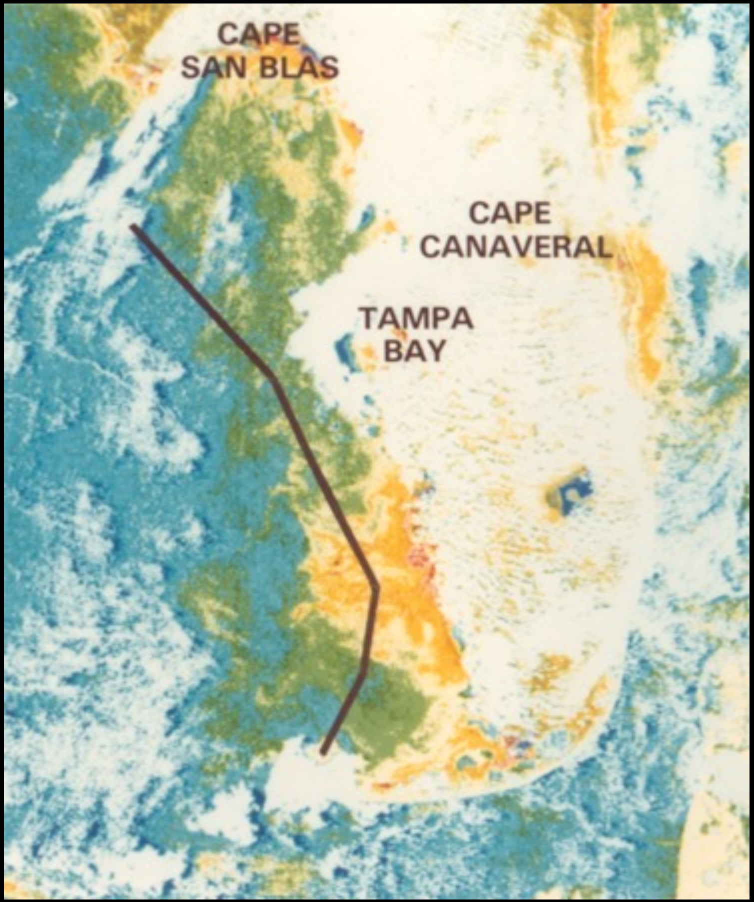
Gordon et al., Appl. Opt. **22**, 20 (1983)

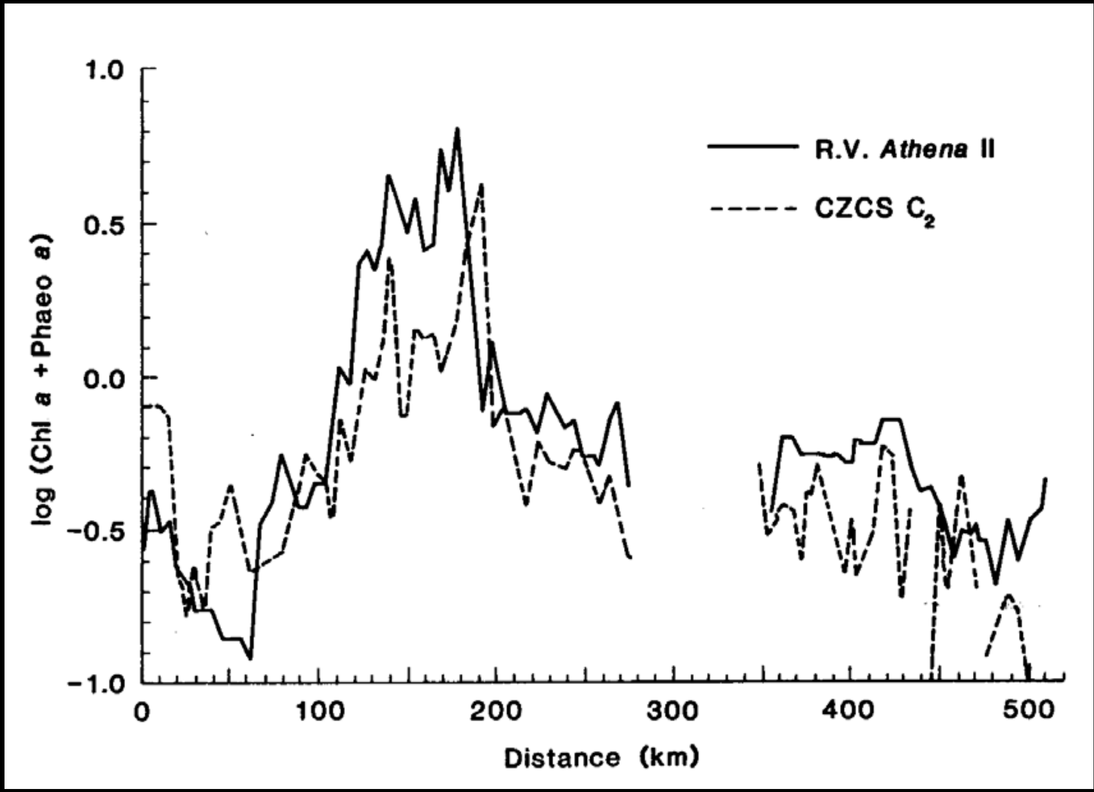
Next came Validation of Pigments

We compared Ship- and CZCS-measured pigments along ship tracks.



RV Athena II an Asheville Class Gunboat (PG-98)

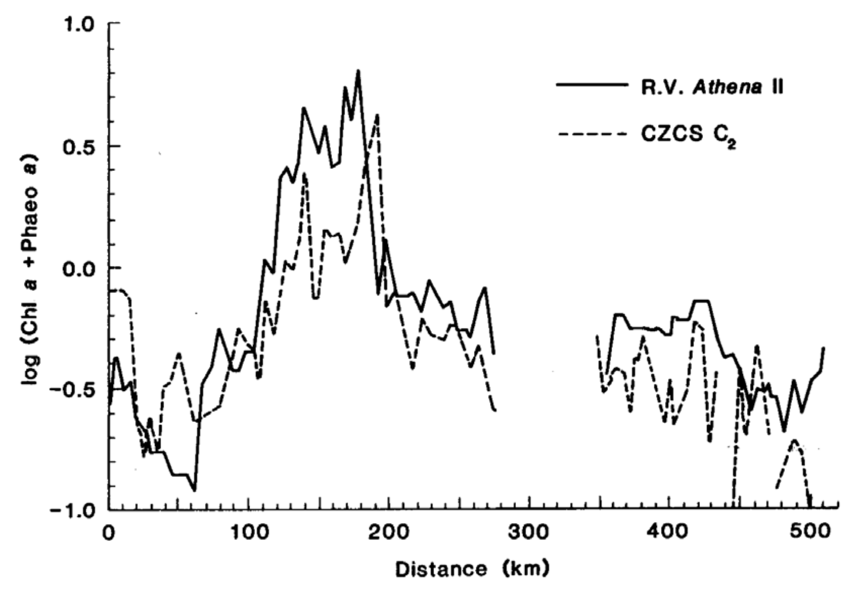


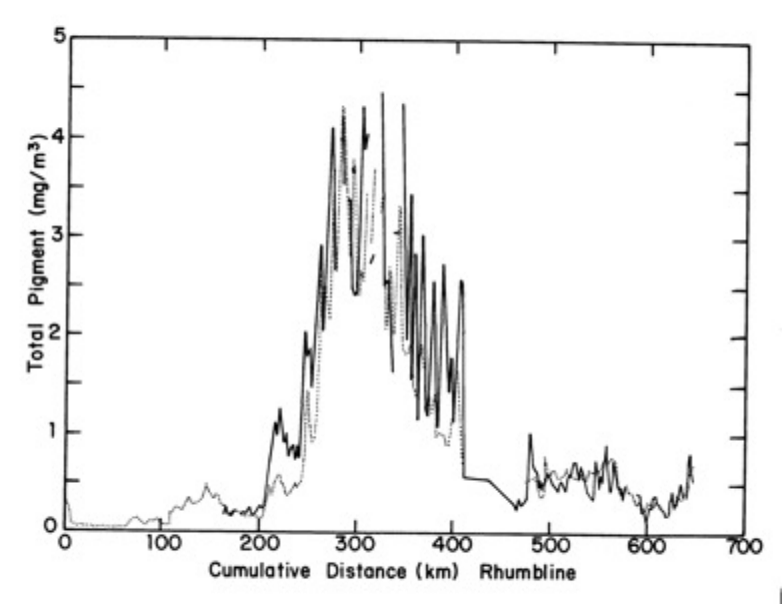


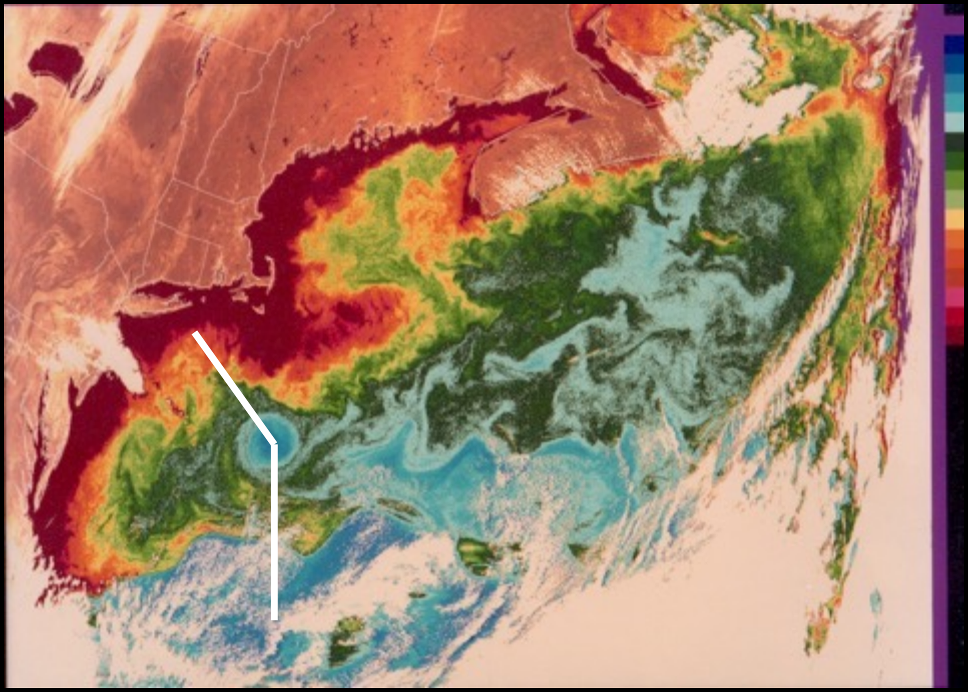
(Raiders 34, Bengals 21)

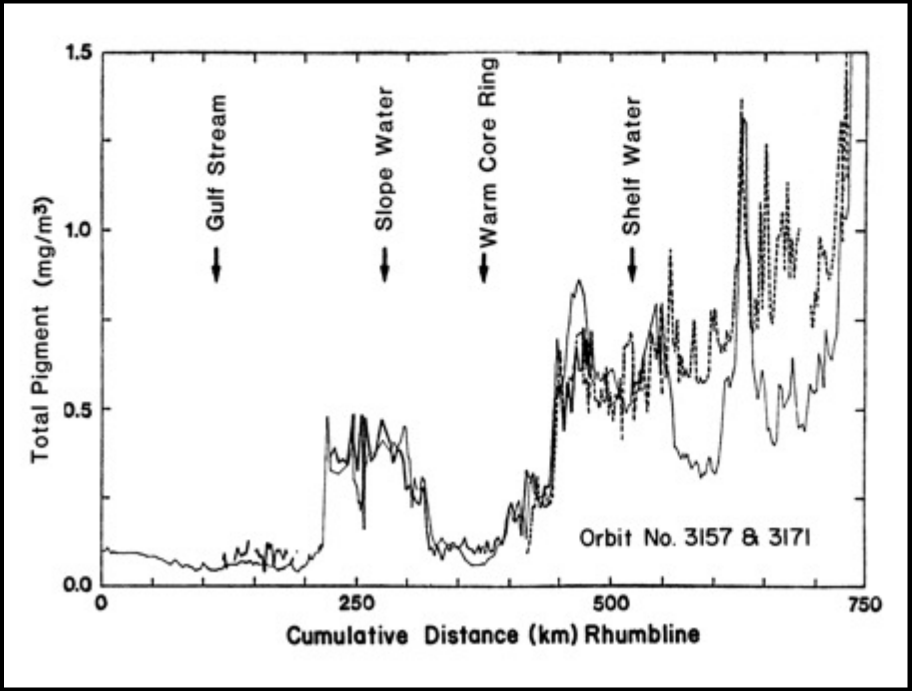
This image was reprocessed later using improved atmospheric correction, improved bio-optical algorithms and vicarious calibration.

Note: Pigment scale no longer logarithmic



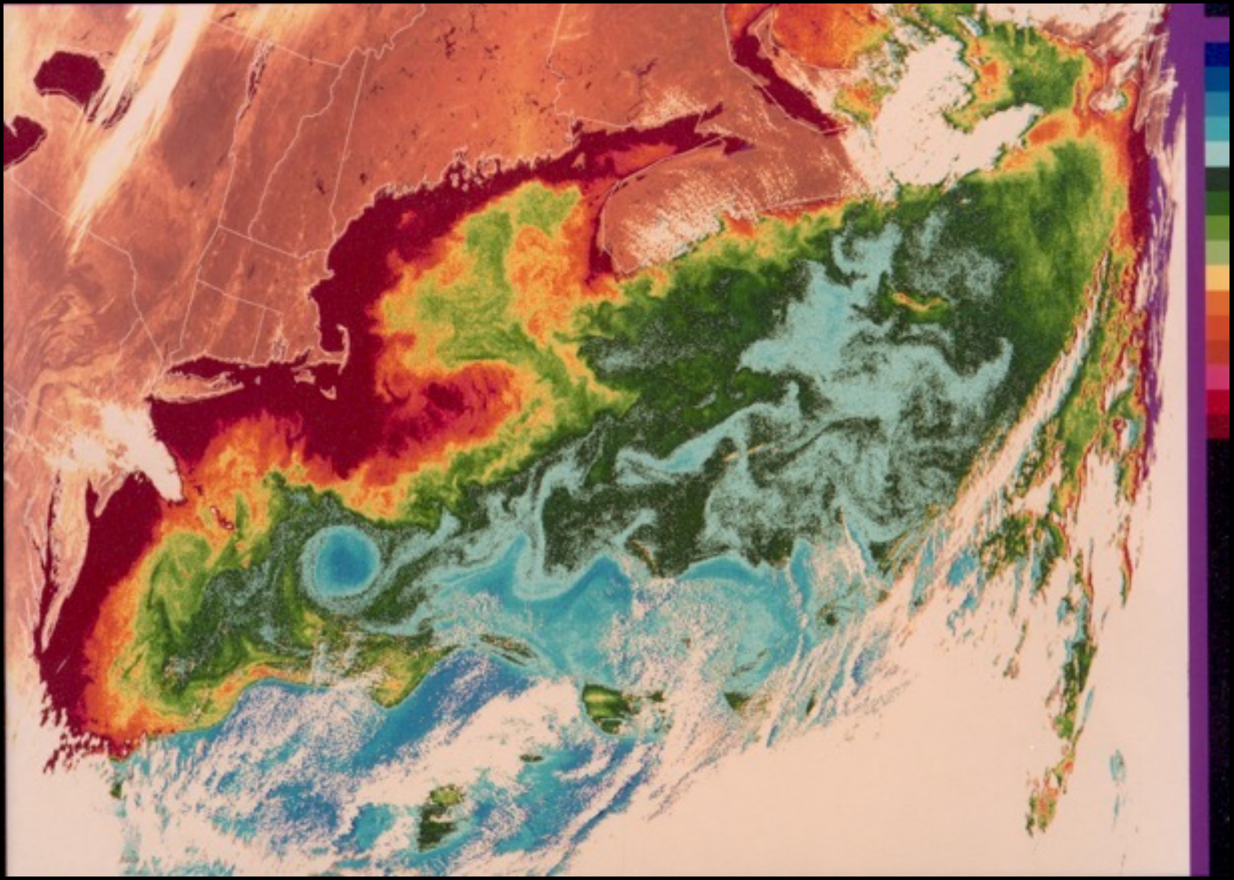






Coastal Zone Color Scanner (CZCS) did not work well near the coast. It did work well in non-coastal areas (most of the oceans), so it would have been more accurately called the Open Ocean Plankton Sensor

(OOPS)



I contend that this is arguably the most famous image of the ocean taken by any space-borne sensor. It first appeared in *National Geographic* in 1981 and later many oceanographic textbooks.

DOUBLE MAP SUPPLEMENT: THE WORLD AND WORLD OCEAN FLOOR

VOL. 160, NO. 6 DECEMBER 1981

NATIONAL GEOGRAPHIC

PANDAS IN THE WILD 735

MOUNT ST. HELENS AFTERMATH 713

ORANGE, A MOST CALIFORNIA COUNTY 750

THE OCEAN
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- AN ERA OF DISCOVERY 792
- BLUE-WATER LIFE BY NIGHT 834

PRESIDENT'S REPORT TO MEMBERS 848

OFFICIAL JOURNAL OF THE NATIONAL GEOGRAPHIC SOCIETY WASHINGTON, D.C.

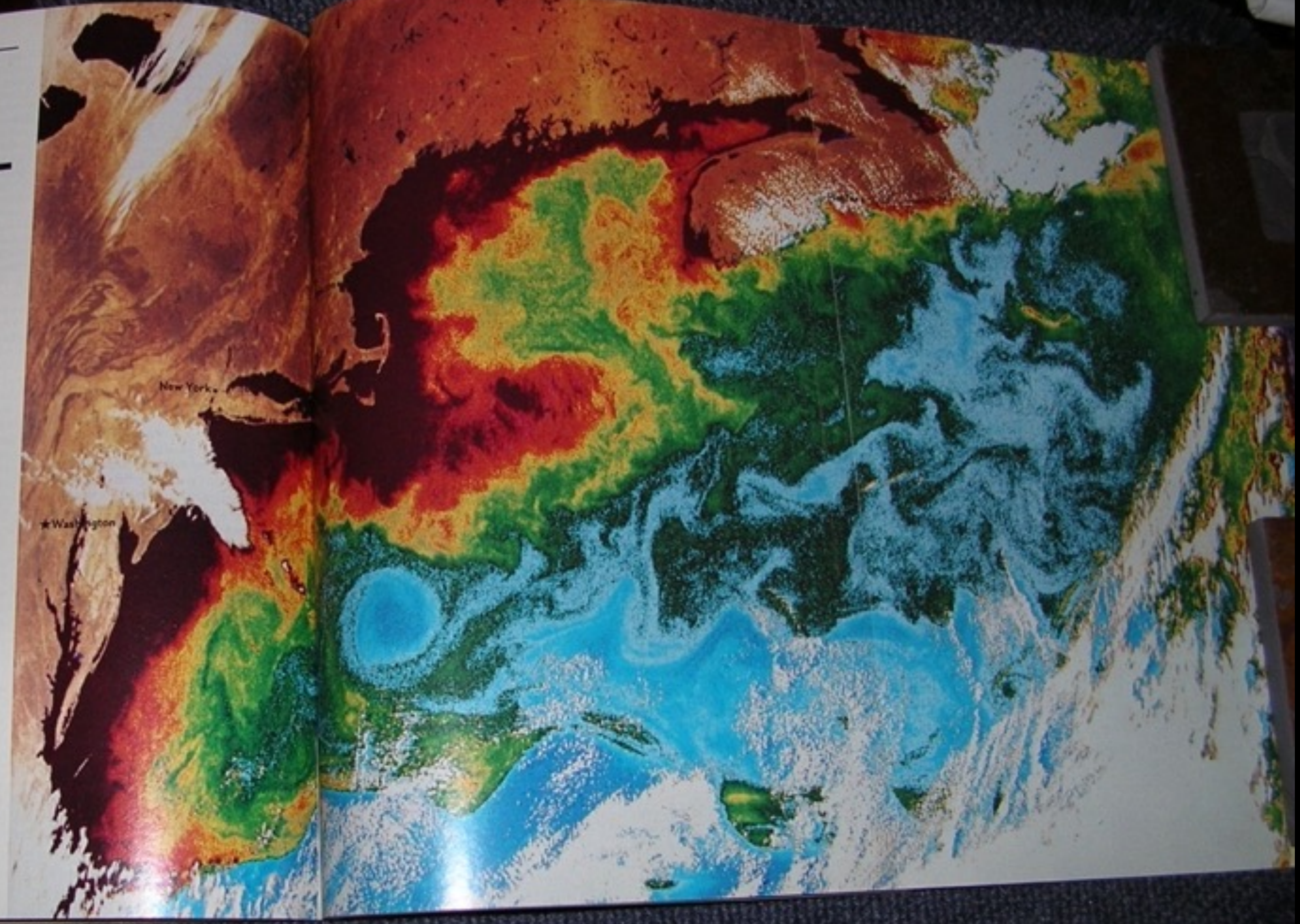
Sensing the ocean's crop by satellite

"WHERE ARE THEY BITING?" That familiar fisherman's question cannot yet be answered directly from space. However, the Coastal Zone Color Scanner (CZCS) aboard the Nimbus 7 satellite can answer this question: Where are the regions of greatest phytoplankton concentration? Where they are abundant, a fully developed food chain follows, including commercially valuable fish.

A CZCS image of the Atlantic (**fold-out, right**), painted by a computer, shows concentrations of phytoplankton. The scanner detects absorption of certain wavelengths of light by the chlorophyll that plankton use for photosynthesis. The dark strip along the coast shows the most intense chlorophyll signal (white areas are clouds; land color is not significant). But it is frontal areas, where dark red changes to orange, that are most productive. One, east and south of Cape Cod, lies above Georges Bank, a shoal where winds and tides promote vertical mixing of water to sustain one of the world's most prolific fishing grounds.

The nutrient-poor Gulf Stream is deep blue, with lighter blue segments breaking toward Nova Scotia. The nearly perfect blue circle is a warm core enclosed by a ring of colder water; south of it a yellow tail of more productive waters is being drawn offshore along the Gulf Stream boundary.

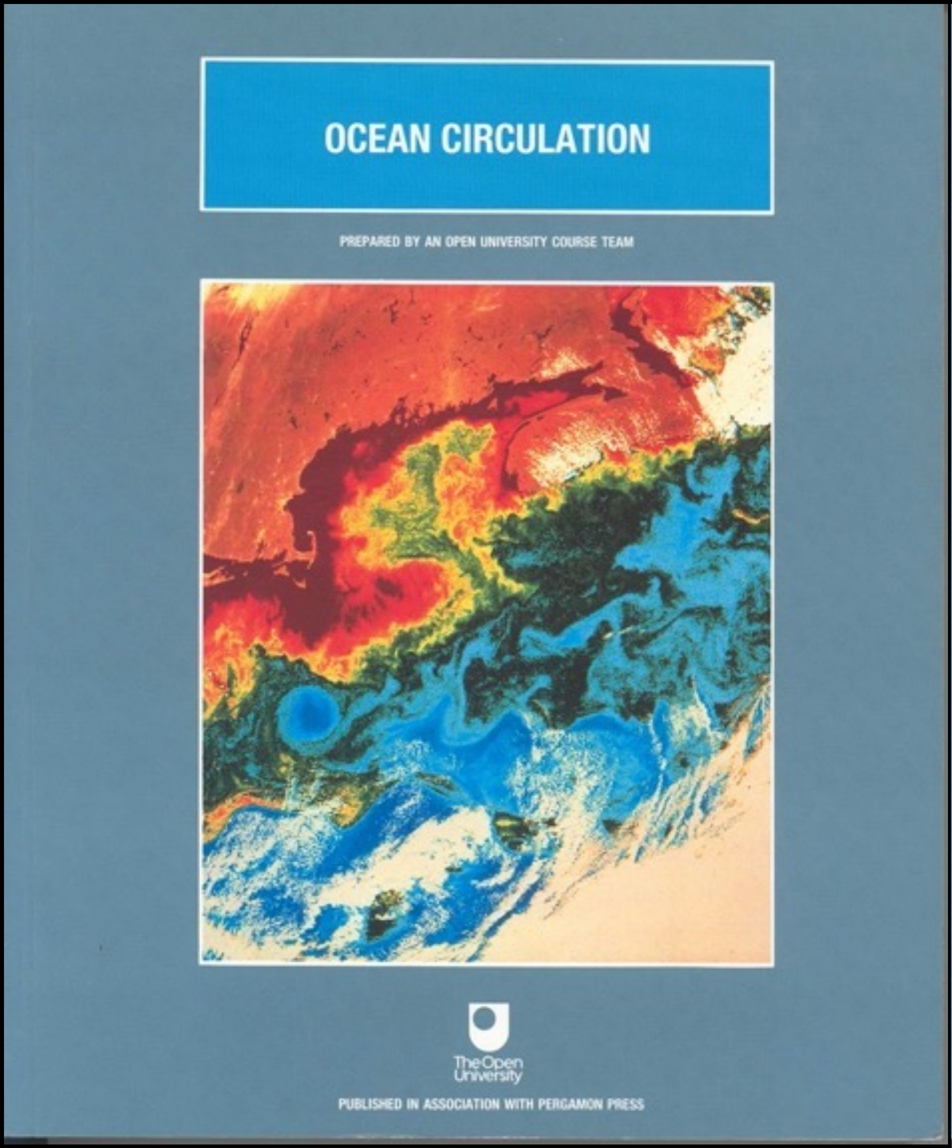
The CZCS is still experimental, and, in a time of budget cutting, its fate is uncertain. Yet it might prove as useful for the study of the sea as Landsat has been for continents and Tiros for weather forecasting.



🟫	🟥	🟨	🟩	🟦	🟦

MORE CHLOROPHYLL LESS

NIMBUS 7 CZCS EXPERIMENT TEAM



OCEAN CIRCULATION

PREPARED BY AN OPEN UNIVERSITY COURSE TEAM

The Open University

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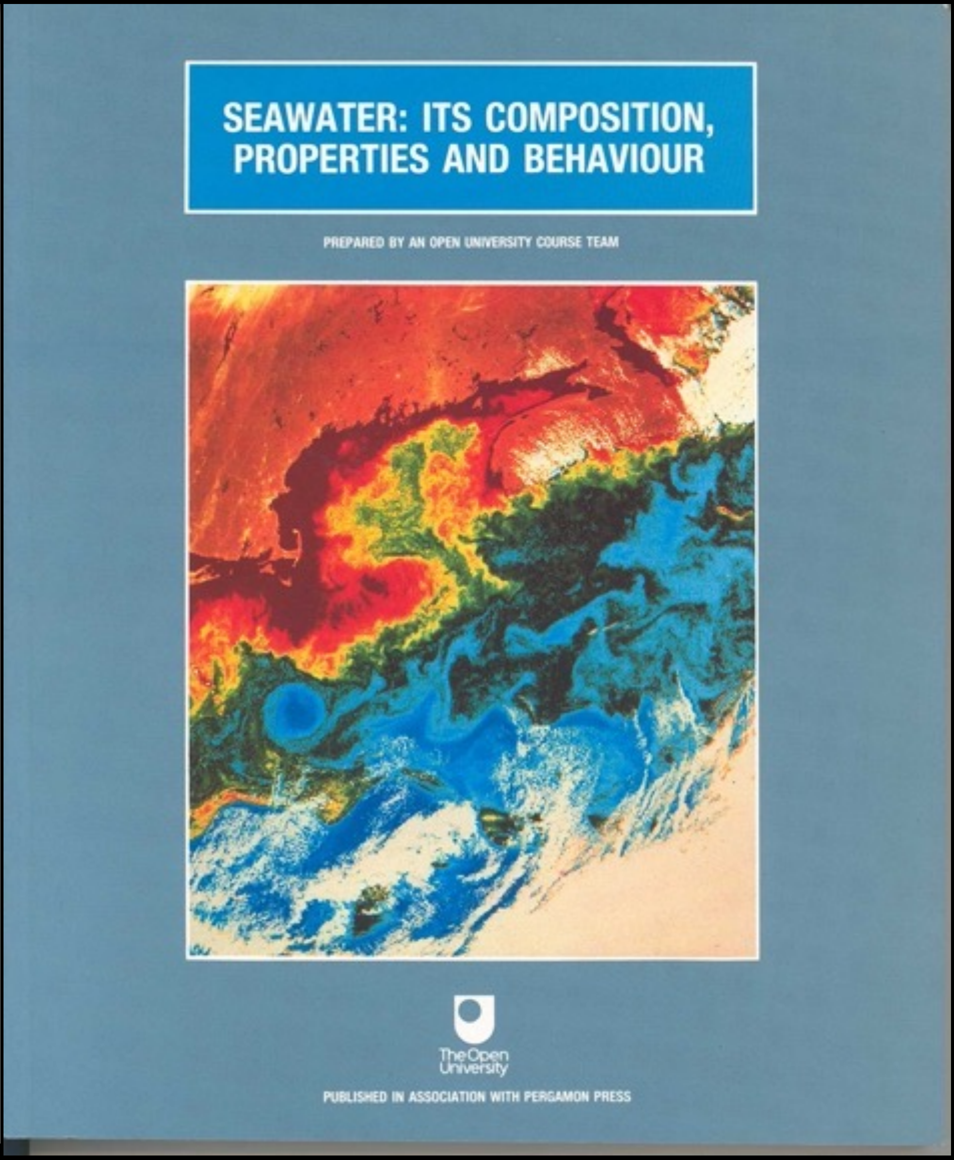

SEAWATER: ITS COMPOSITION, PROPERTIES AND BEHAVIOUR

PREPARED BY AN OPEN UNIVERSITY COURSE TEAM

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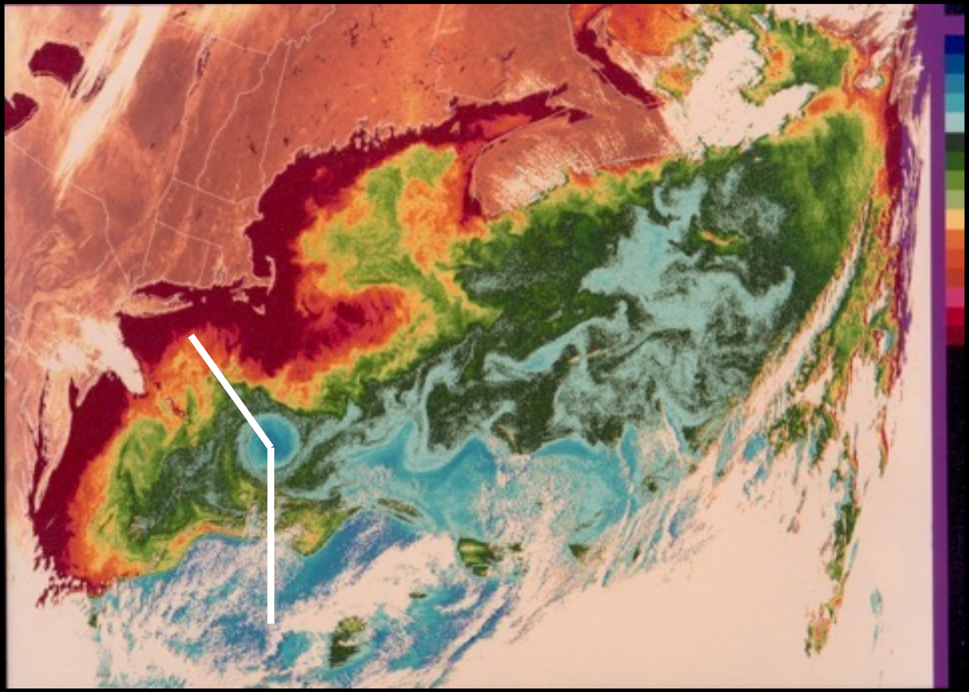
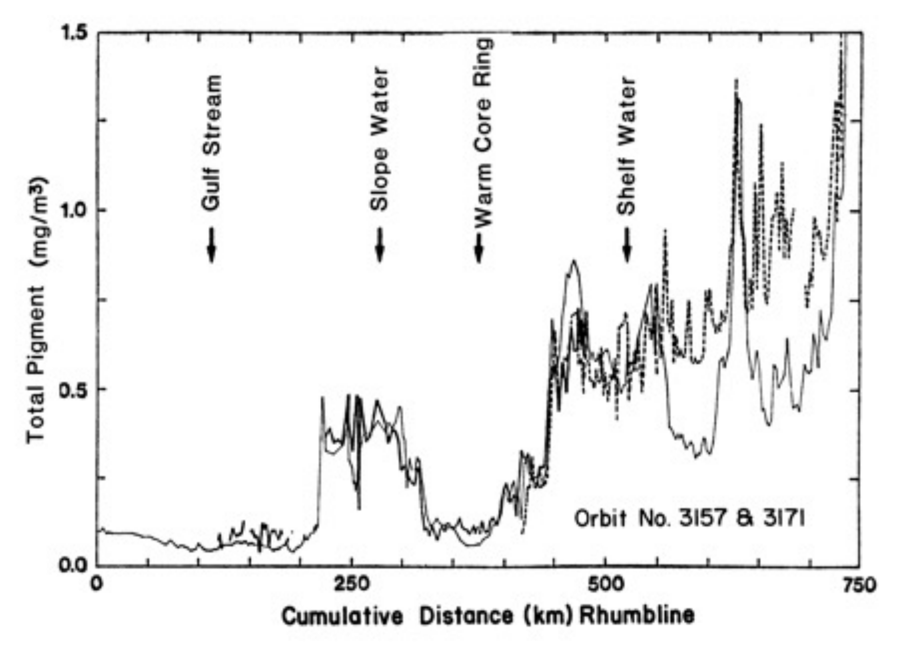
Computation was always a significant challenge





This track line
was processed on
this computer !

We (CZCS Team) were considered the lunatic fringe by much of the oceanographic community:

Just prior to launch (1978), in a laboratory-wide program review a NOAA lab, where I was on a one-year leave-of-absence from U. Miami, we were instructed by upper management not to even mention the CZCS.

In another program review after the initial validation: “I know of no respectable biologist who thinks this [ocean color] is important.” (1981)

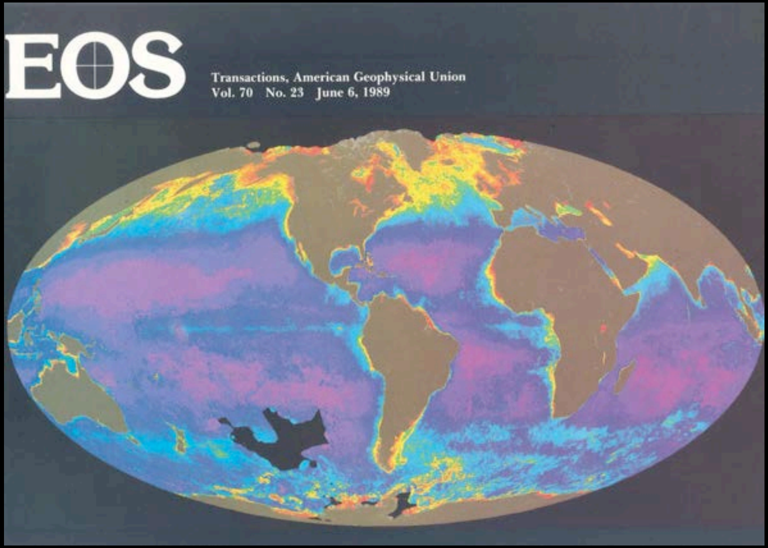
In contrast, when biologists recognized its potential -- ’82-’83:

Dick Barber: “I had to rearrange everything I knew…”

He later referred to CZCS as one of the seven most important developments in marine biology in the last 50 years! “

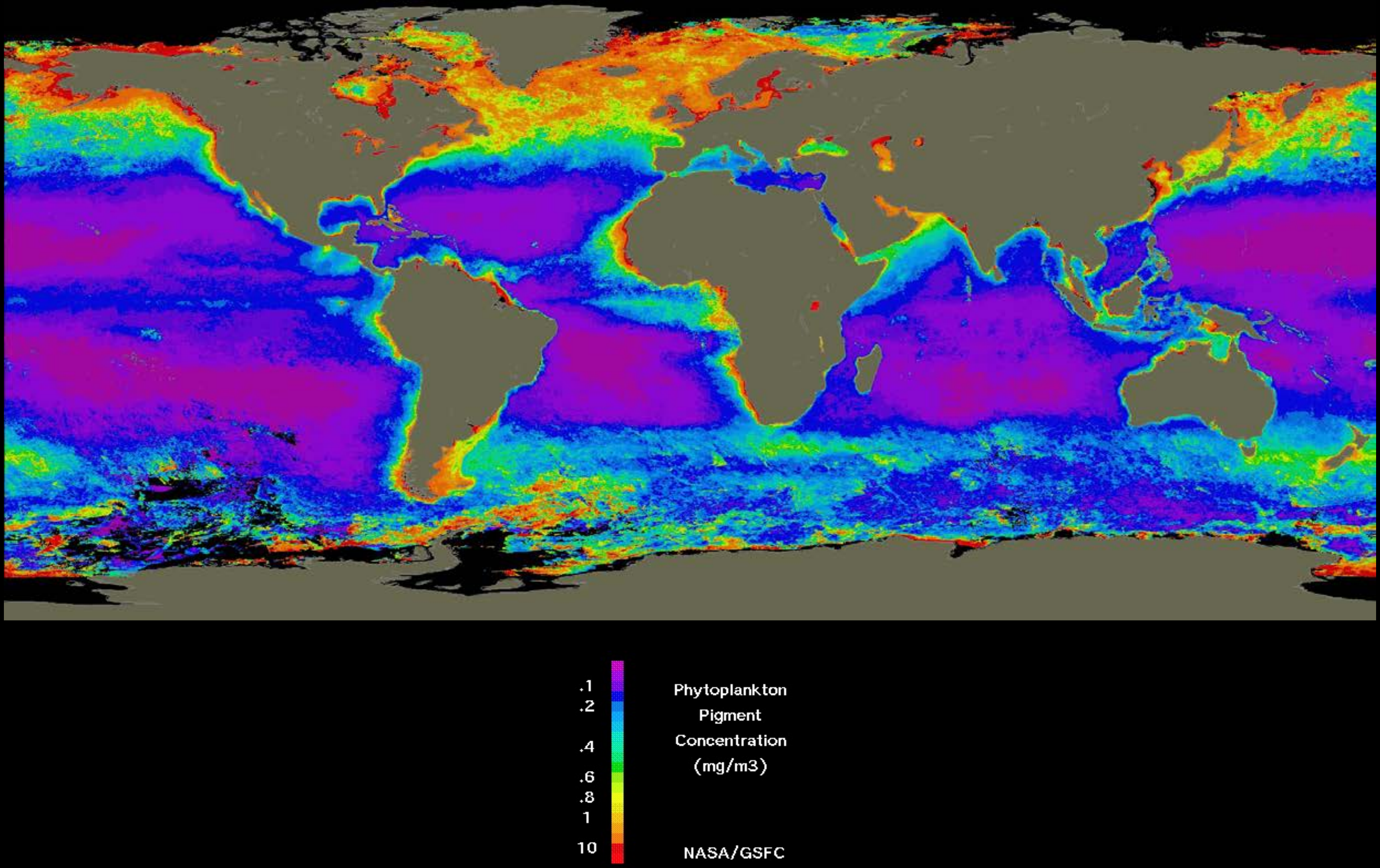
The Global Data Set

CZCS could only operate 2 hours per day. One of the most important decisions the experiment team made in the early 80’s was reserve a block of time each day to image the global oceans, i.e., not just the costal zones. This paid off when computers became sufficiently fast to process the entire CZCS data set (~180 days including manual QA).



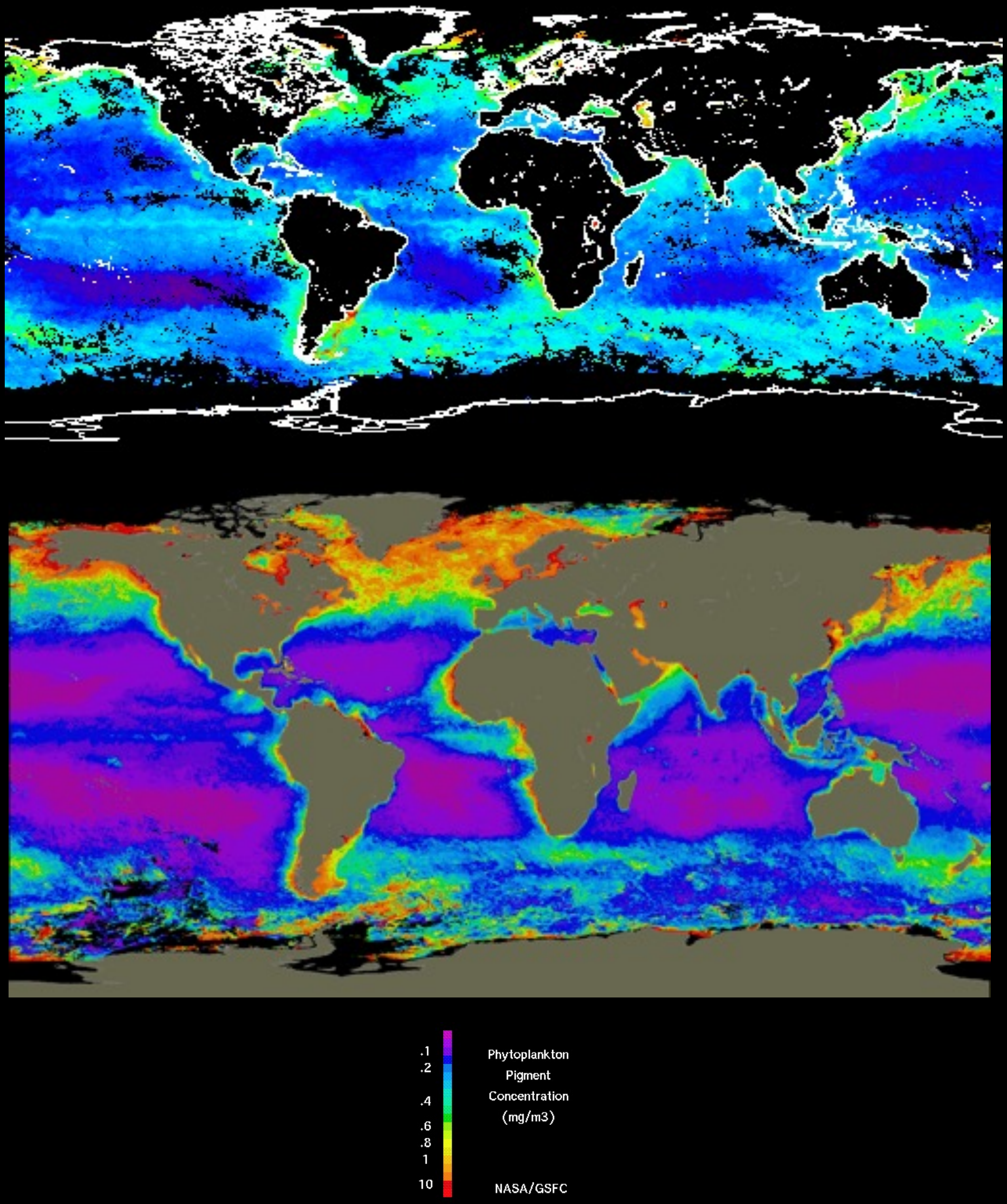
For reference, the 2009 reprocessing of the entire SeaWiFS data set required 9.5 hours!

CZCS 1978 – 1986 ($\alpha = 0$)



Problems with CZCS addressed with SeaWiFS

- No spectral bands for which $L_w = 0$. (NIR Bands)
- No way to monitor the radiometric stability of the sensor (Imaging the Moon)
- Radiometric calibration poor at best: a 1% error in L_t →10% error in L_w. (Calibration Buoy - MOBY)
- Variations in atmospheric pressure, winds, and O_3 concentration are ignored. (Data Assimilation)
- Poor temporal coverage (Continuous Operation)

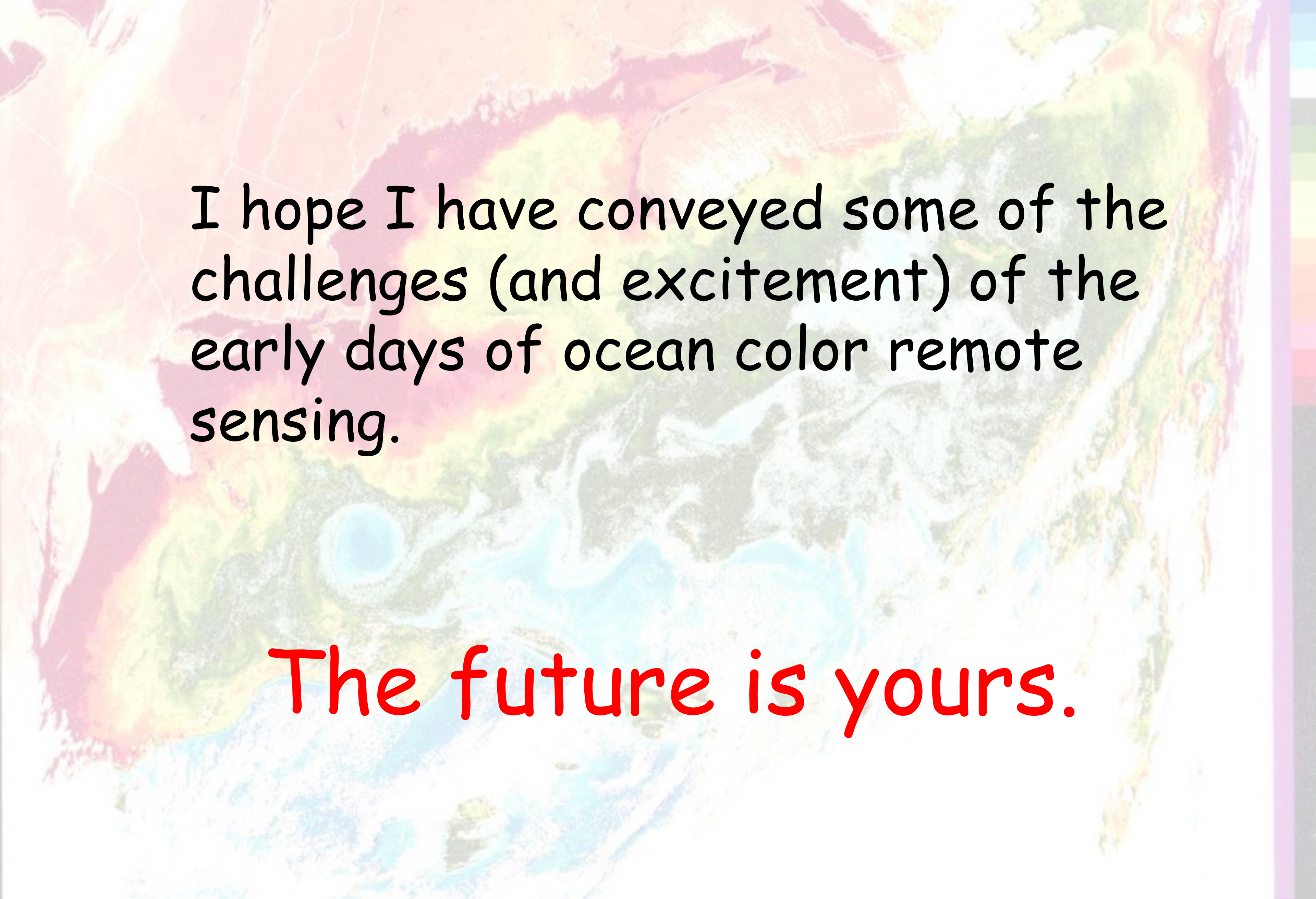


SeaWiFS

1 Week

CZCS

8 Years



I hope I have conveyed some of the challenges (and excitement) of the early days of ocean color remote sensing.

The future is yours.

Acknowledgements

Dennis Clark, NOAA/NESDIS

W. Hovis, F. Anderson, R.W. Austin, E.T. Baker,
D. Clark, S.Z. El-Sayed, B. Sturm, R.C. Wrigley,
C.S. Yentsch. The CZCS Experiment Team

K. Voss, O. Brown, and R. Evans, U. Miami

Ken Carder, Wayne Esaias, Curt Davis, Jim Yoder, Frank Muller-Karger, Marlon Lewis, Gregg Mitchell, Robert Frouin, Janet Campbell, John Marra, and Chuck Trees and Paula Bontempi. NASA/HQ

C. McClain, G. Feldman, W. Esaias NASA/GSFC

All of my many graduate students and postdocs

NASA for 35 years of funding

La Commedia è Finita