united nations educational, scientific and cultural organization
international atomic energy agency
the **abdus salam** international centre for theoretical physics

COURSE ON CLIMATE VARIABILITY STUDIES IN THE OCEAN
"Tracing & Modelling the Ocean Variability"
16 - 27 June 2003

301/1507-9

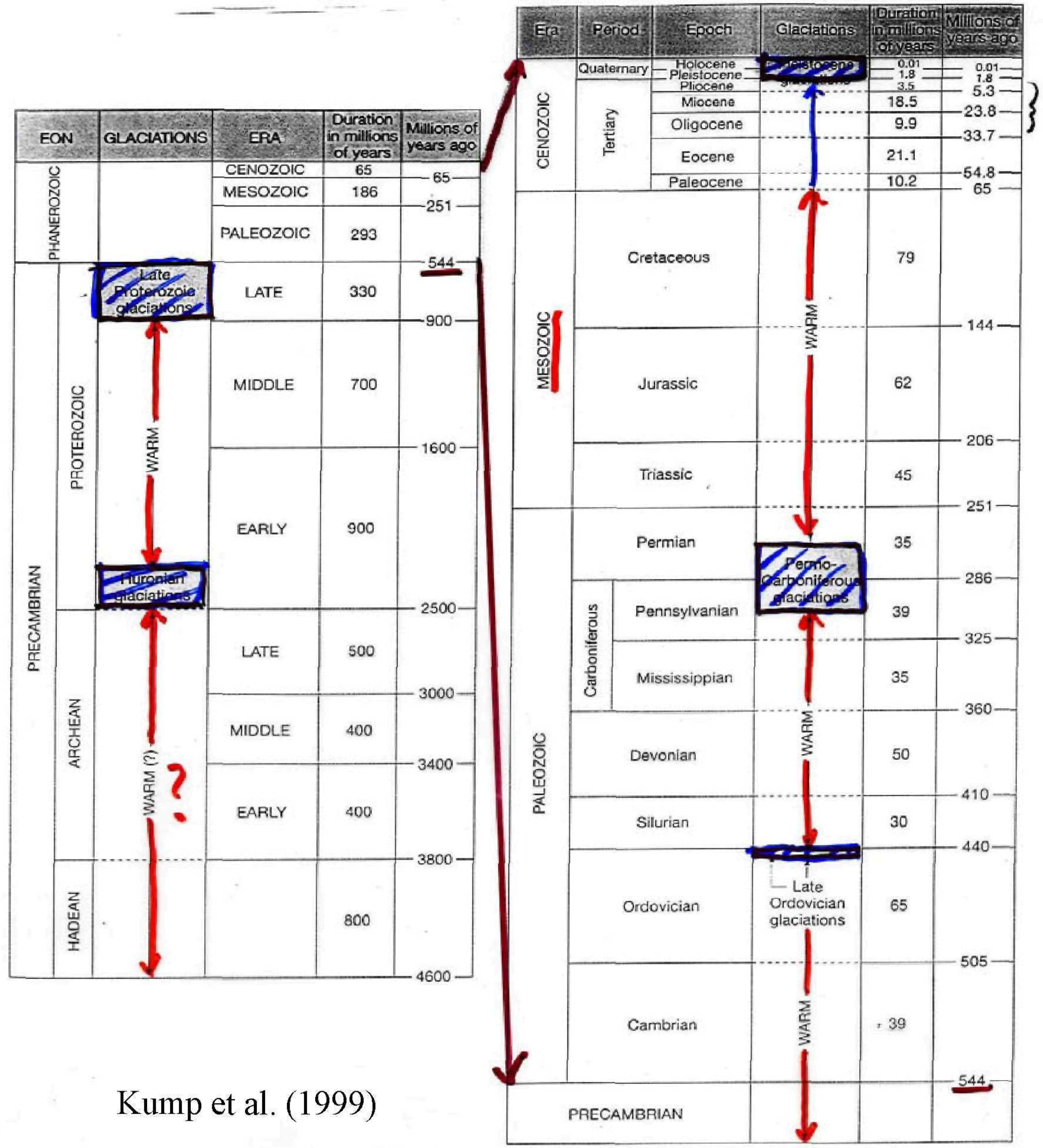
Ocean Surface Temperatures During the Last 150,000 Years-I

Julian Sachs
MIT
Cambridge, MA
USA

Ocean Surface Temperatures During the Last 150,000 Years-I

Julian Sachs
Dept. of Earth, Atmospheric & Planetary Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts, USA

"Mostly Sunny with a 10% Chance of Snow"



EON		GLACIATIONS	ERA	Duration in millions of years	Millions of years ago
PHANEROZOIC			CENOZOIC	65	65
			MESOZOIC	186	251
			PALEOZOIC	293	544
PRECAMBRIAN	PROTEROZOIC	Late Proterozoic glaciations	LATE	330	900
		WARM	MIDDLE	700	1600
		Huronian glaciations	EARLY	900	2500
	ARCHEAN	WARM (?)	LATE	500	3000
			MIDDLE	400	3400
			EARLY	400	3800
	HADEAN			800	4600

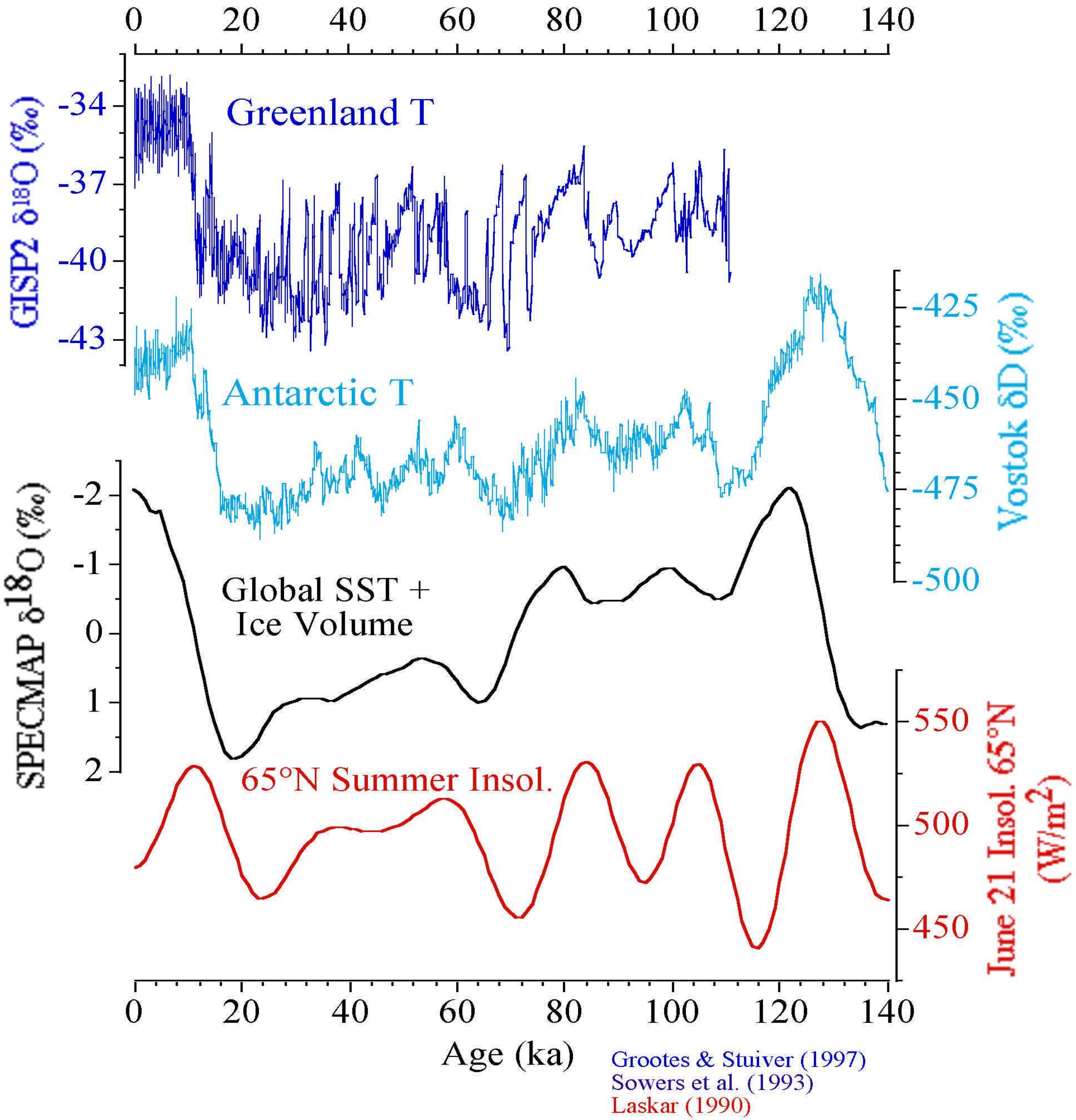
Era	Period		Epoch	Glaciations	Duration in millions of years	Millions of years ago
CENOZOIC	Quaternary		Holocene	Pleistocene glaciations	0.01	0.01
			Pleistocene		1.8	1.8
	Tertiary		Pliocene		3.5	5.3
			Miocene		18.5	23.8
			Oligocene		9.9	33.7
			Eocene		21.1	54.8
			Paleocene		10.2	65
MESOZOIC	Cretaceous			WARM	79	144
	Jurassic				62	206
	Triassic				45	251
PALEOZOIC	Permian			Permo-Carboniferous glaciations	35	286
	Carboniferous	Pennsylvanian			39	325
		Mississippian		WARM	35	360
	Devonian				50	410
	Silurian				30	440
	Ordovician			Late Ordovician glaciations	65	505
	Cambrian			WARM	39	544
PRECAMBRIAN						

Kump et al. (1999)

4.5×10^9 Yr of Climate on Earth

Mostly Sunny with a 10% Chance of Snow

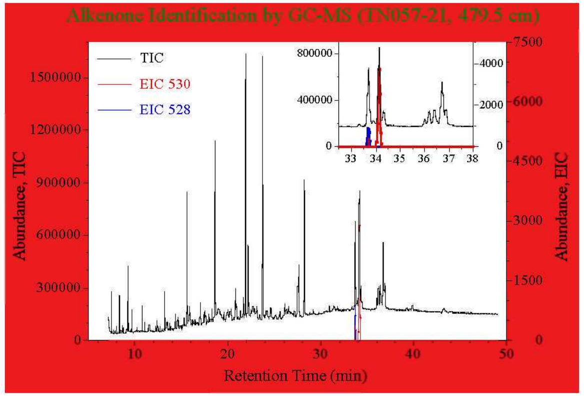
Climate of the last Glacial Cycle

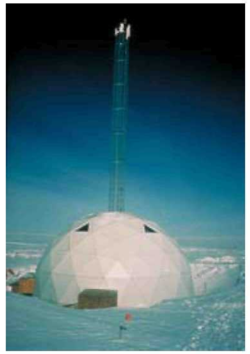


Climate of the Last 150,000 Years

A Complete Glacial Cycle

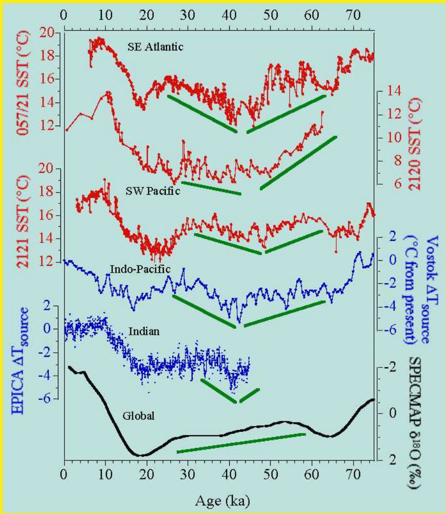
•Climate archives in ice & sediment



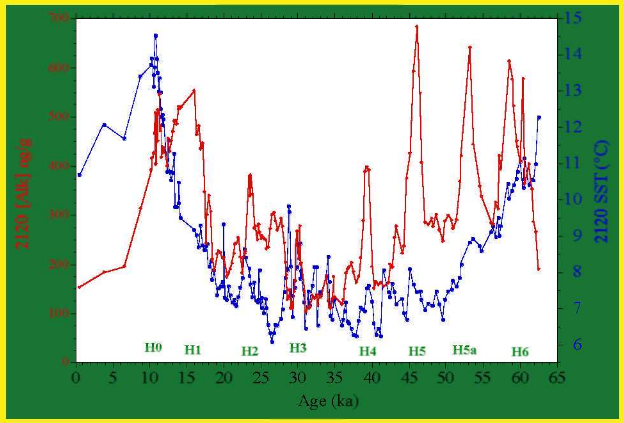


• Alkenone paleothermometry

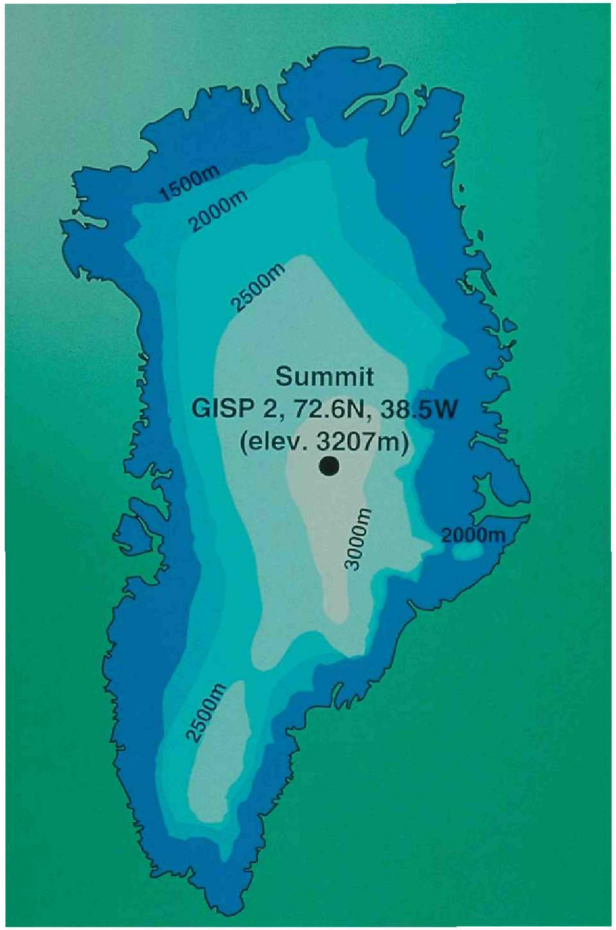
•Part I: Glacial temperatures in southern mid-latitudes



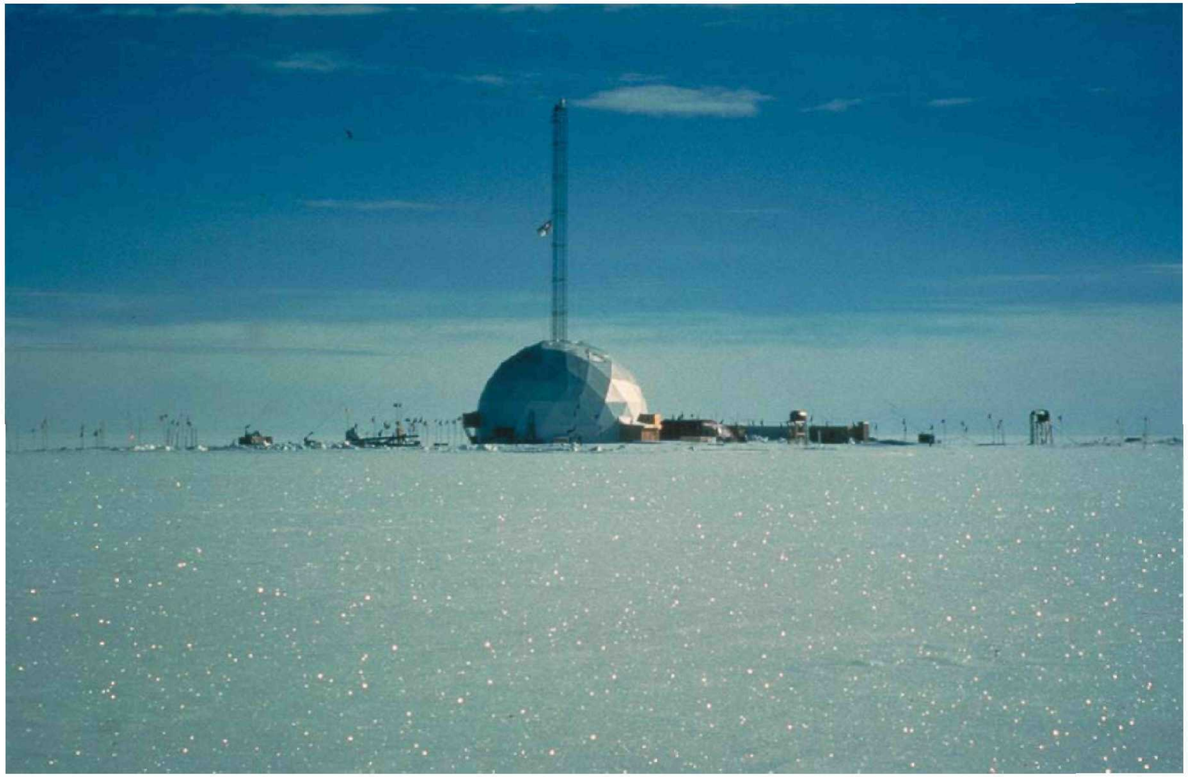
•Part II: Southern Ocean Expression of Massive Ice Discharge Events in the N. Atlantic



Climate Archives in Ice & Sediment

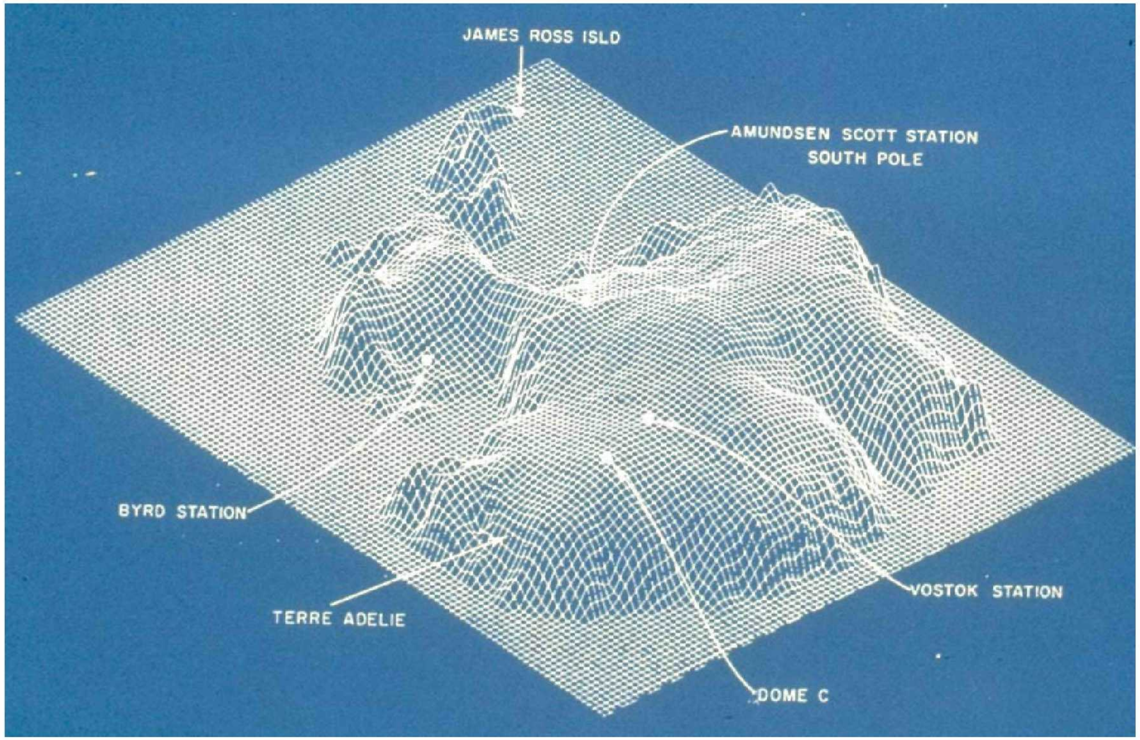


Greenland Ice Cores



Accomodations

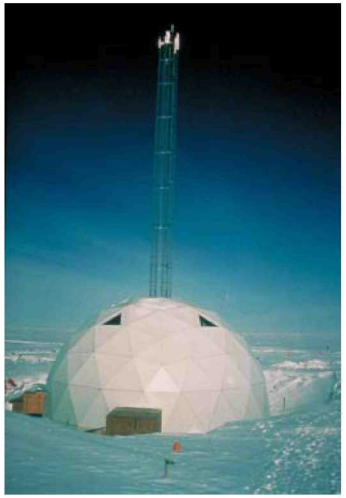
www.noaa.gov

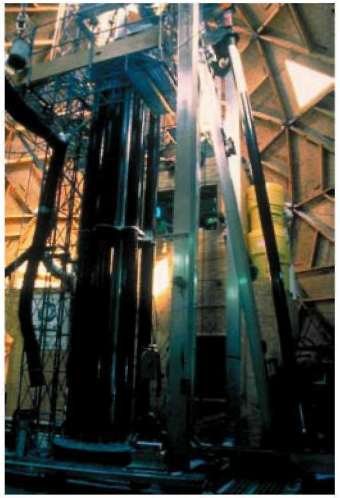


Antarctic Ice Cores

www.noaa.gov

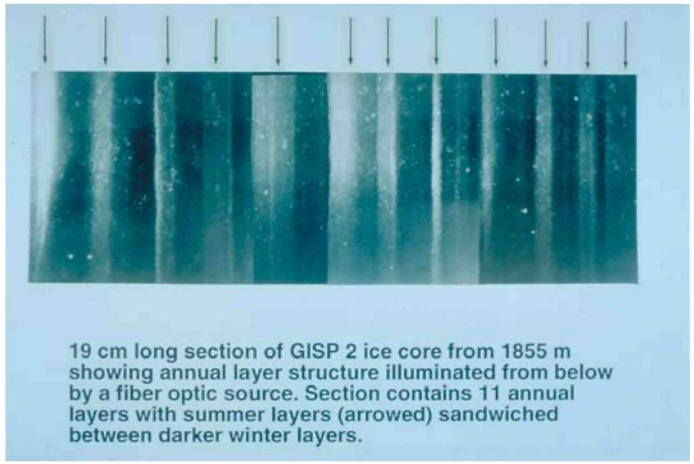
Processing Ice Cores





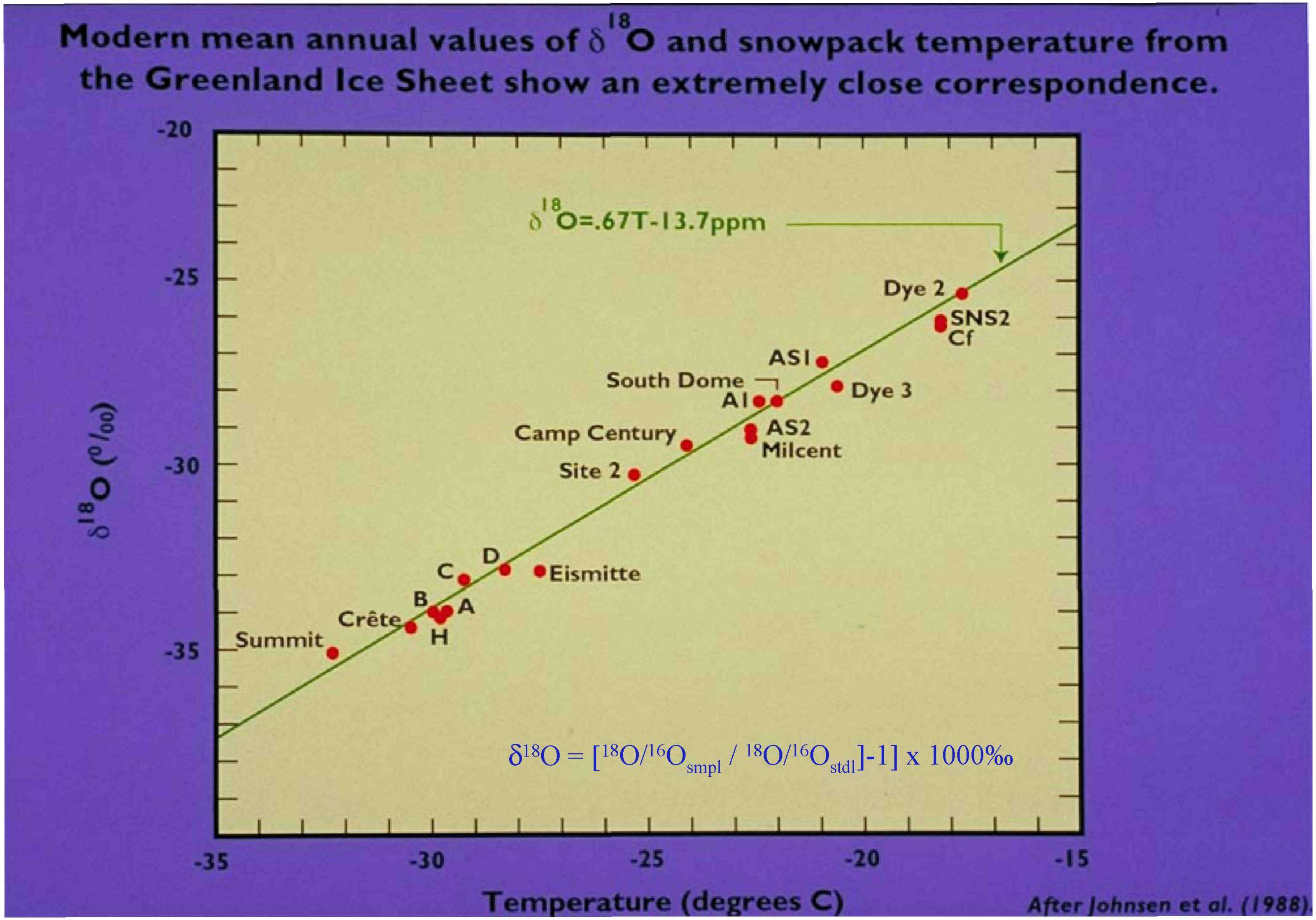
Transport

Storage
(NICL, Denver, USA)



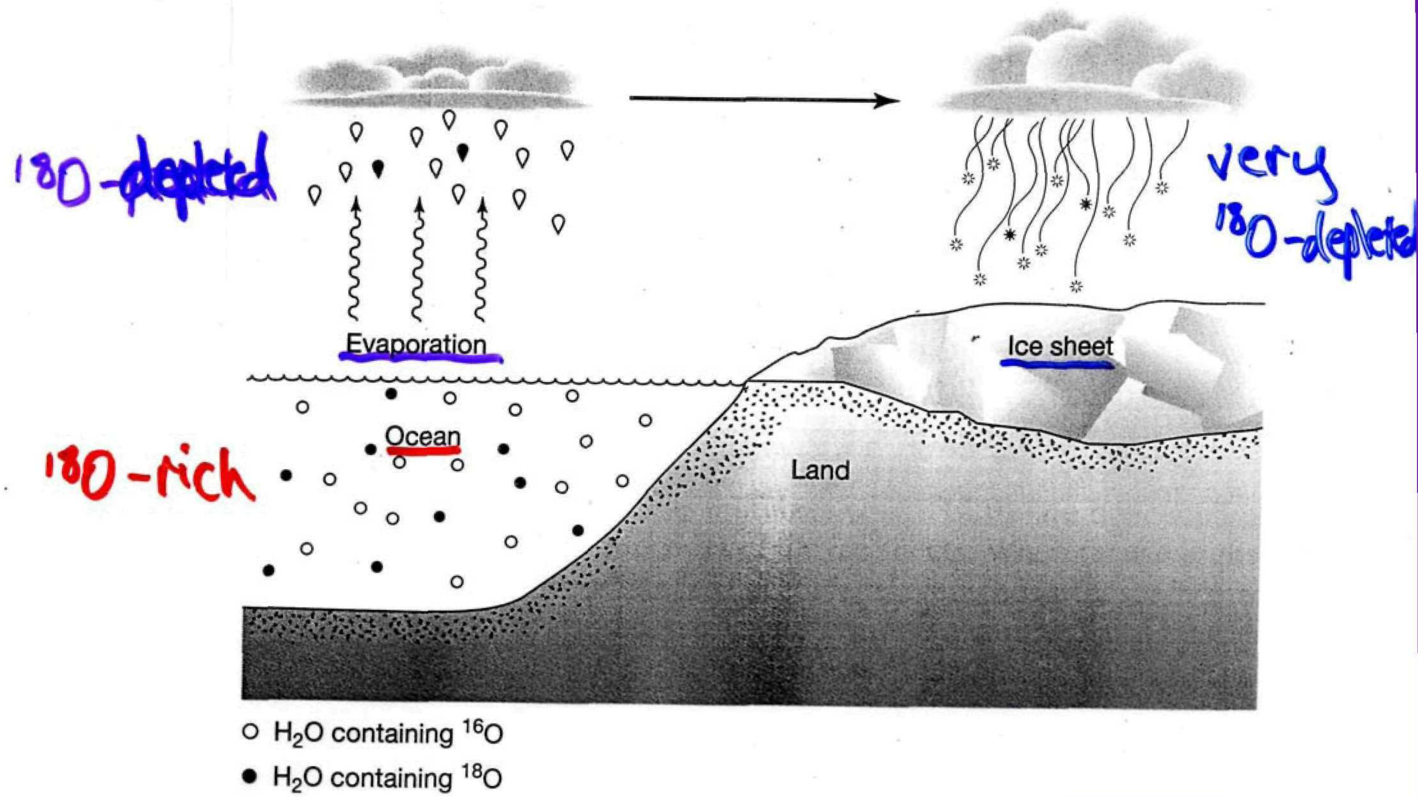
Dating

Determining Paleotemperature from Isotopes of Ice (H_2O)



$$\delta^{18}O = [^{18}O/^{16}O_{smpl} \;/\; ^{18}O/^{16}O_{stdl}] - 1] \times 1000‰$$

Influence of Continental Ice Volume on Oxygen Isotope Ratio of the Ocean



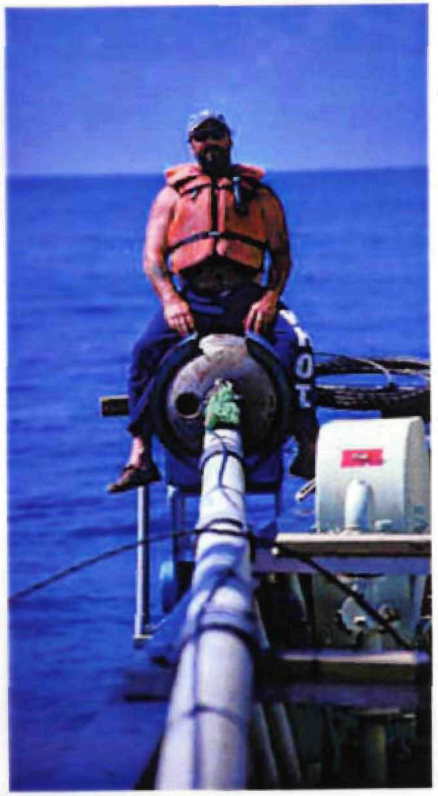
$H_2{}^{18}O$ ~ 1% Lower Vapor Pressure than $H_2{}^{16}O$

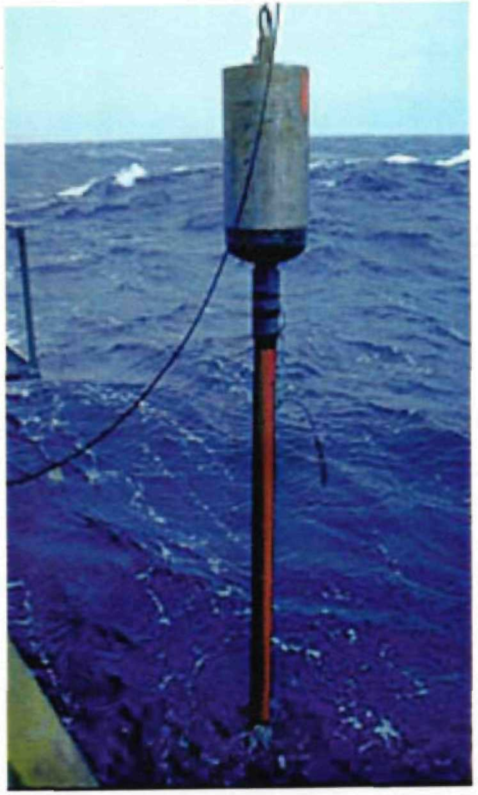
$$\delta^{18}O = [{}^{18}O/{}^{16}O_{smpl} \;/\; {}^{18}O/{}^{16}O_{stdl}]-1] \times 1000‰$$

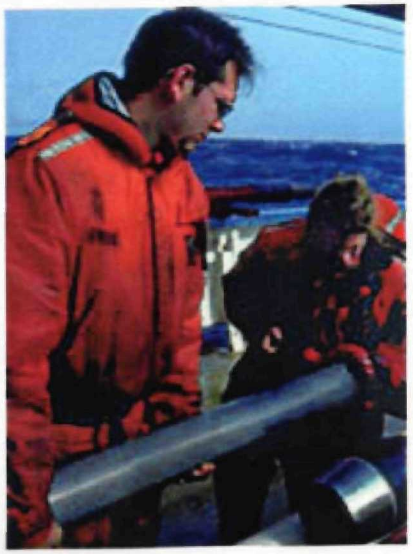
Std = Std. Mean Ocean Water

UELEN

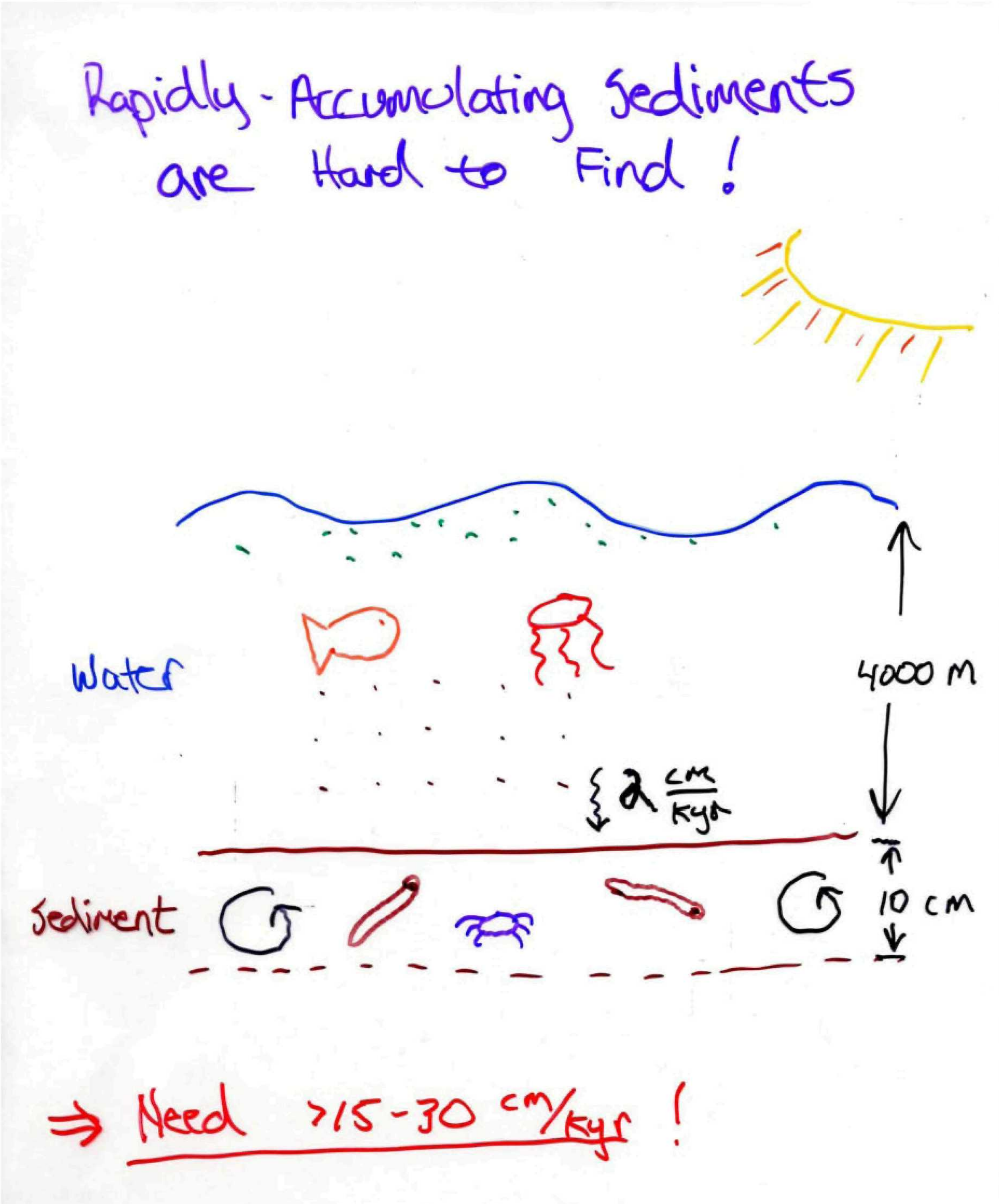
IFRTP





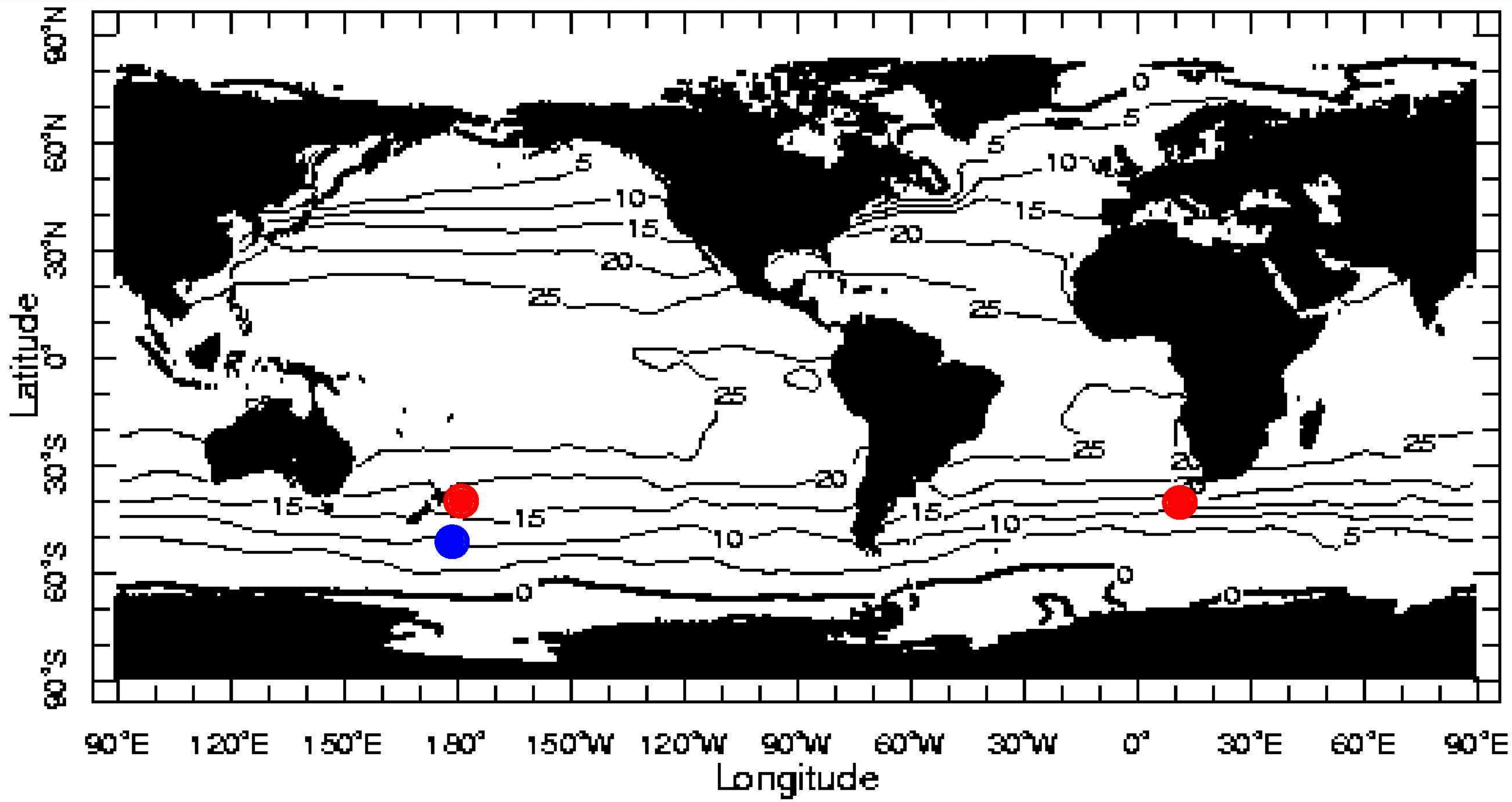


Coring the Seafloor



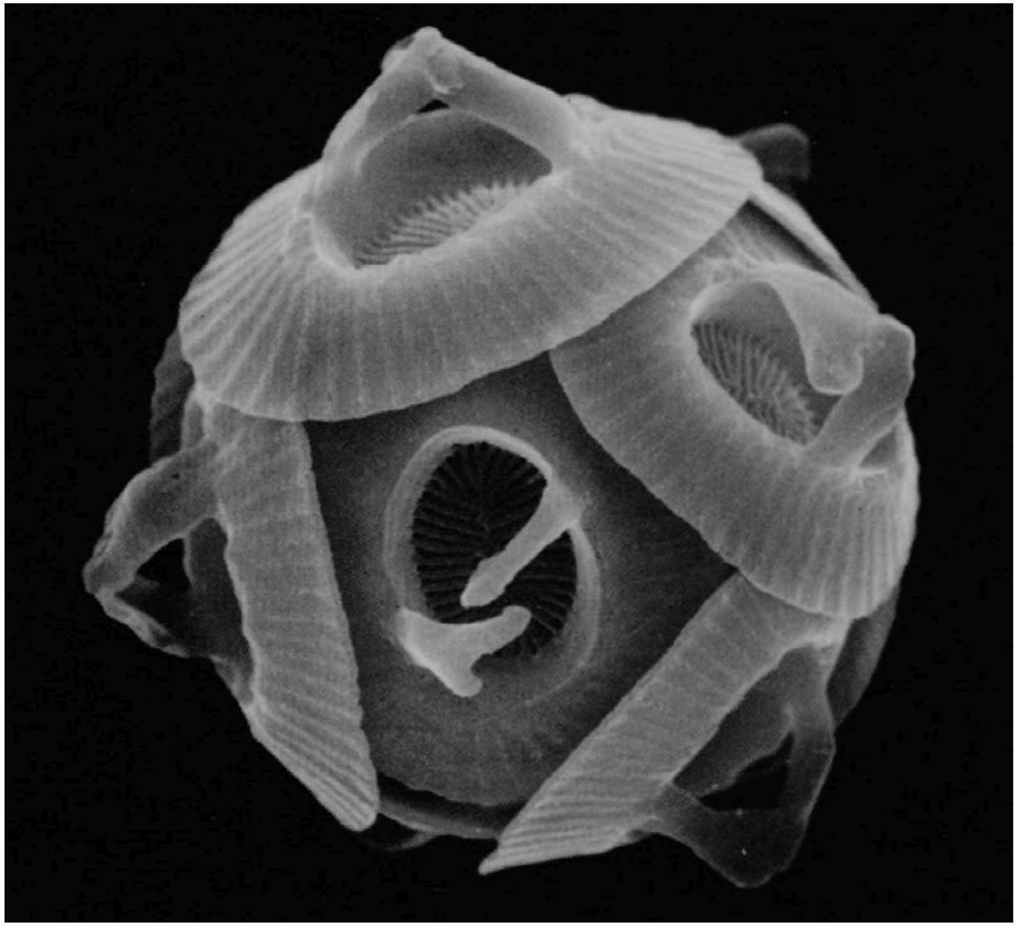
High Temporal Resolution Requires Rapidly-Accumulating Sediments…

Rapidly-Accumulating Sediments Analyzed in this Study



0.0 m Jan

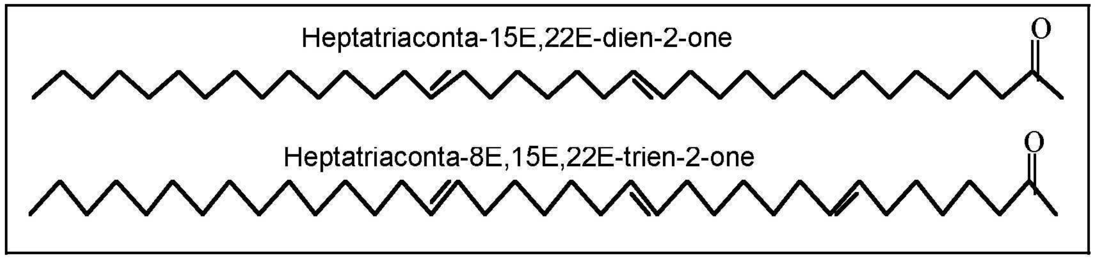
Alkenone Paleothermometry



Coccoliths

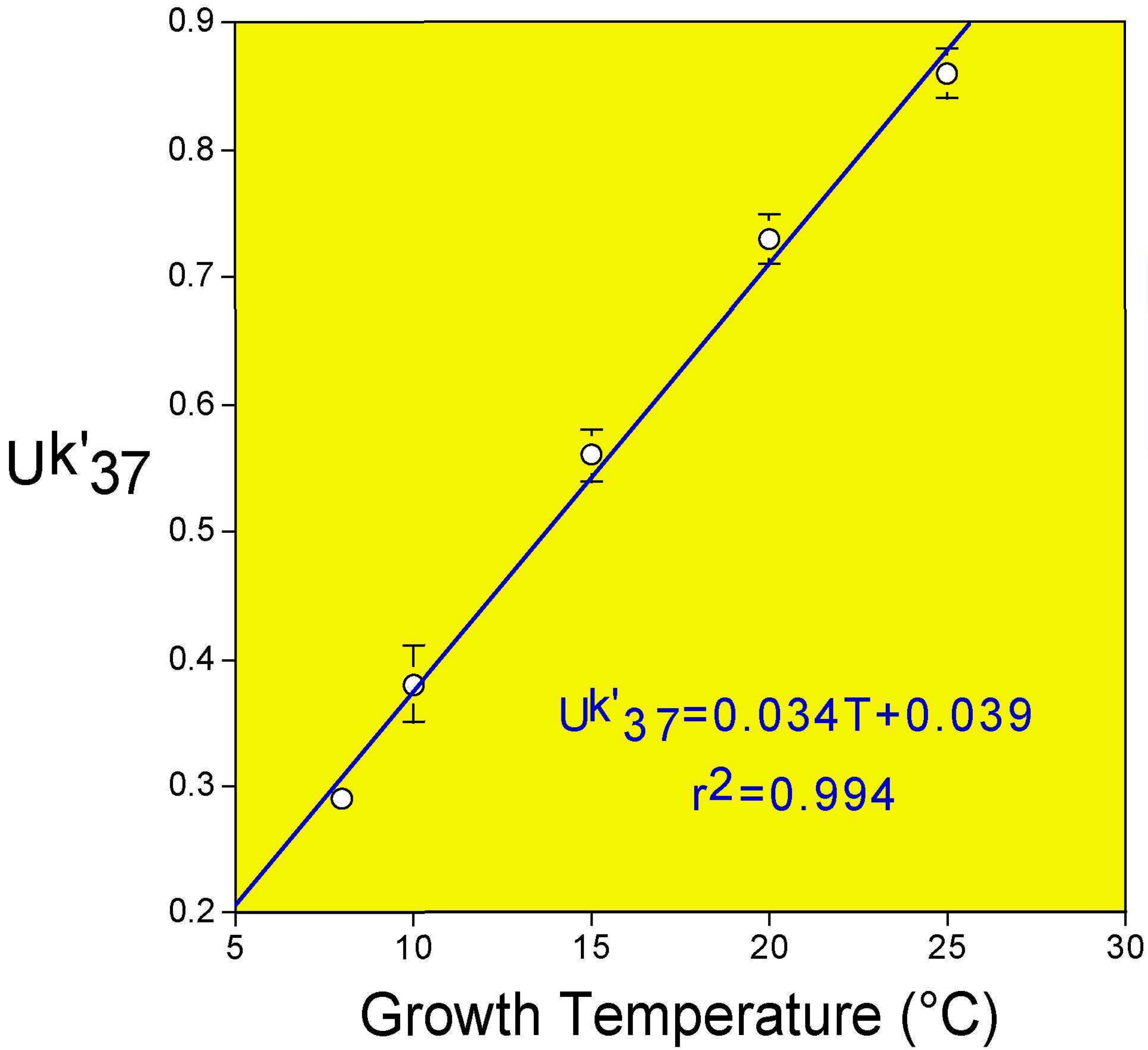
Emiliania huxleyi

Gephyrocapsa oceanica



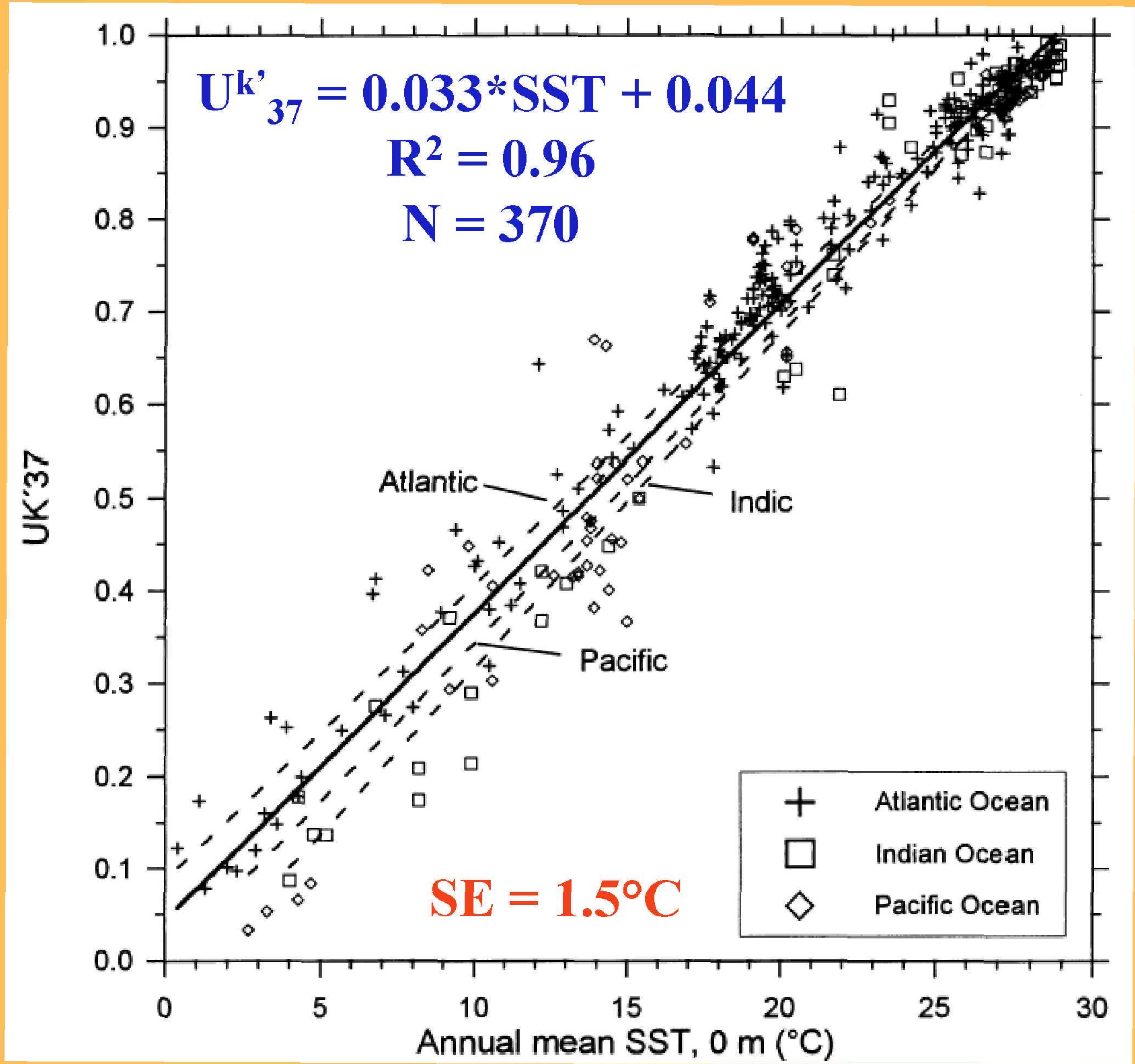
Alkenones

Alkenone Temperature Relationship



$$U^{k©}_{37} = \frac{C_{37:2}}{C_{37:2} + C_{37:3}}$$

Prahl et al. (1988)

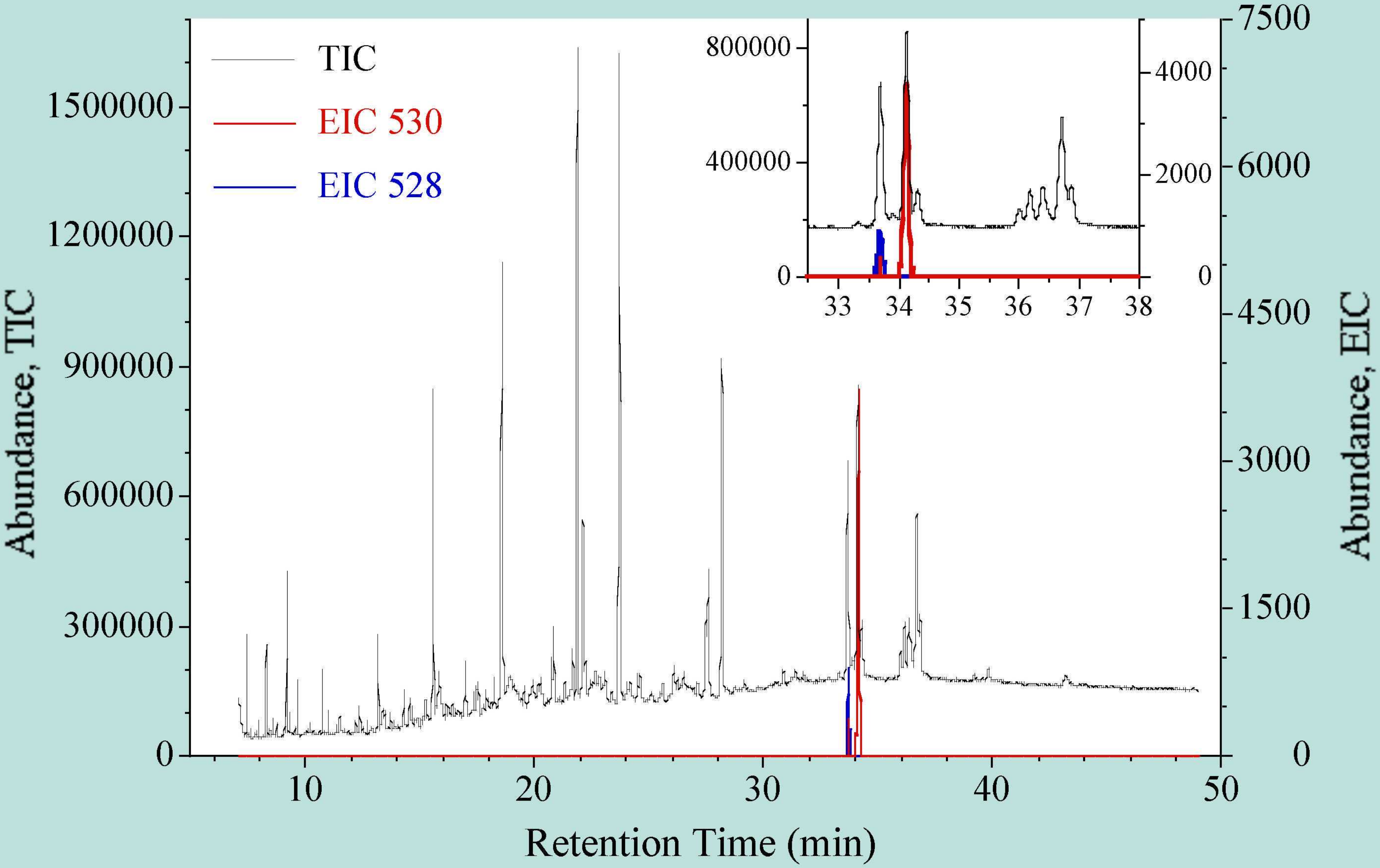


Global Core-Top Calibration of Alkenone Thermometer

60°S - 60°N

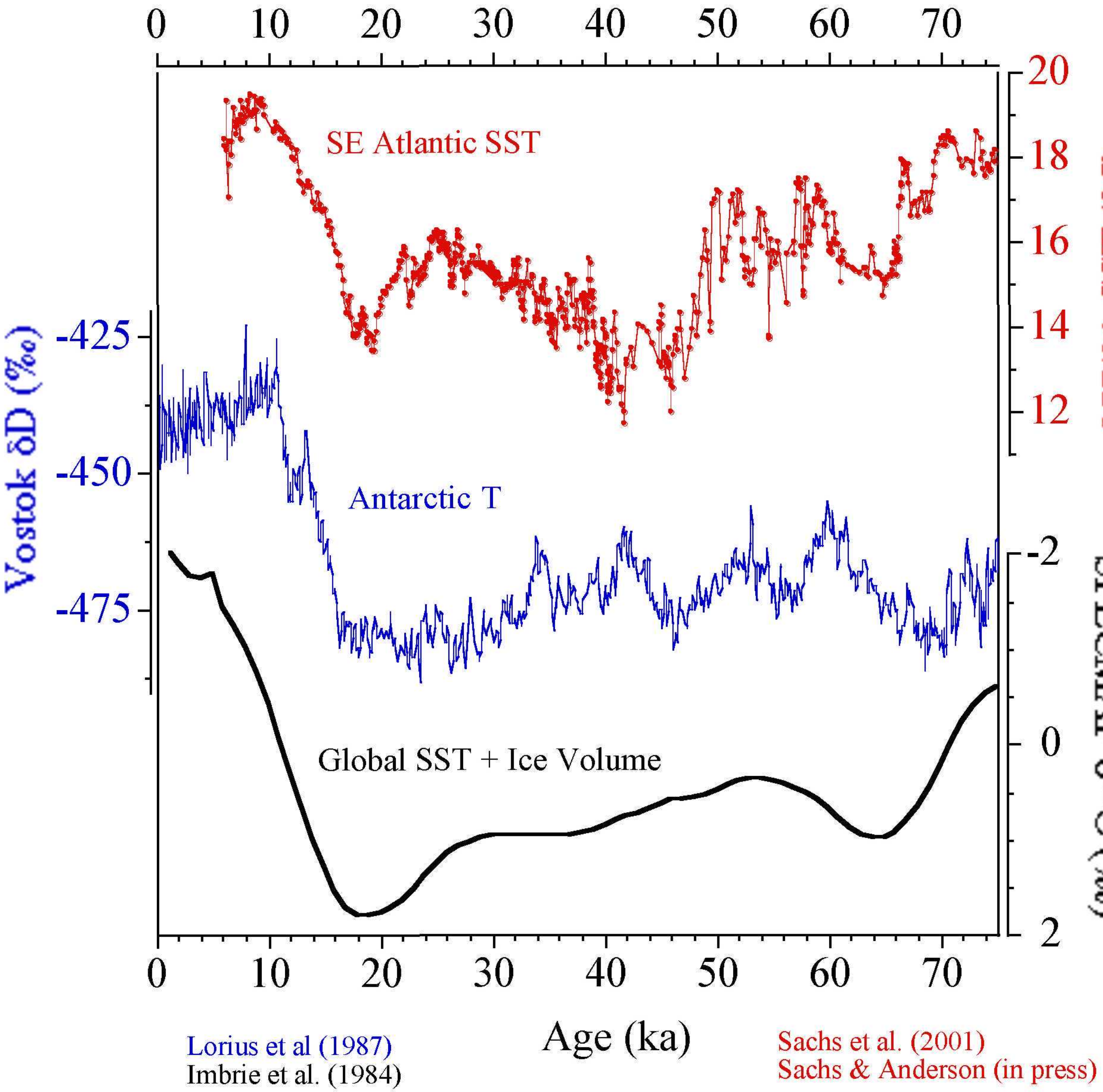
Müller et al. (1998)

Alkenone Identification by GC-MS (TN057-21, 479.5 cm)



Part I: The (unexpected) temperature history of southern mid-latitudes during the last glacial period

Unexpected SST History in Glacial SE Atlantic



Unexpected SST History of Glacial SE Atlantic

Criticisms

(1) Sediment transport compromises fidelity of SST signal.

SST record in nearby non-drift core

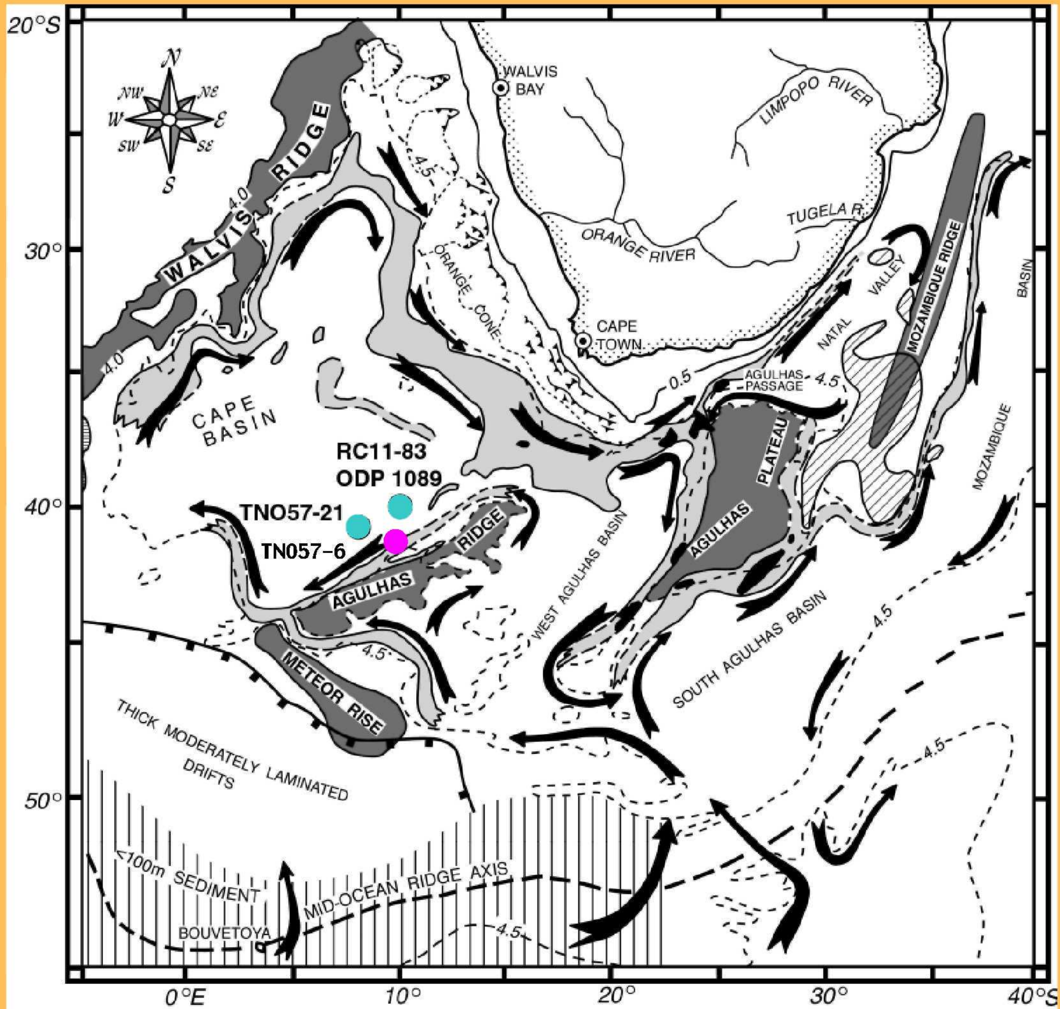
(2) Cannot extrapolate beyond local scale.

SST records in SW Pacific
Antarctic deuterium excess

Fidelity of the SST Proxy

Do down-core changes in SST reflect sediment transport or surface temperature?

Cape Basin Sediment Cores

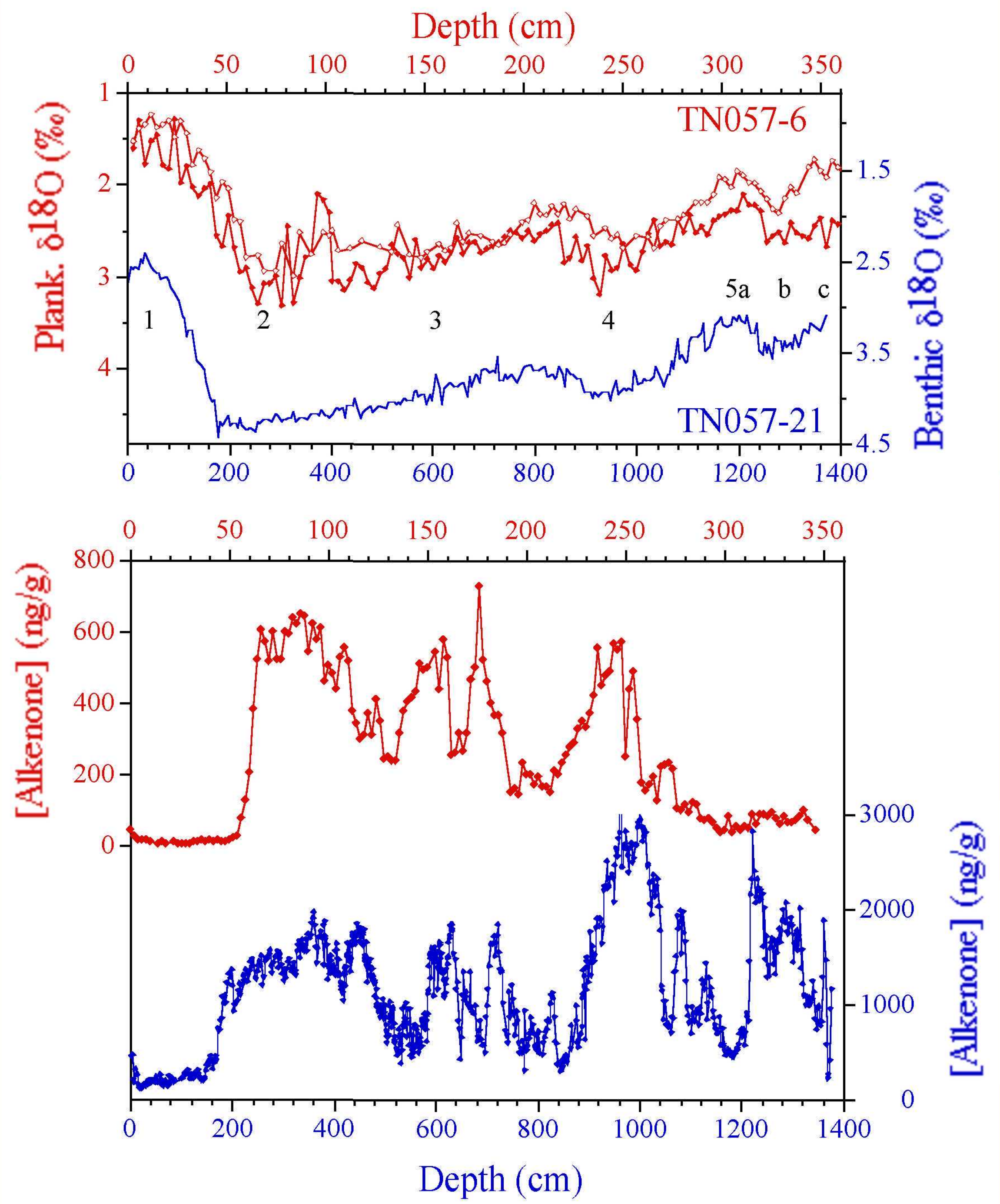


Core	Latitude	Longitude	Water Depth (m)	Sed. Rate (cm/kyr)
ODP 1089	40°56.18'S	9°53.64'E	4621	16.2
TN057-21-PC2	41°08' S	7°49' E	4981	12.5
TN057-6-PC4	42°54.8'S	8°54'E	3751	3.4

Tucholke & Embley (1984)

- Cores from Sediment Drifts

- Non-drift core

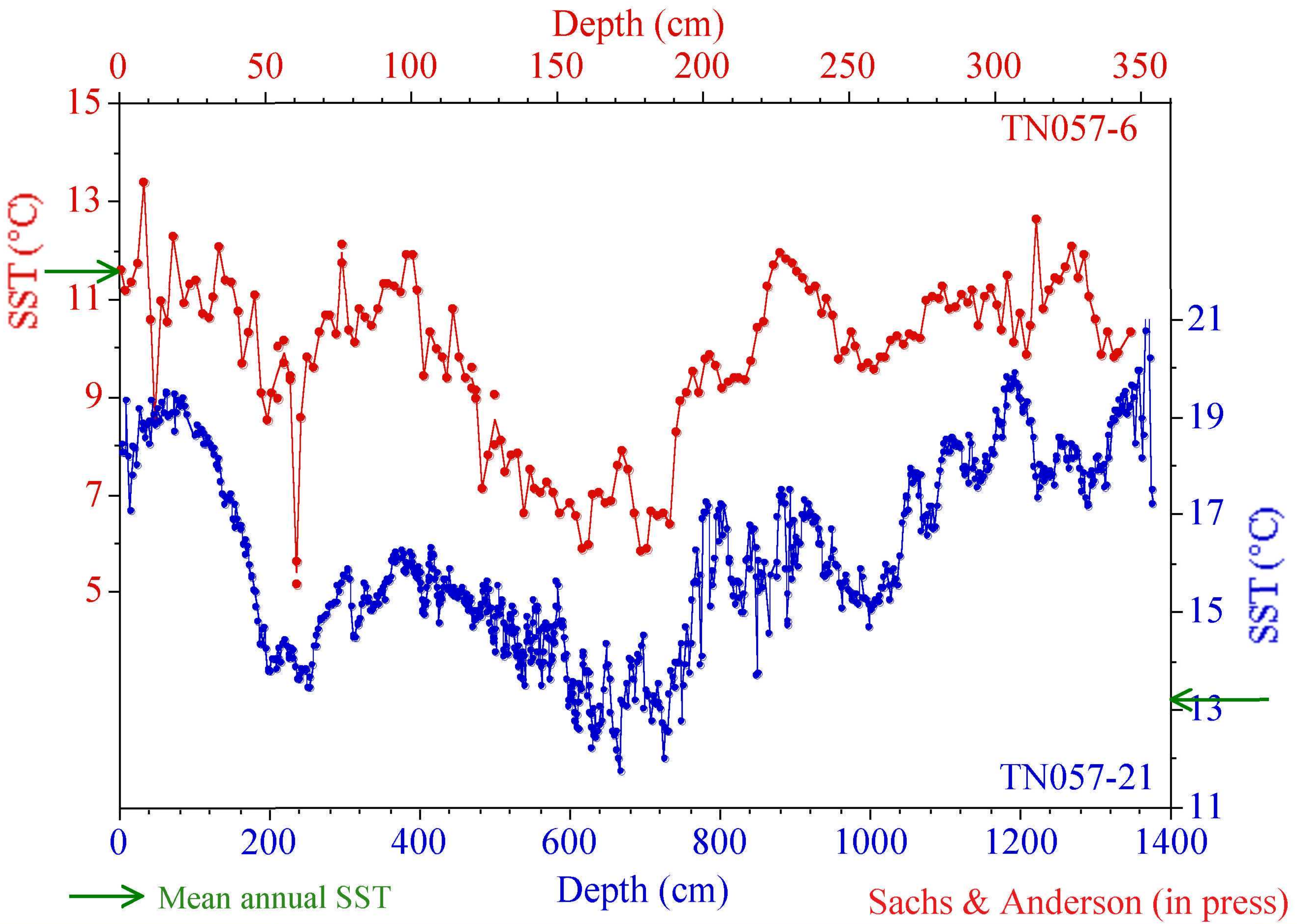


Synchronize Drift (TN057-21) & Non-Drift (TN057-6) Cores

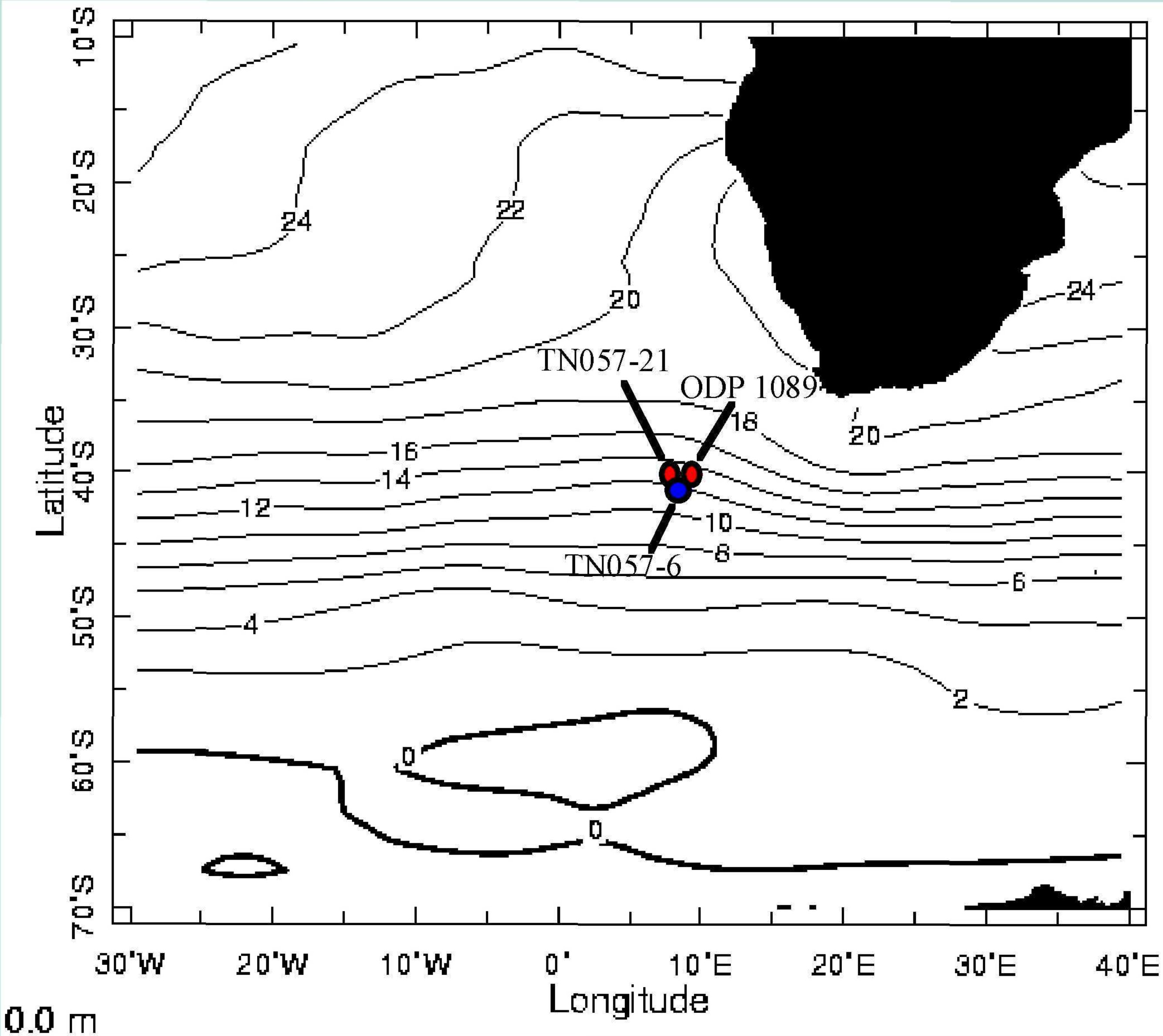
Sachs & Anderson (in press)

$\delta^{18}O$ data:
Hodell et al. (2000) &
Ninnemann et al. (1999)

SSTs at a Drift & Non-Drift Site

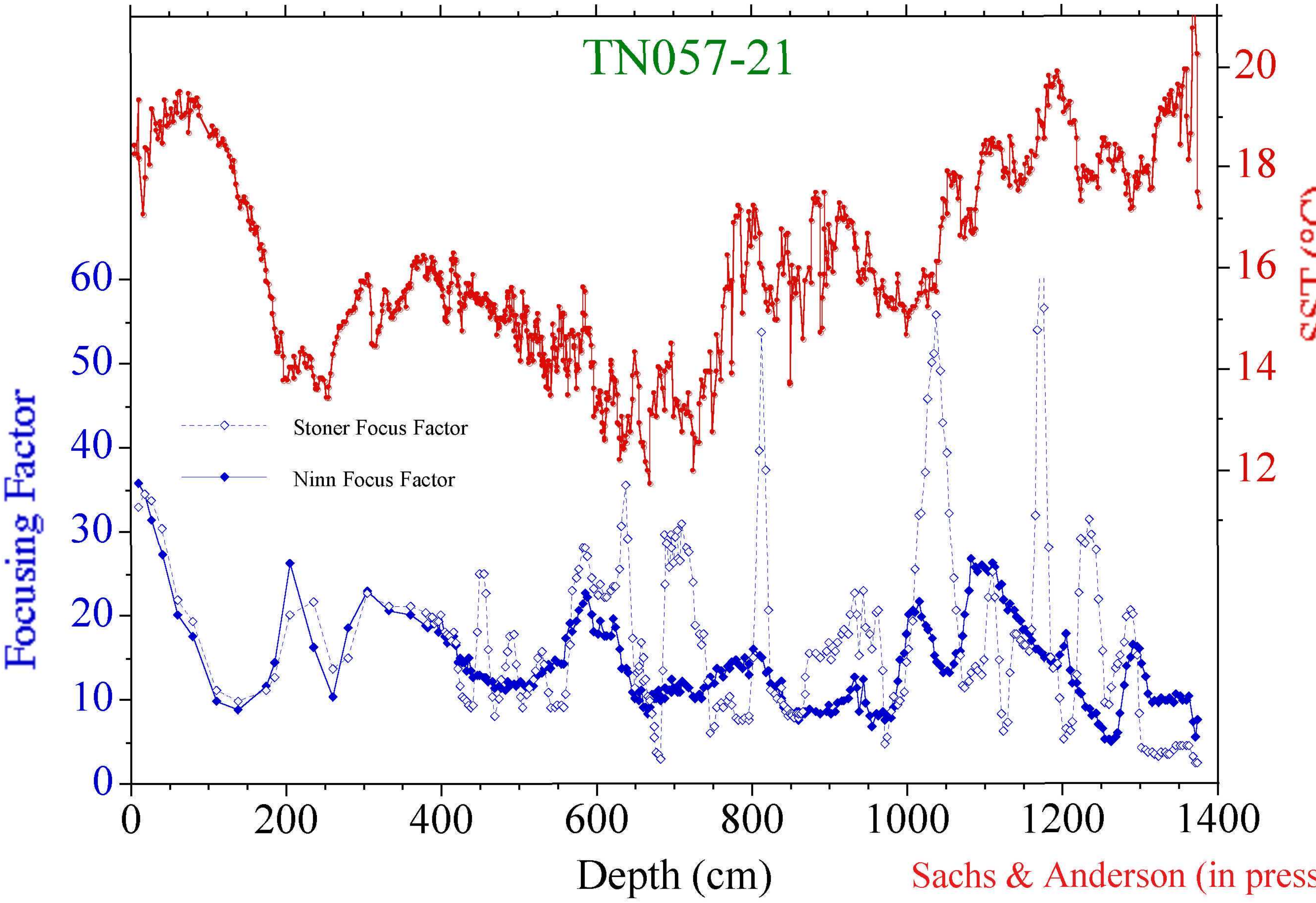


Climatological SST & Position of Cores



Levitus (1994)

Sediment Focusing and SST



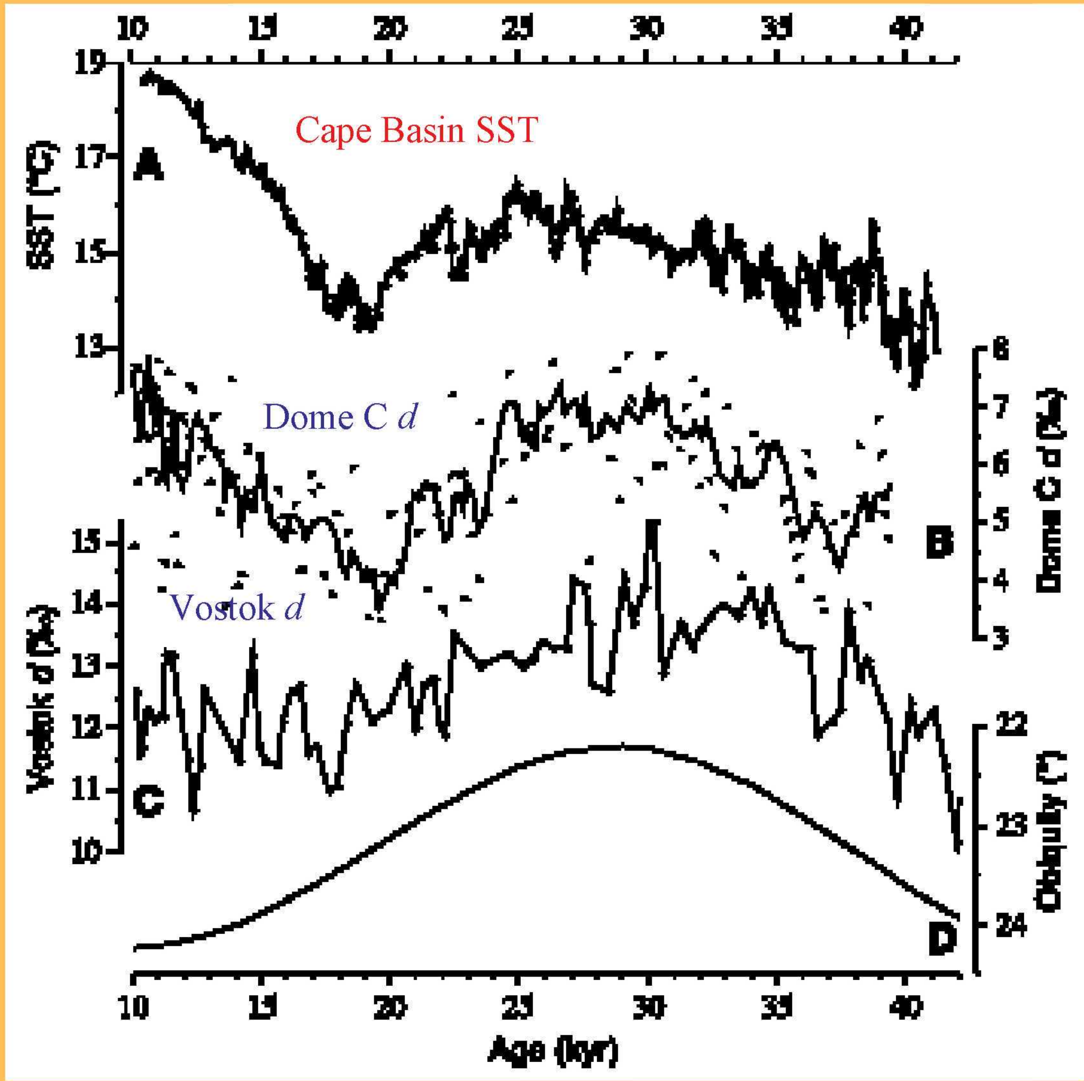
Sachs & Anderson (in press)

Circum-hemispheric vs Regional Climate

Over what spatial scale is the Cape Basin SST record representative?

Glacial Surface Temperatures of the Southeast Atlantic Ocean

Julian P. Sachs,[1*] Robert F. Anderson,[2] Scott J. Lehman[3]



SCIENCE VOL 293 14 SEPTEMBER 2001

•Justification for extrapolation to hemisphere-scale: precipitation source T records in AA ice

$d = \delta D - 8 * \delta^{18}O$

1‰ ~ 1°C (ΔT_{source})

(Vimeux et al. 1999; Jouzel et al. 1982)

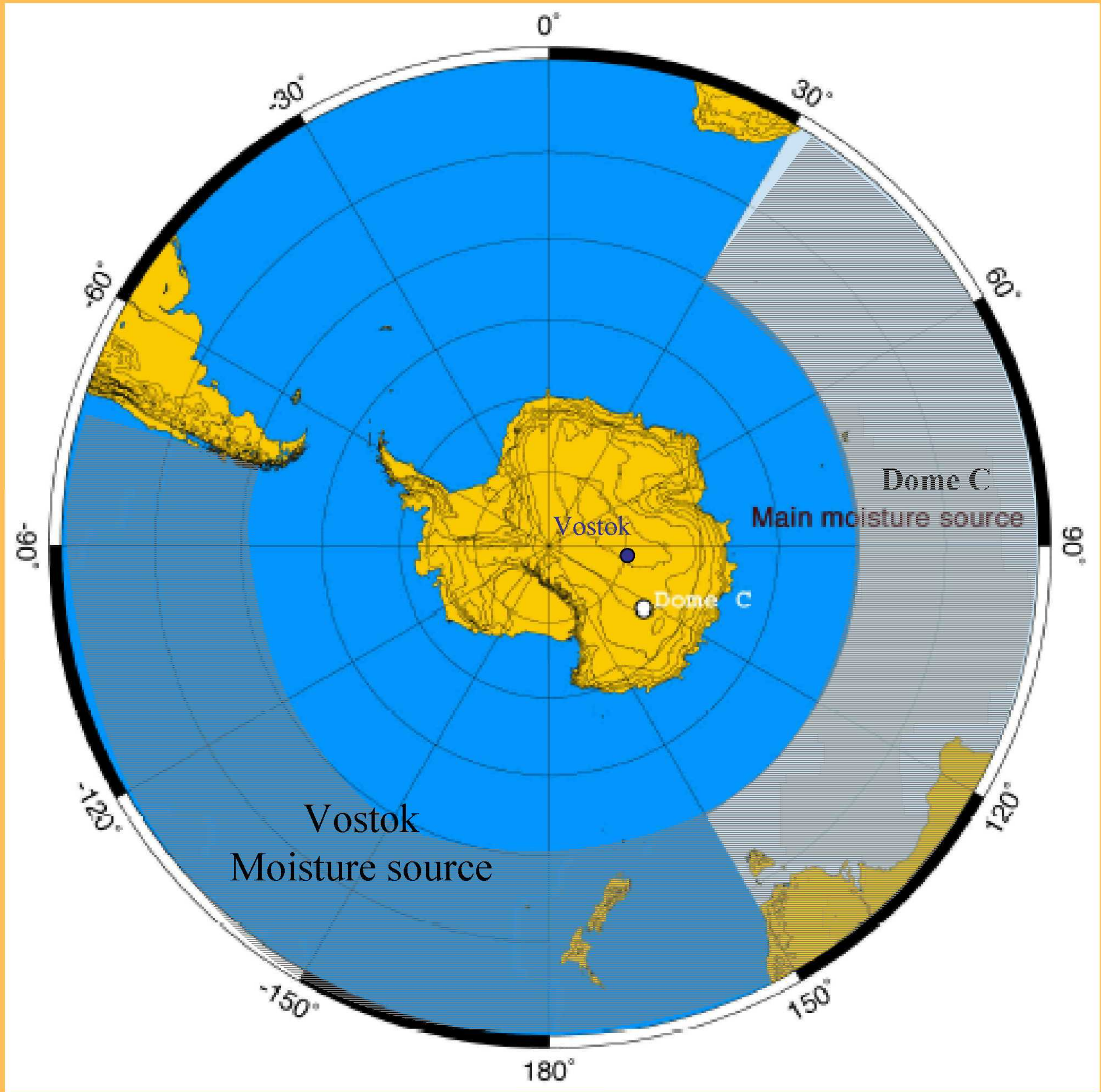
•Vostok precip: mid-latitude Indian & Pacifc

(Koster et al. 1992; Delaygue et al. 2000)

•Dome C precip: mid-latitude Indian

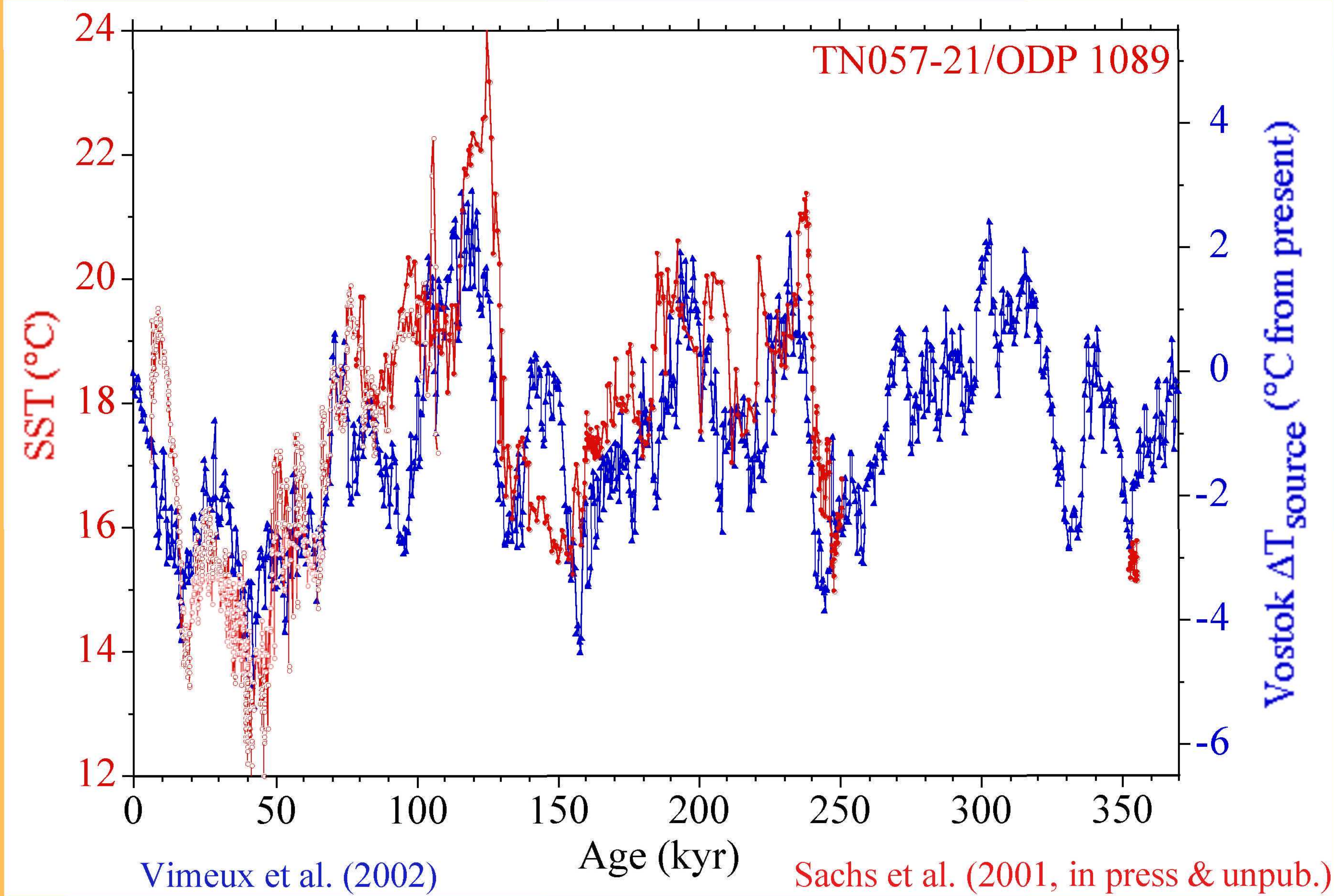
(Stenni et al. 2001)

Moisture Sources for Central East Antarctic Ice Cores



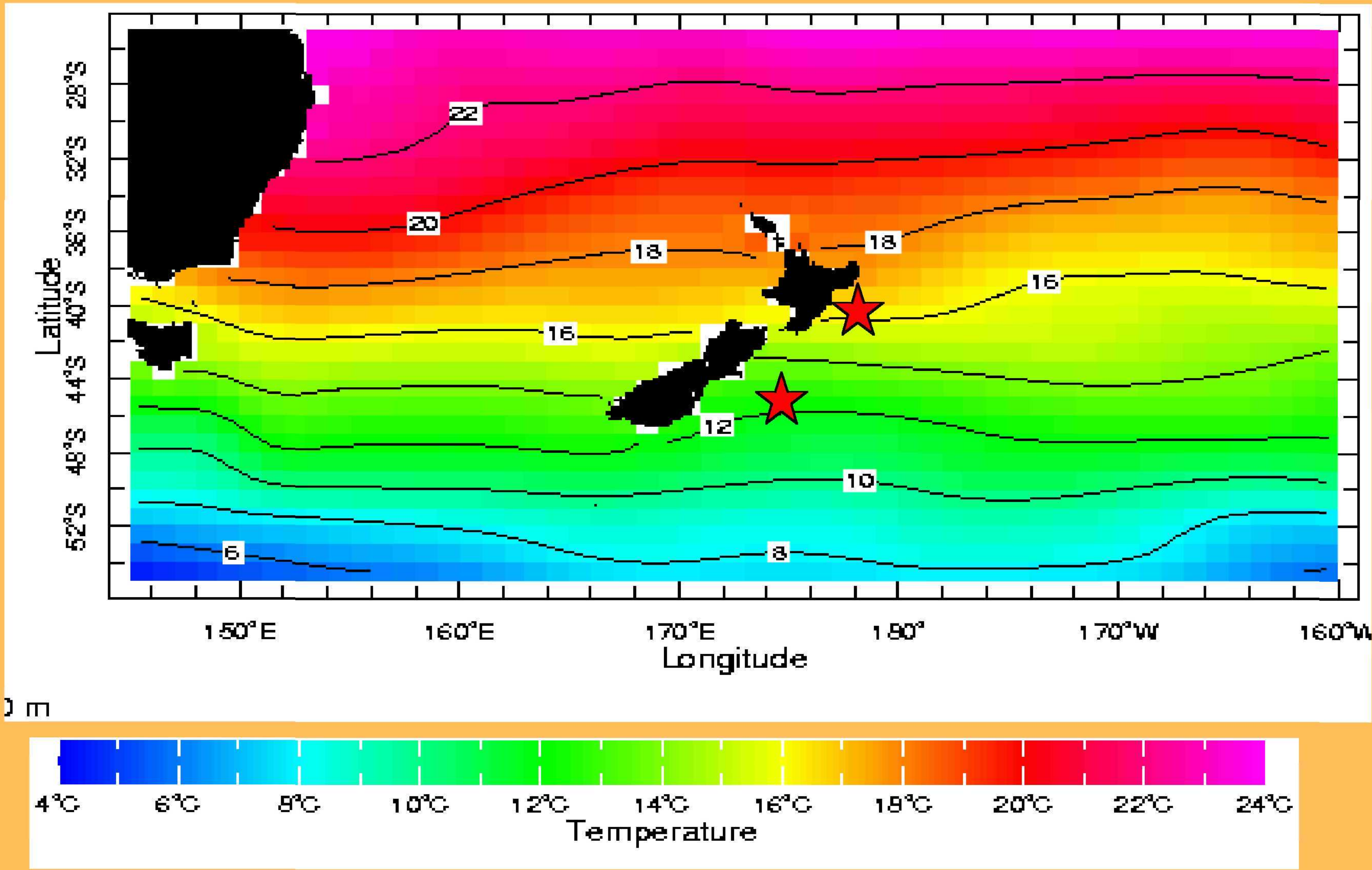
Adapted from Stenni et al. (2001); Koster et al. (1992); Delaygue et al.(2000)

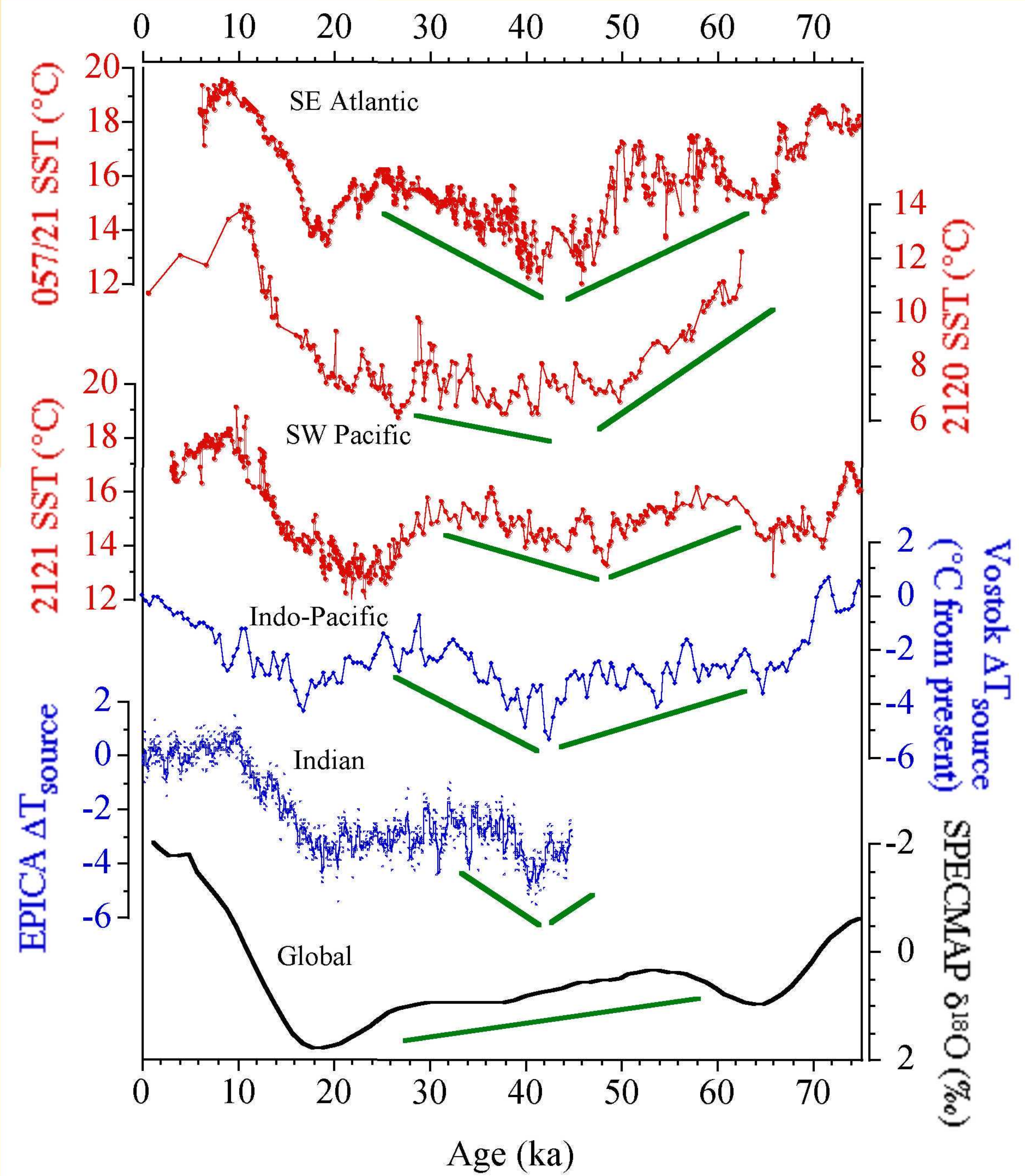
Cape Basin SST & Vostok ΔT_{source}



Southwest Pacific Cores

MD97-2121 40°S, 178°E, 2314 m
MD97-2120 46°S, 175°E, 1210 m

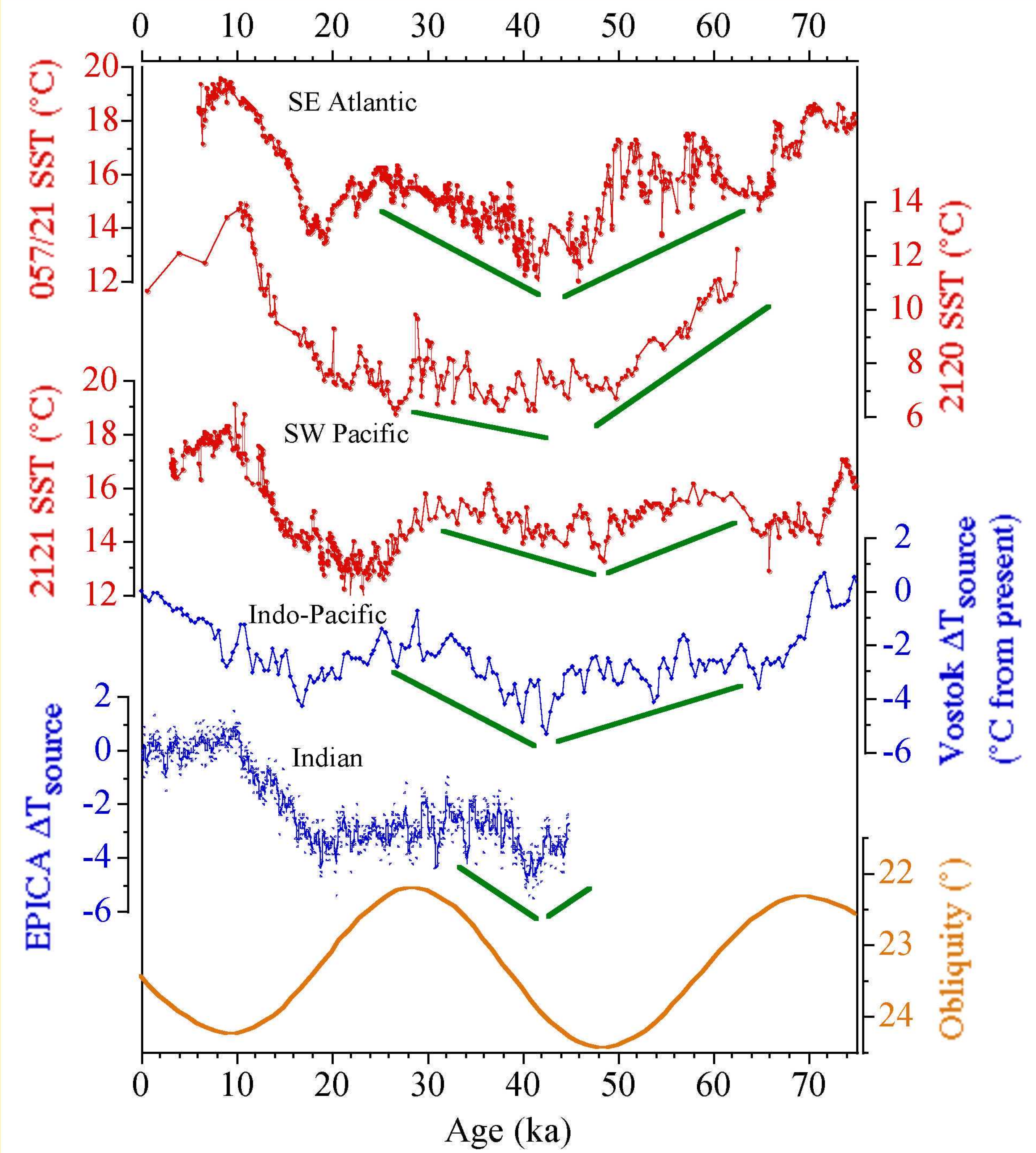




Glacial Climate of Southern Mid-latitudes

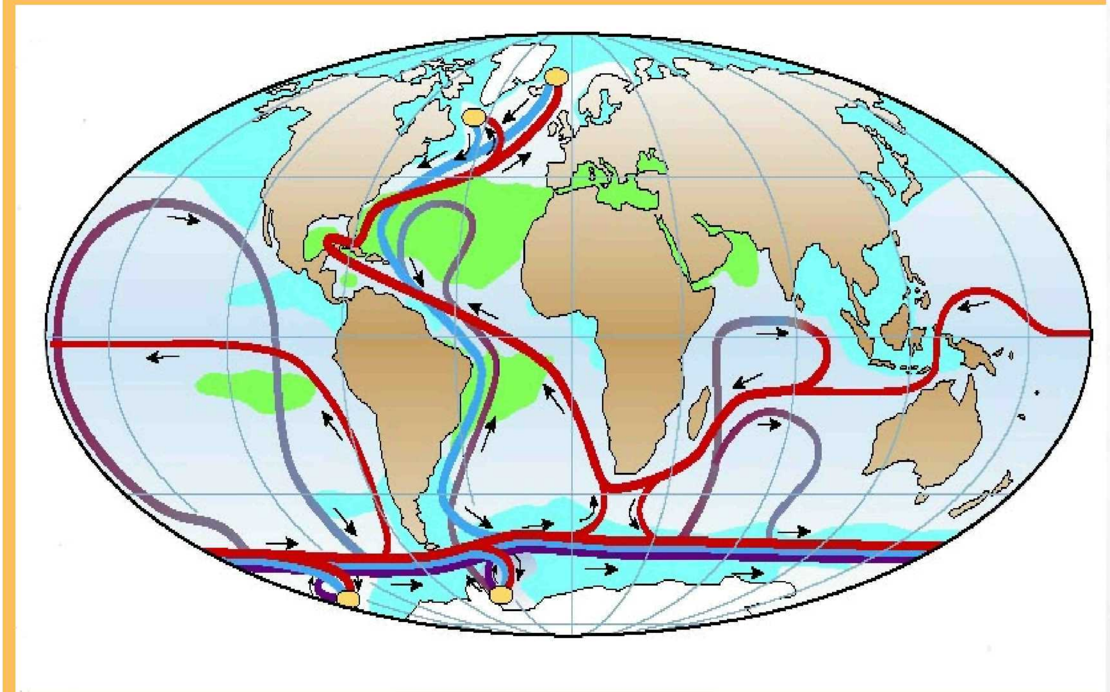
Sachs et al. (2001, in press & unpub.)
Vimeux et al. (2002)
Stenni et al. (subm.)
Imbrie et al. (1984)

Climate Forcing by Changes in Earth's Tilt?

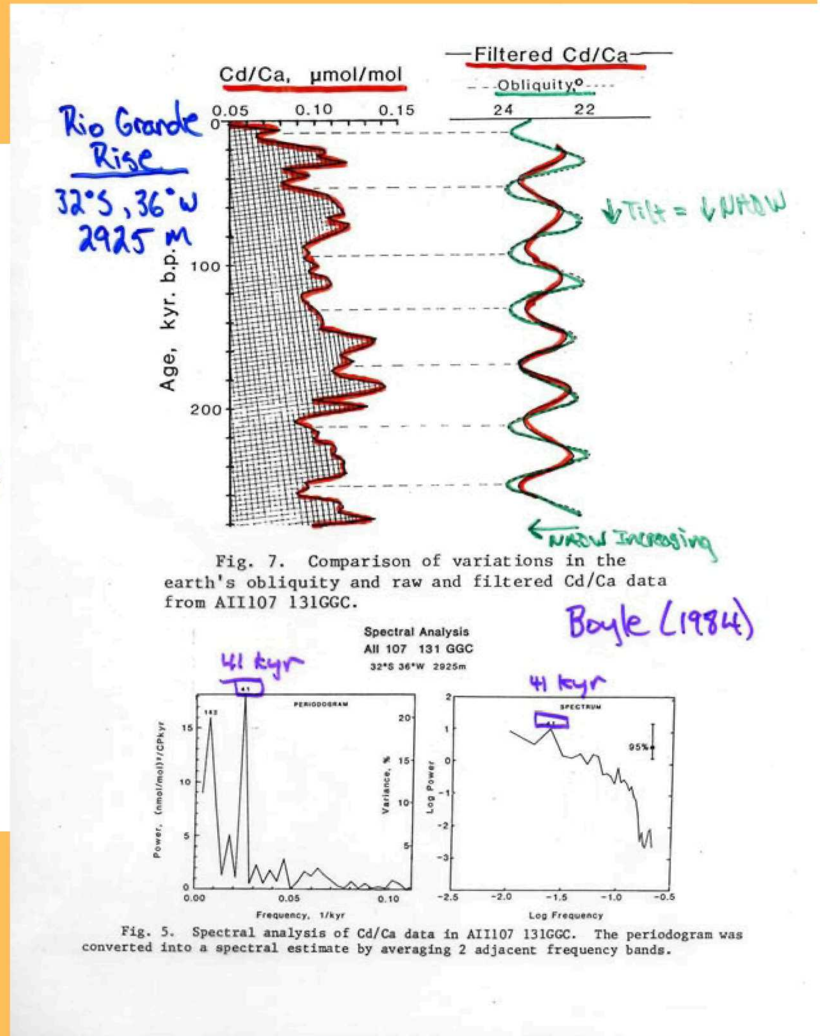


Sachs et al. (2001, in press & unpub.)
Vimeux et al. (2002)
Stenni et al. (subm.)
Berger (1978)

The Ocean's Thermohaline Circulation Likely Varied in Concert with Changes in Earth's Tilt…

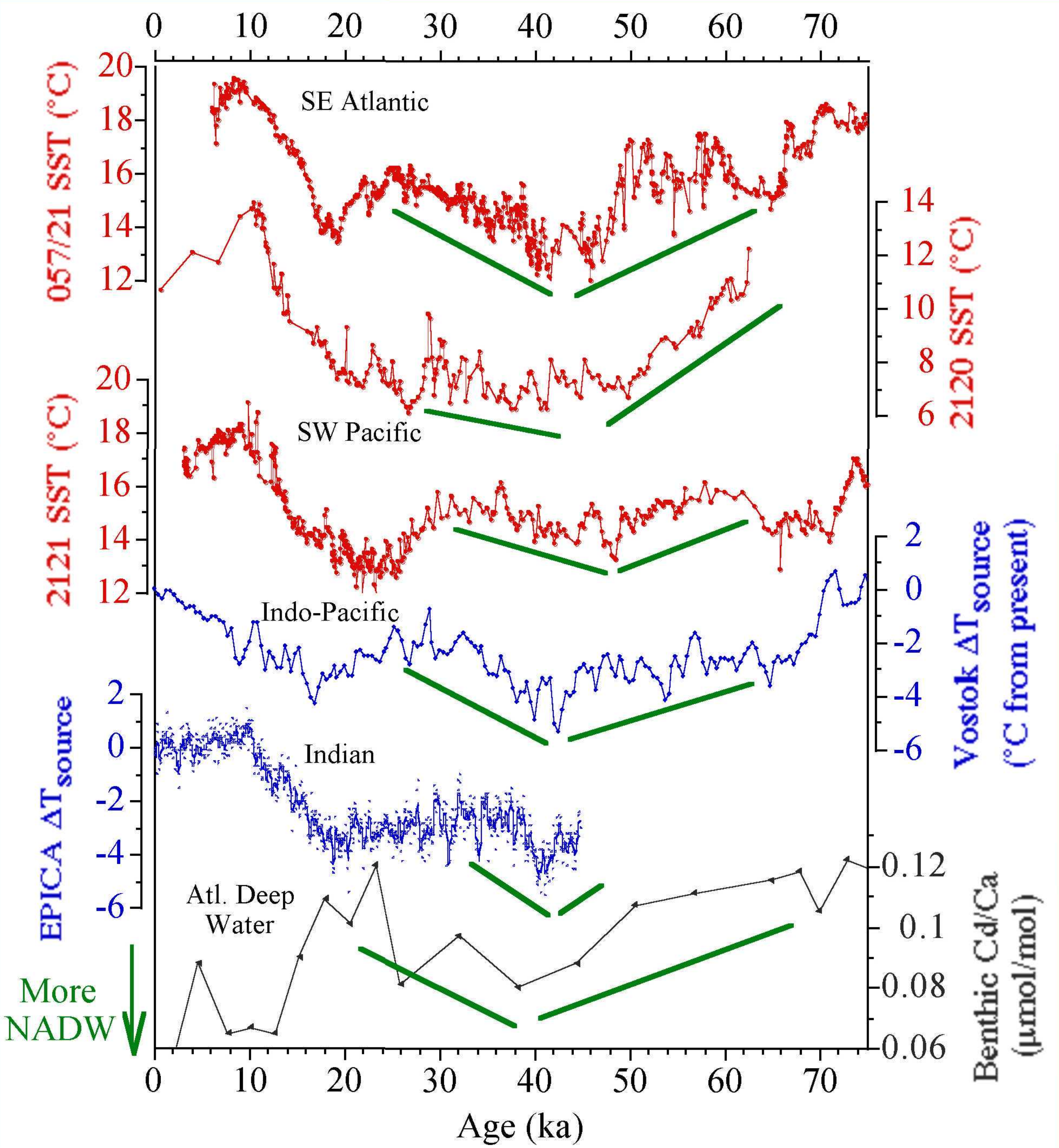


Rahmstorf (2002)



Boyle (1984)

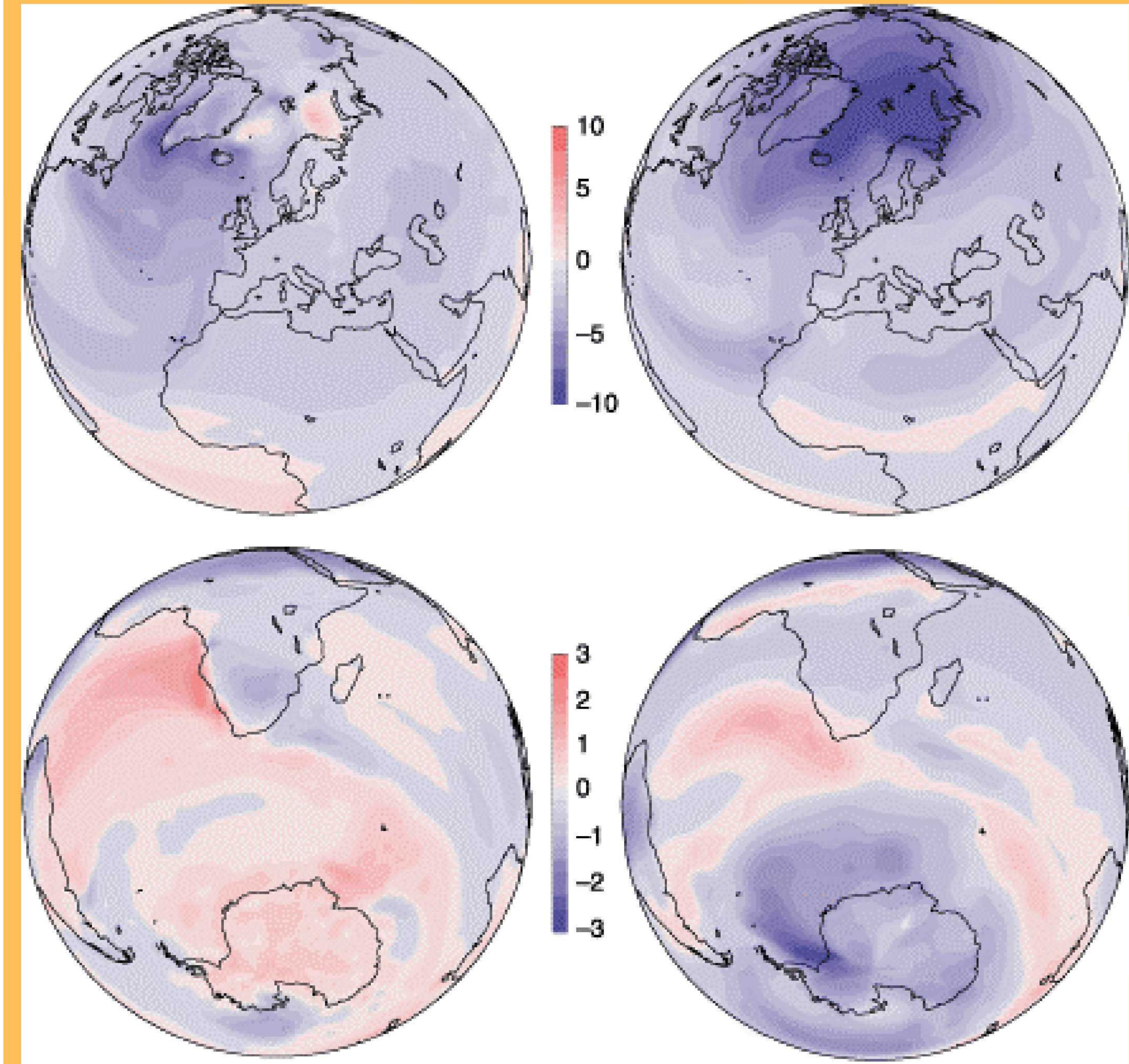
Co-variation of Thermohaline Circulation & Southern Mid-latitude SST?



Cooling: More NADW
Warming: Less NADW

Rio Grande Rise
32°S 2925 m
Boyle (1984)

Models indicate S. Mid-latitudes Warm in Response to Diminished N. Atlantic Deep Water Production

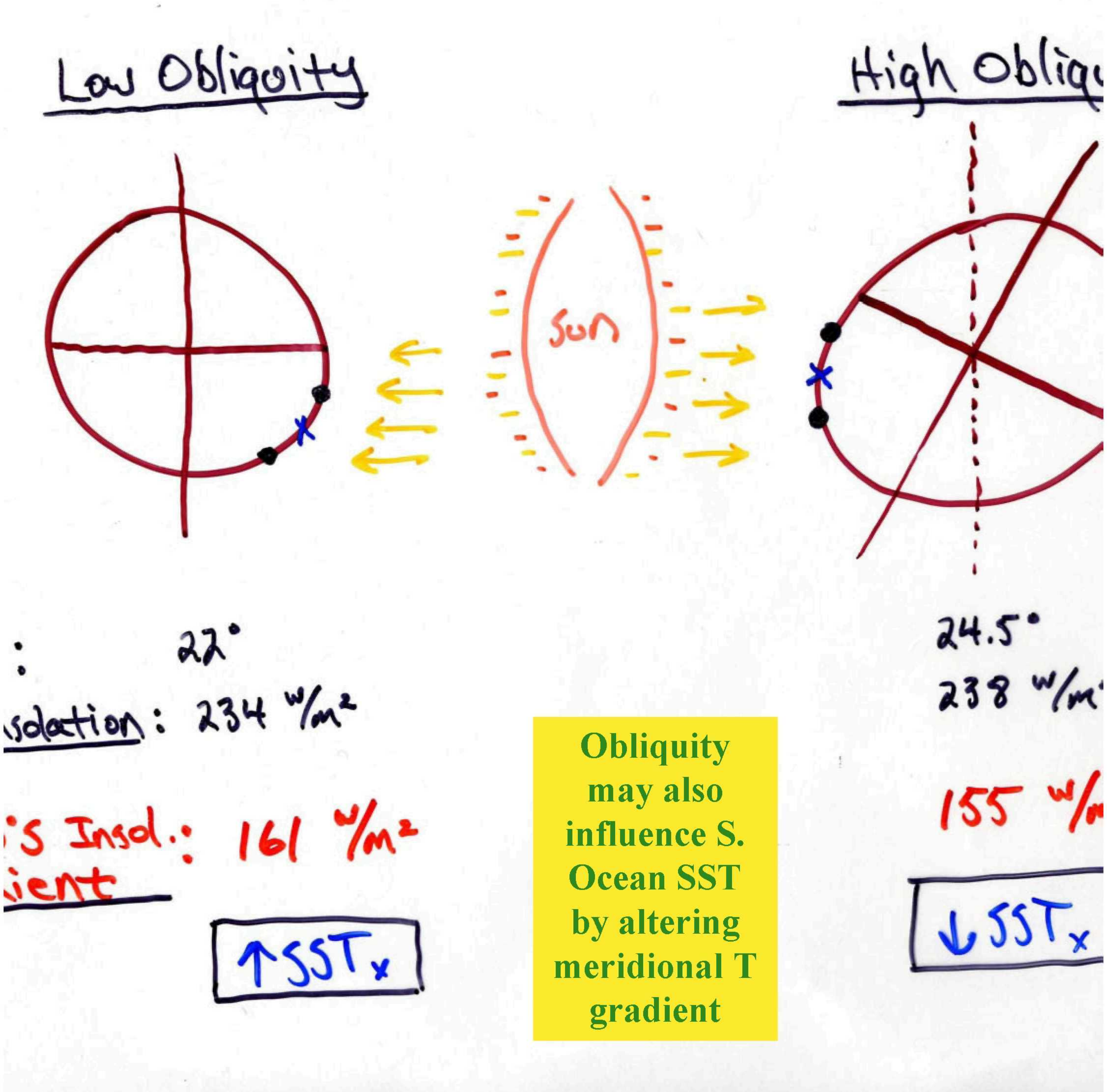


Vellinga & Wood (2002)

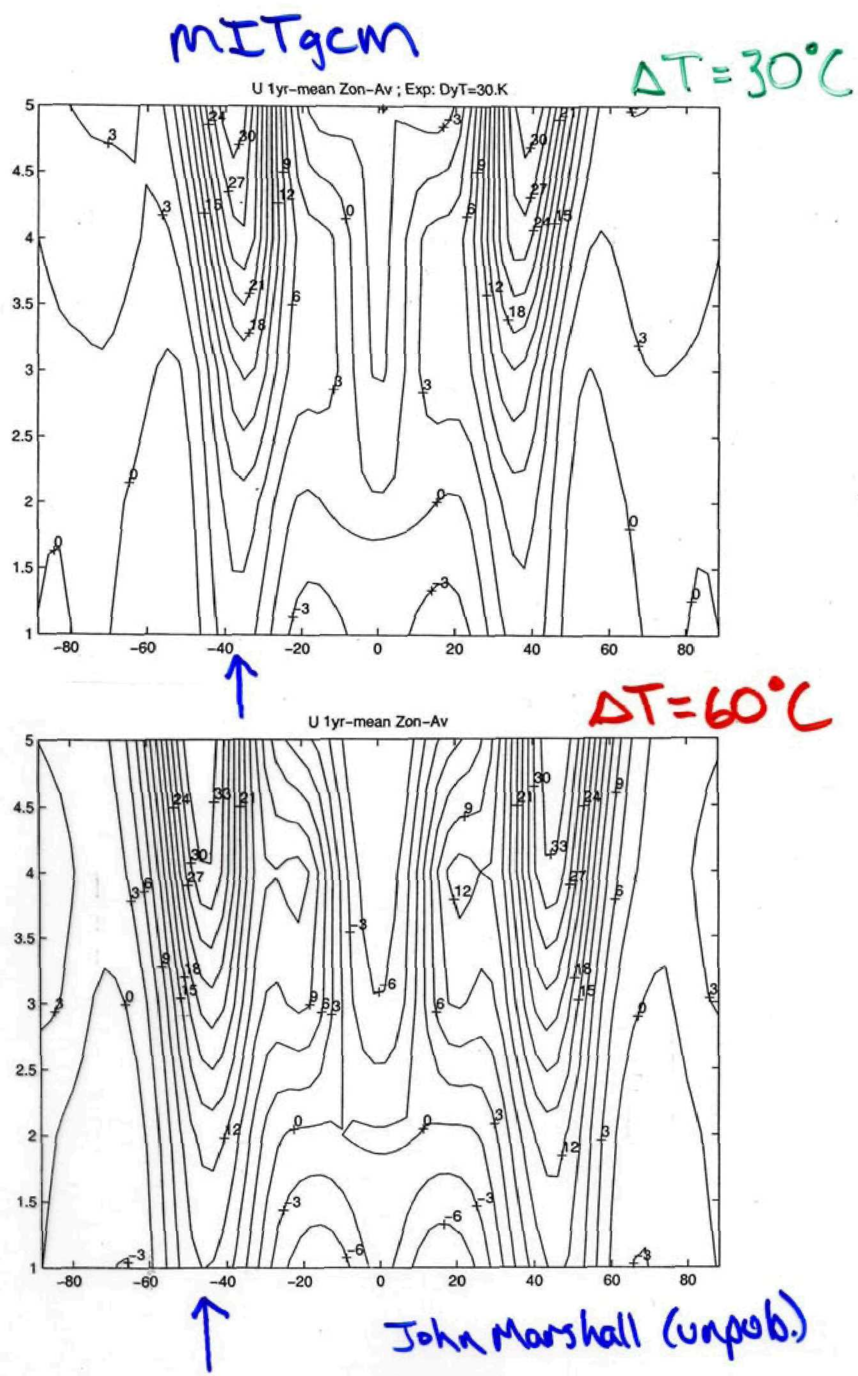
Rind et al. (2001)

Coupled GCM Evidence for a "Bipolar Seesaw"

Stocker (2002)



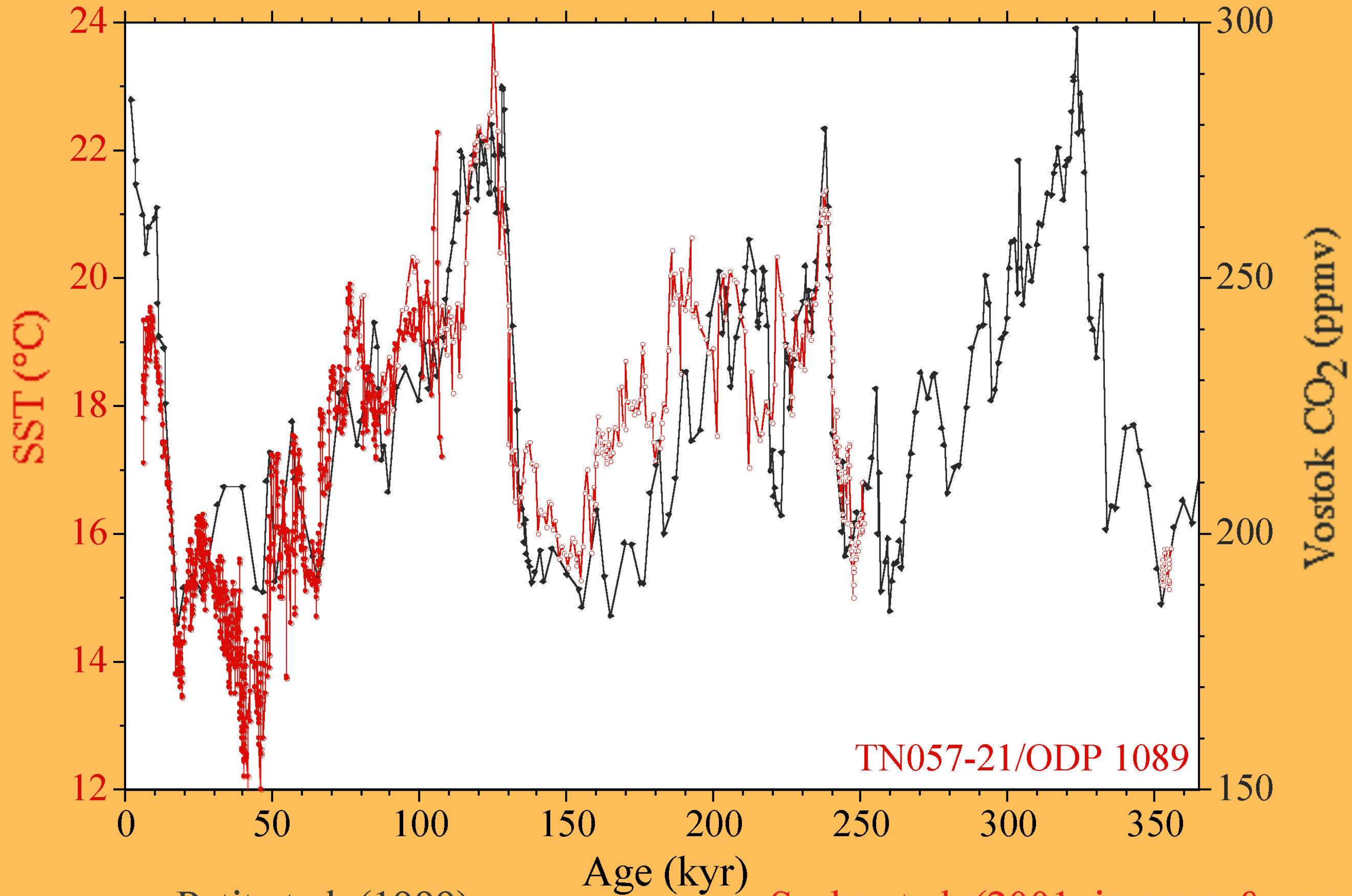
Obliquity may also influence S. Ocean SST by altering meridional T gradient



Poleward Shift of Westerlies in Response to Increased Eq-Pole T Gradient

J. Marshall (unpub.)
MITgcm

Cape Basin SST & Vostok CO_2



Petit et al. (1999)

Sachs et al. (2001, in press & unpub.)

Part I: Conclusions

- Climate of S mid-latitudes differed from that of globe & N hemisphere during last glacial period
- Cooling 60-40 ka followed by warming 40-25 ka
- May have been associated with changes in Atlantic Thermohaline Circulation
- Antarctic air T poor proxy for much of S Hemisphere climate
- Additional & longer SST records needed to evaluate forcing mechanisms

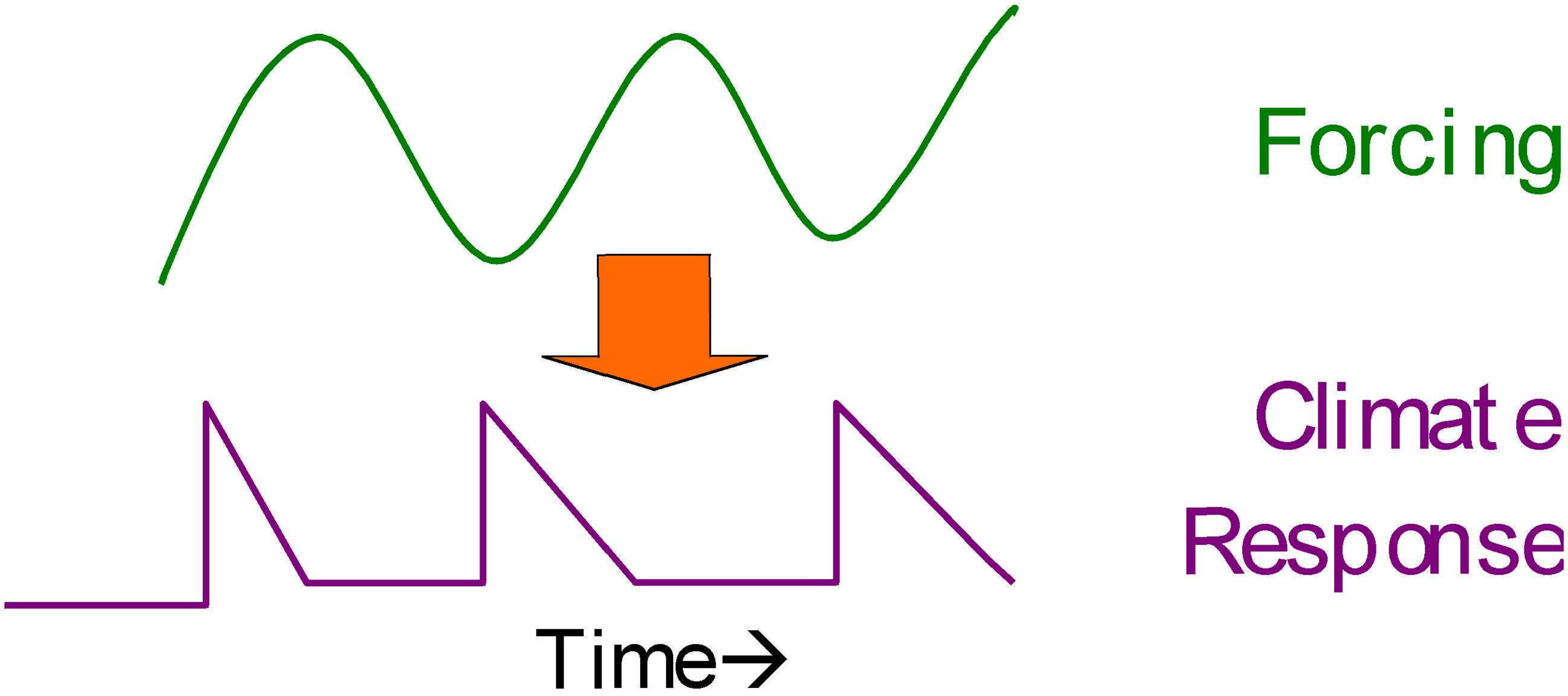
Ocean Surface Temperatures During the Last 150,000 Years-II

Julian Sachs
Dept. of Earth, Atmospheric & Planetary Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts, USA

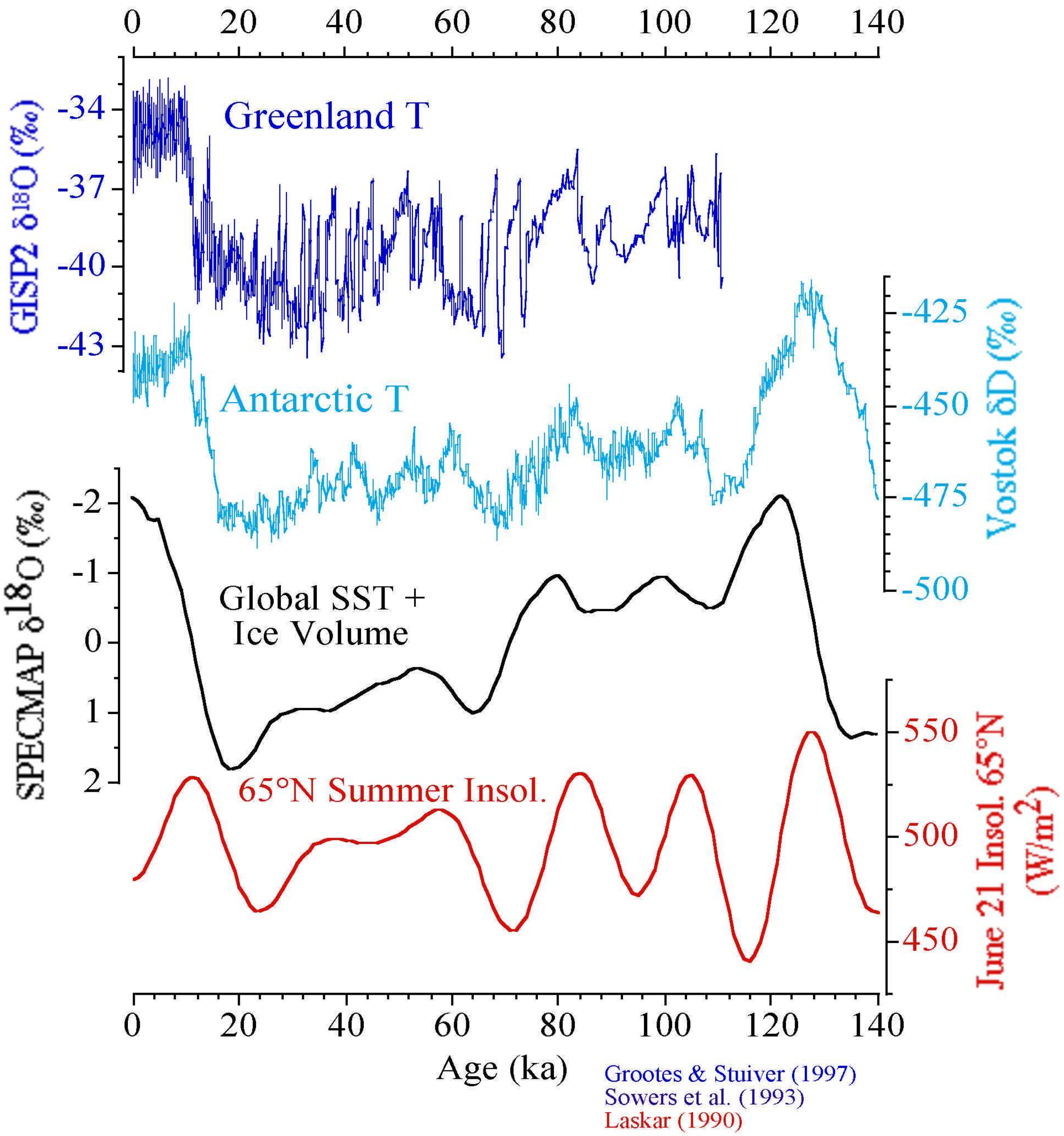
Part II: Southern Ocean Expression of Massive Ice Discharge Events in the North Atlantic

"Abrupt Climate Change"

A change in climate that occurs more rapidly than a known forcing.

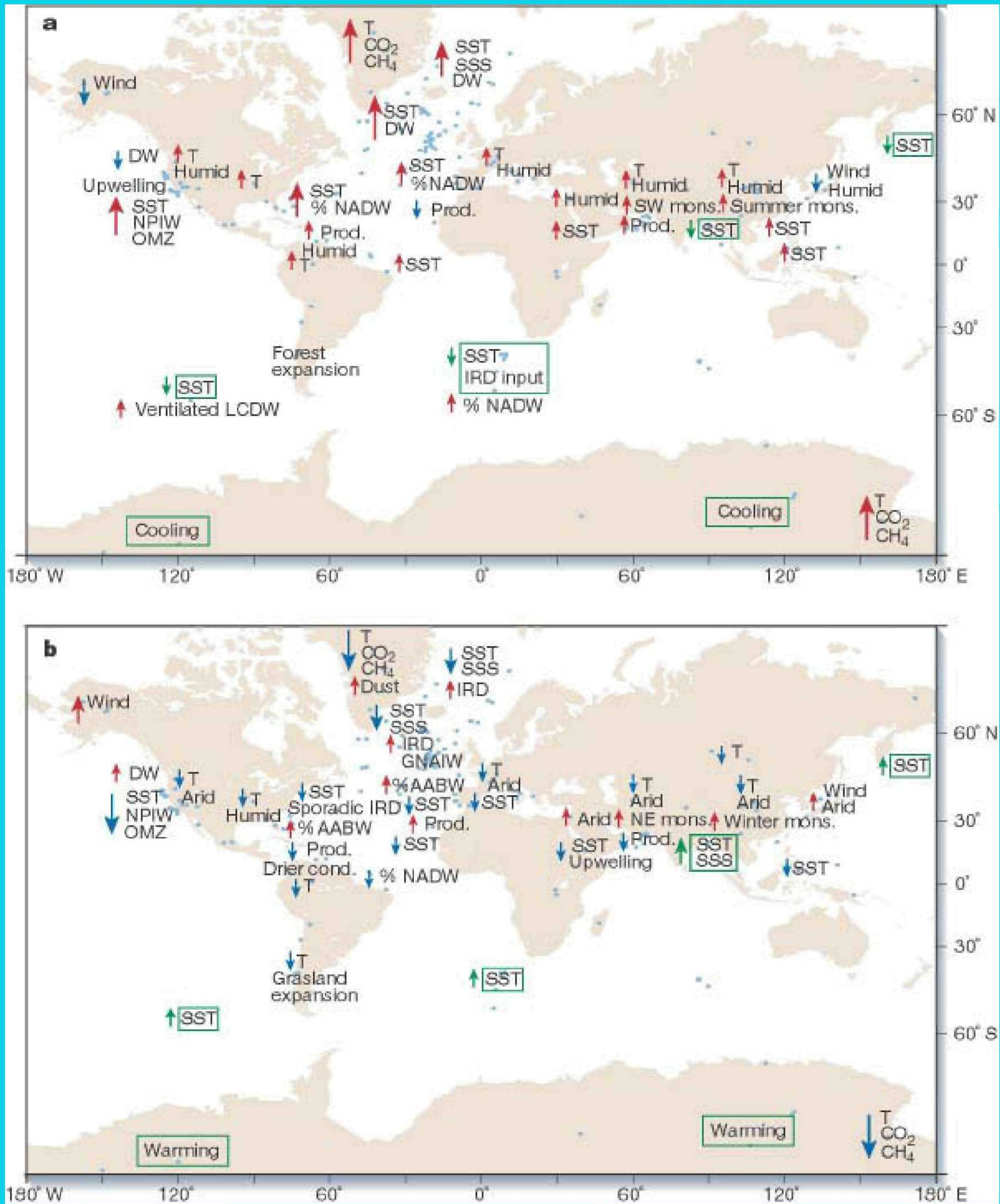


Climate of the last Glacial Cycle



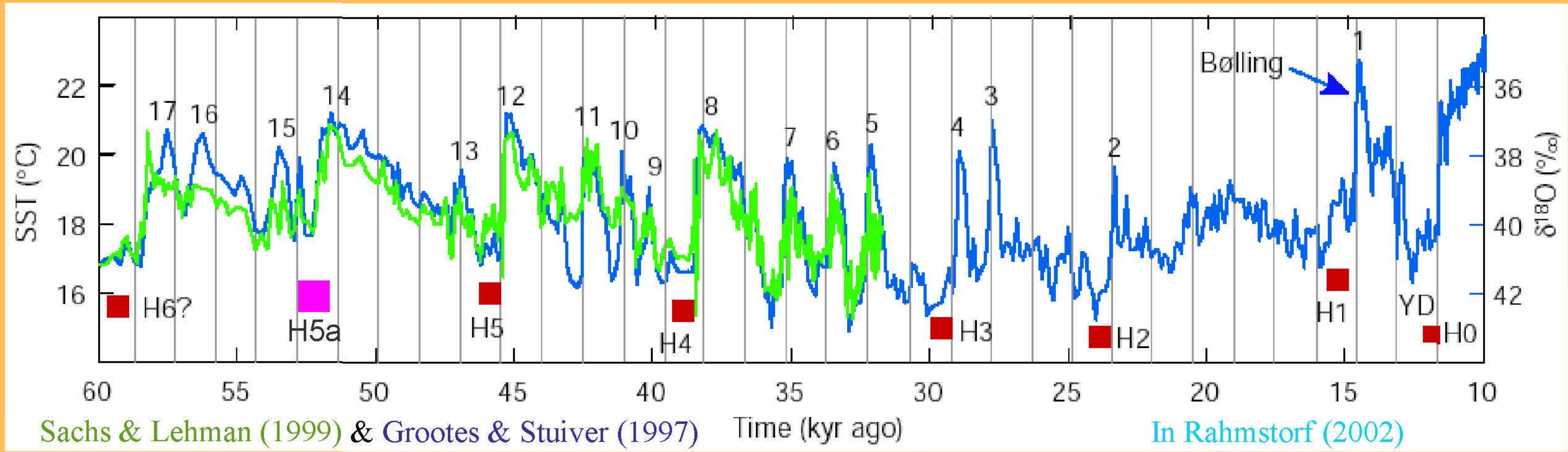
Climate of the Last Glacial Cycle

Global Character of Abrupt Climate Change During Glacial Period



- **Much of N. Hem. changed in concert**
- **Few detailed paleoclimate records from vast Southern Hemisphere oceans**

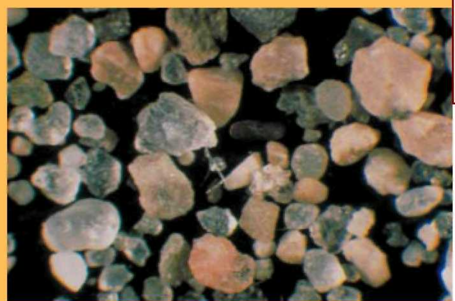
Voelker et al. (2002) in Rahmstorf (2002)

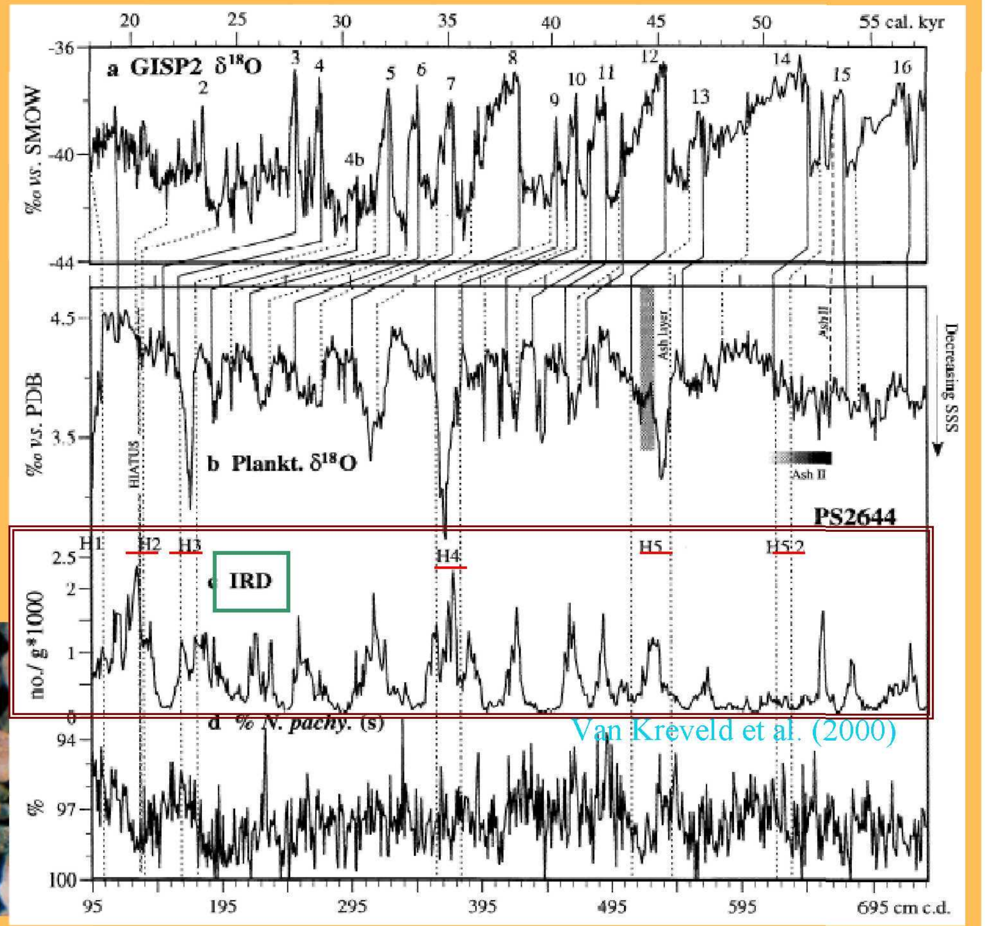


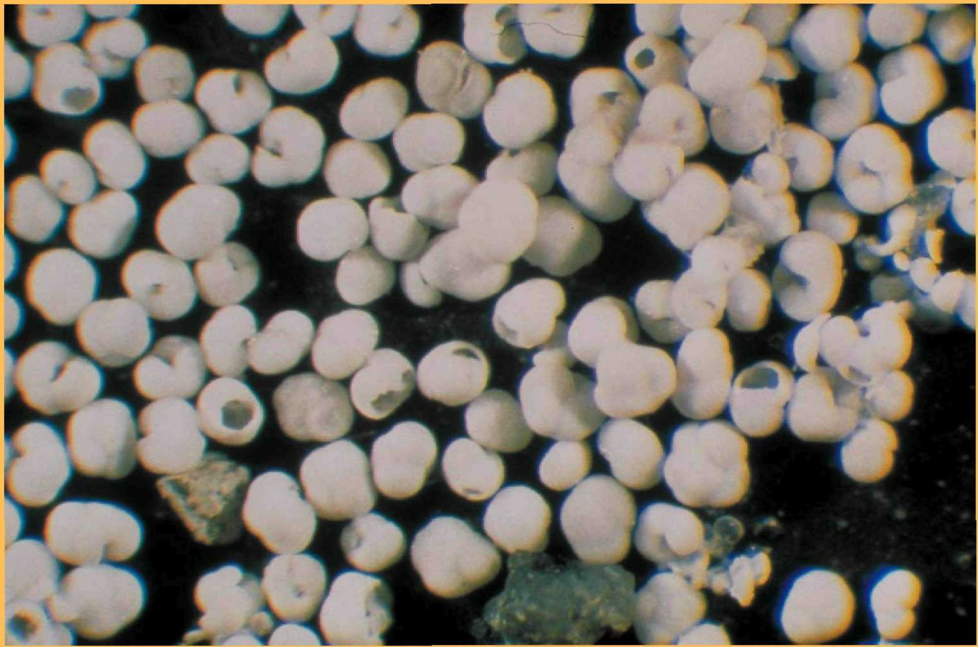
Two Types of Abrupt Climate Events in the Glacial North Atlantic:

Dansgaard-Oeschger Events

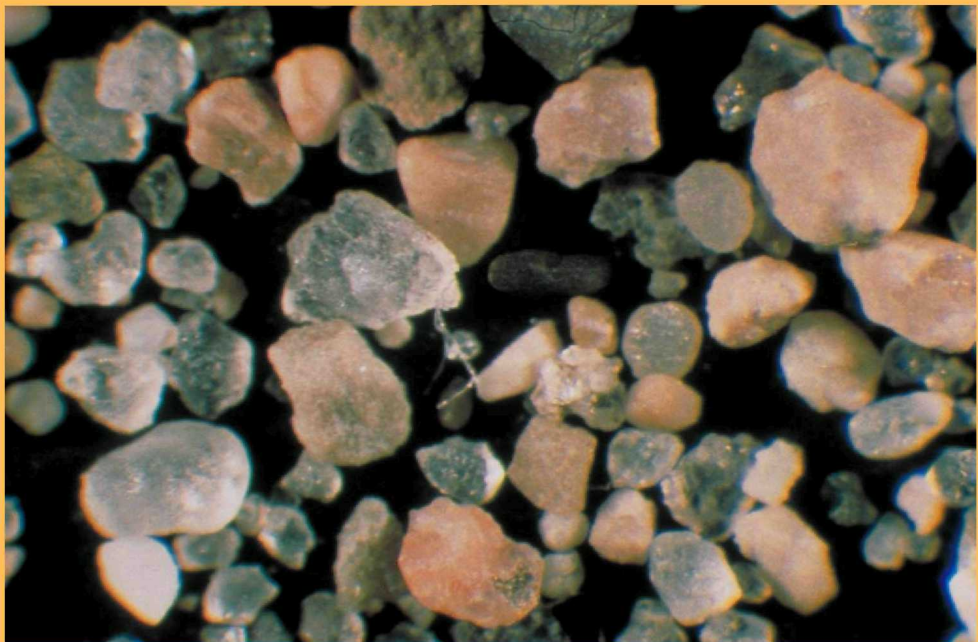
Heinrich Events





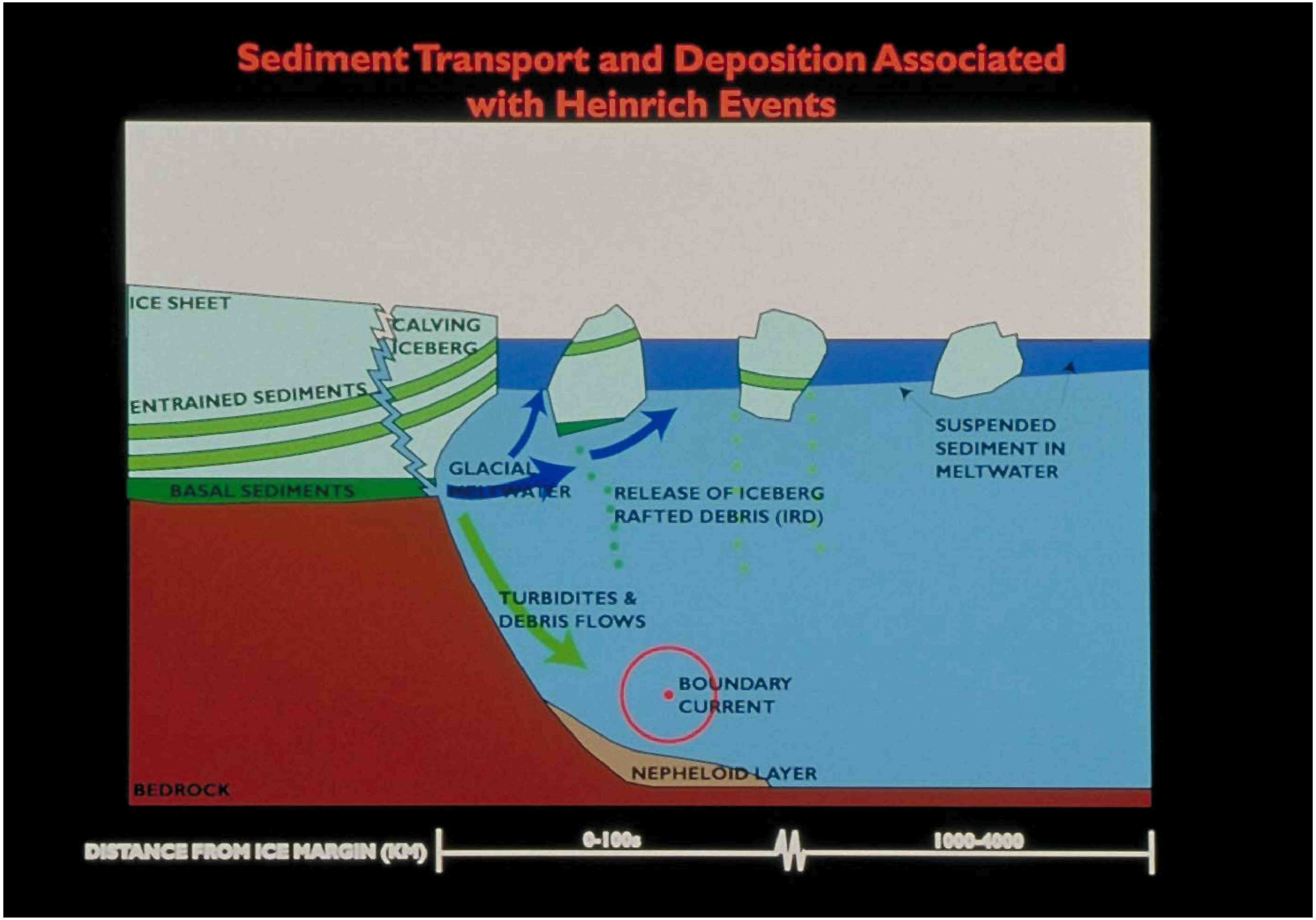


Typical Sand-Size (> 150 µm) Fraction in NW Atlantic Core
Foraminifera



Sand-Size Fraction in Heinrich Layer-2 in NW Atlantic (670-672 cm)
Ice-Rafted Debris

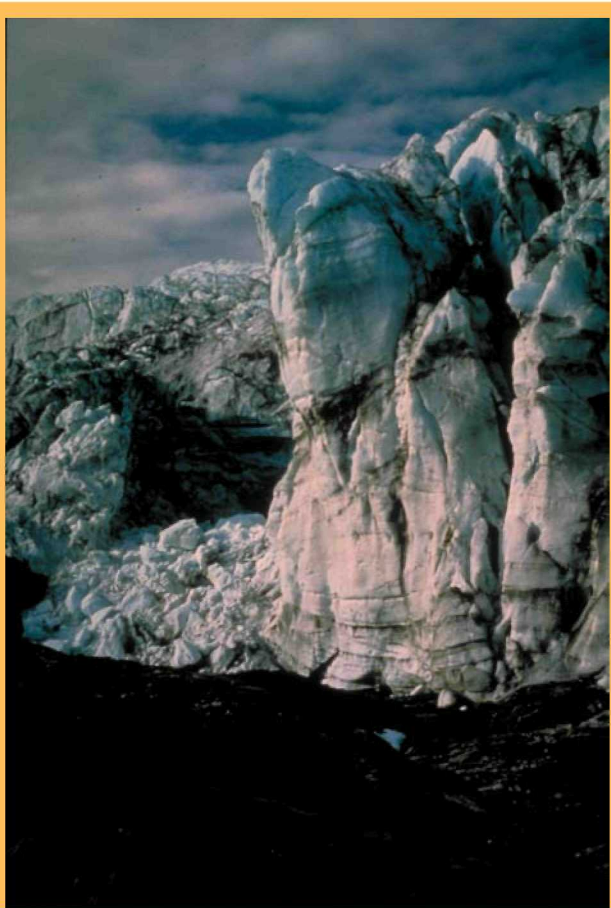
www.noaa.gov


Sediment Transport and Deposition Associated with Heinrich Events
ICE SHEET
CALVING ICEBERG
ENTRAINED SEDIMENTS
BASAL SEDIMENTS
GLACIAL MELTWATER
RELEASE OF ICEBERG RAFTED DEBRIS (IRD)
SUSPENDED SEDIMENT IN MELTWATER
TURBIDITES & DEBRIS FLOWS
BOUNDARY CURRENT
NEPHELOID LAYER
BEDROCK
DISTANCE FROM ICE MARGIN (KM)
0-100s
1000-4000

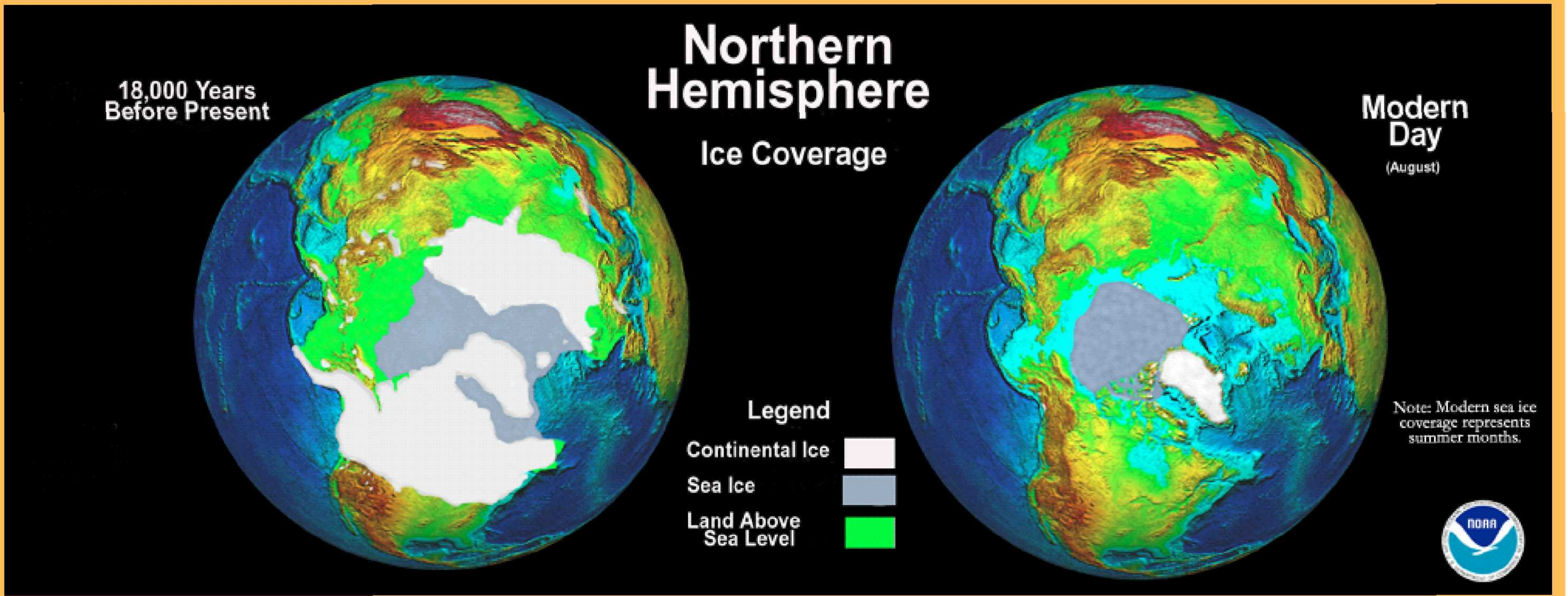
www.noaa.gov

Icebergs

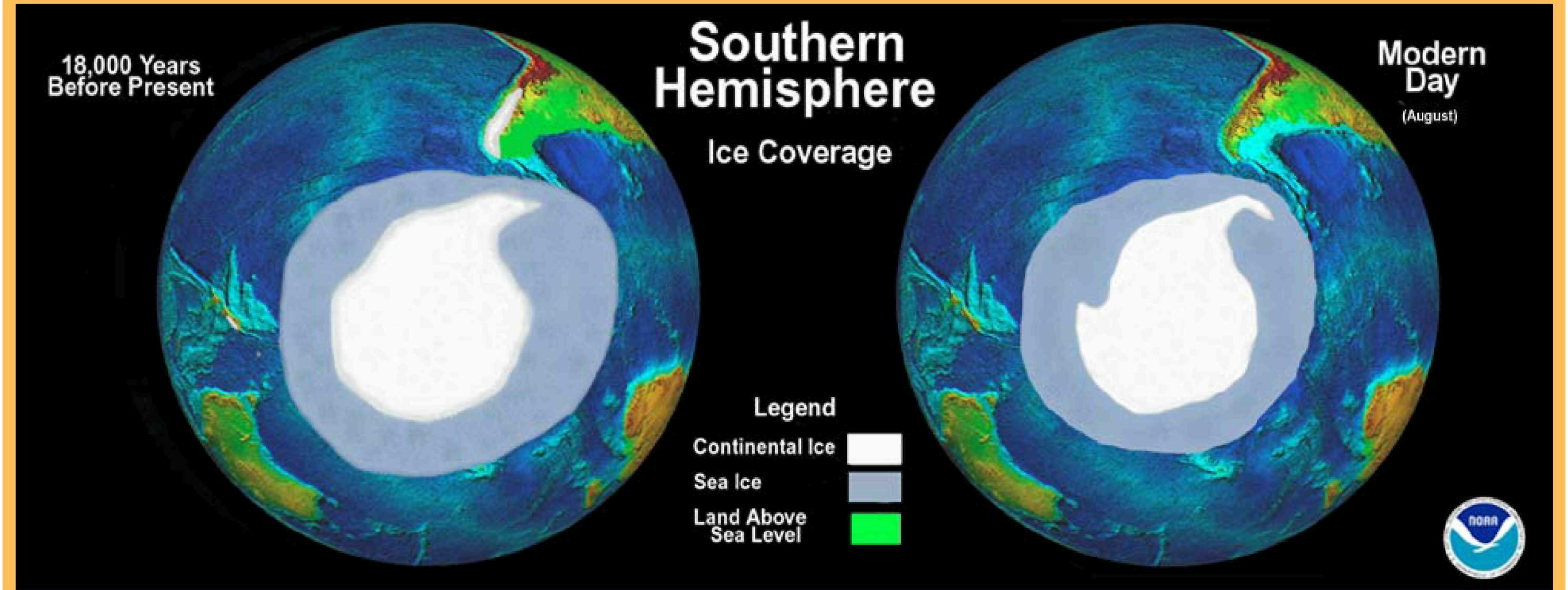
www.noaa.gov



Northern Hemisphere Ice Sheets During the Last Glacial Period



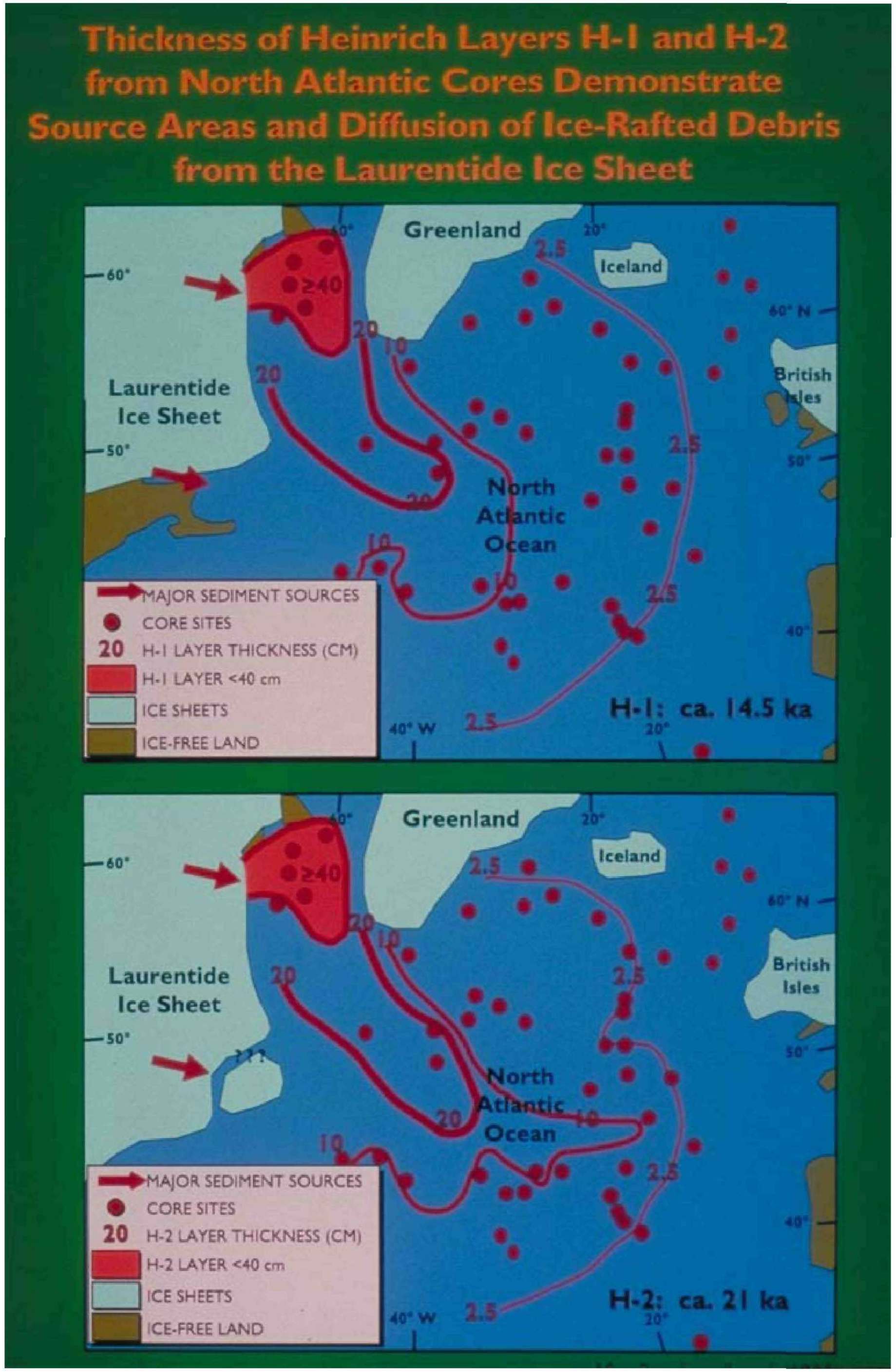
Southern Hemisphere Ice Sheets During the Last Glacial Period



•Little additional land-based ice in S. Hemisphere during glacial period

Heinrich *Layers* in the North Atlantic

www.noaa.gov




Sites
Exhibiting
Heinrich Events
or Events
Synchronous
with Heinrich
Events
#, Location, Type of Record
1. Chile, Glacial Chronology
2. North Pacific, Ice Rafting Data
3. Rocky Mountains, Glacial Records
4. Great Basin, Lake Level Changes
5. Florida, Pollen Data
6. Great Lakes, Laurentide Ice Sheet fluctuations
7. Baffin Bay, Detrital Carbonate Events
8. Northwest Labrador Sea, Detrital Carbonate Events
9. Labrador Sea and SW Greenland, Changes in Mineraology and Isotopes
10. Newfoundland/St. Lawrence, Mineralogy of IRD Lithic fraction
11. Greenland Ice Sheet, Changes in Snow Accumulation
12. SE Greenland, IRD Layers
13. Central North Atlantic, IRD Events and Geochemistry of Sediments
14. Nordic Seas, IRD Events and Mineralogy
15. Eastern North Atlantic, IRD Events and Mineralogy
16. West of Spain & Portugal, Increase in Lithic Content of Cores
17. Santa Barbara Basin, Changes in Sediment Character
1
2
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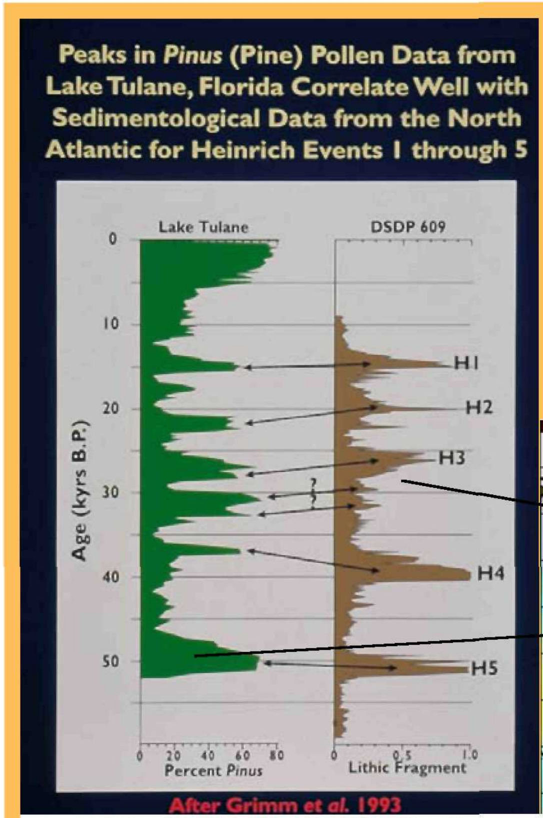
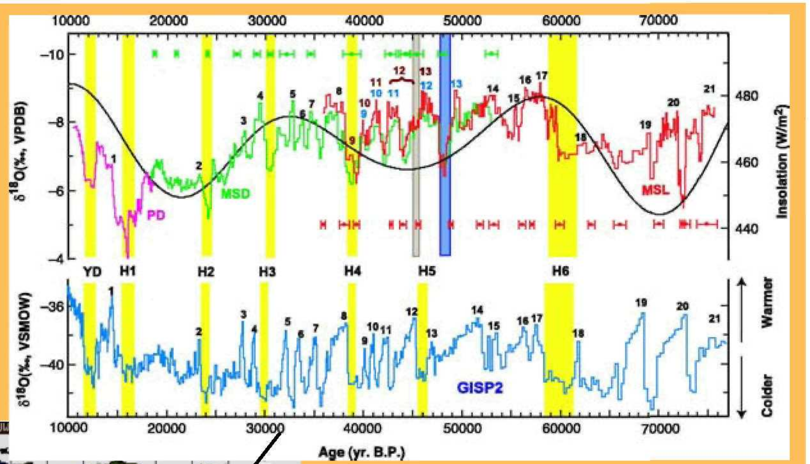
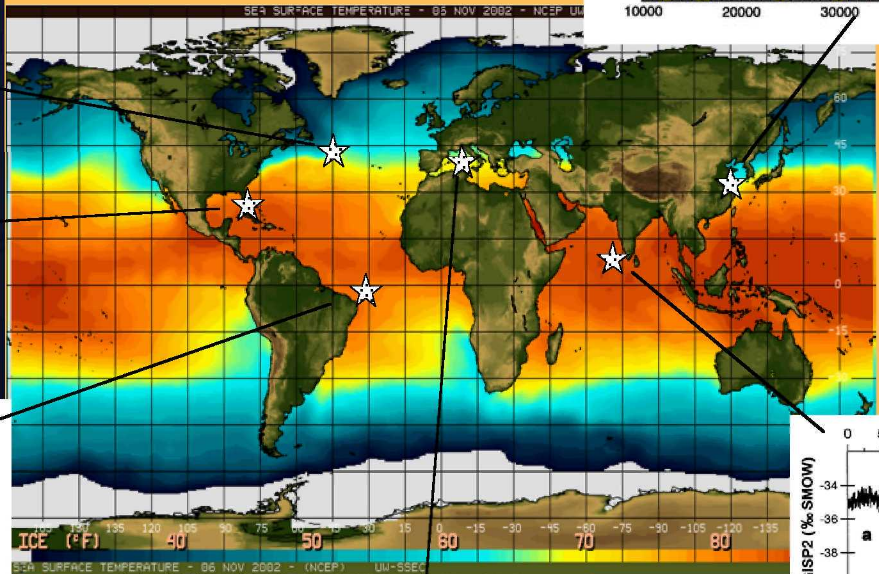
17

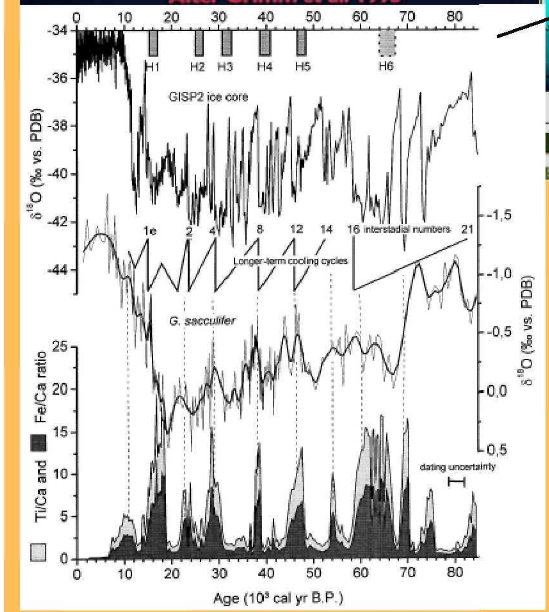
Global (?) Impact of Heinrich Events

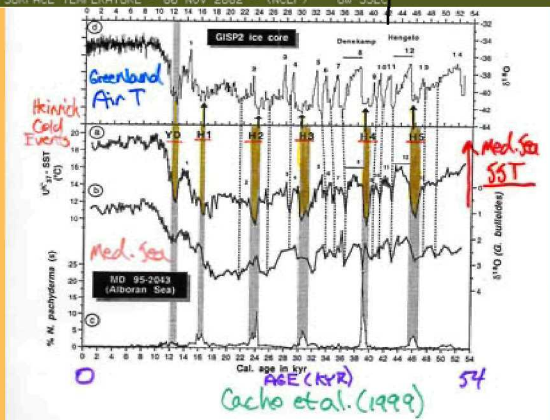


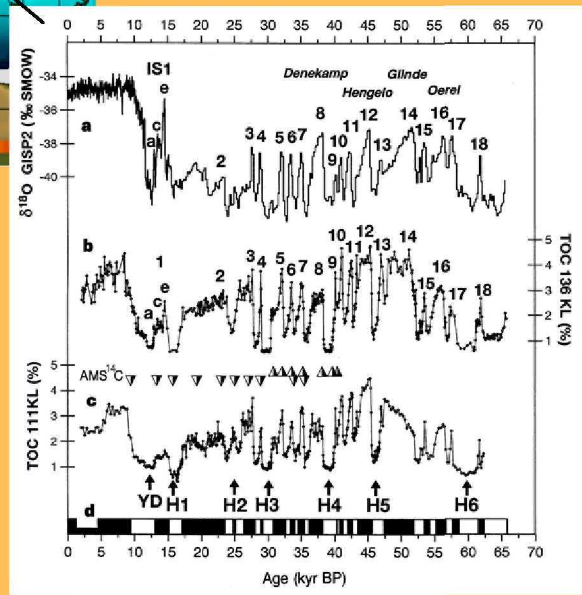




Wang et al. (2001)
Schulz et al. (1998)
Arz et al. (1998)
Cacho et al. (1999)
Grimm et al. (1997)

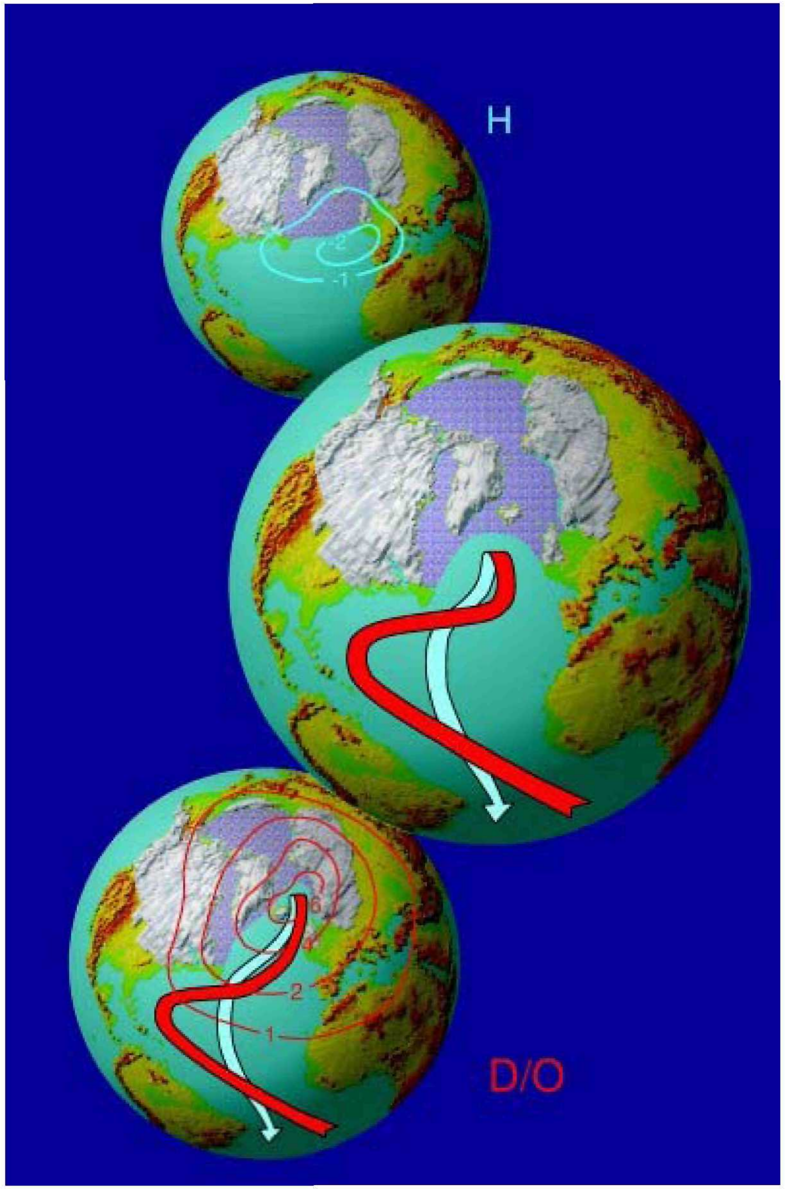


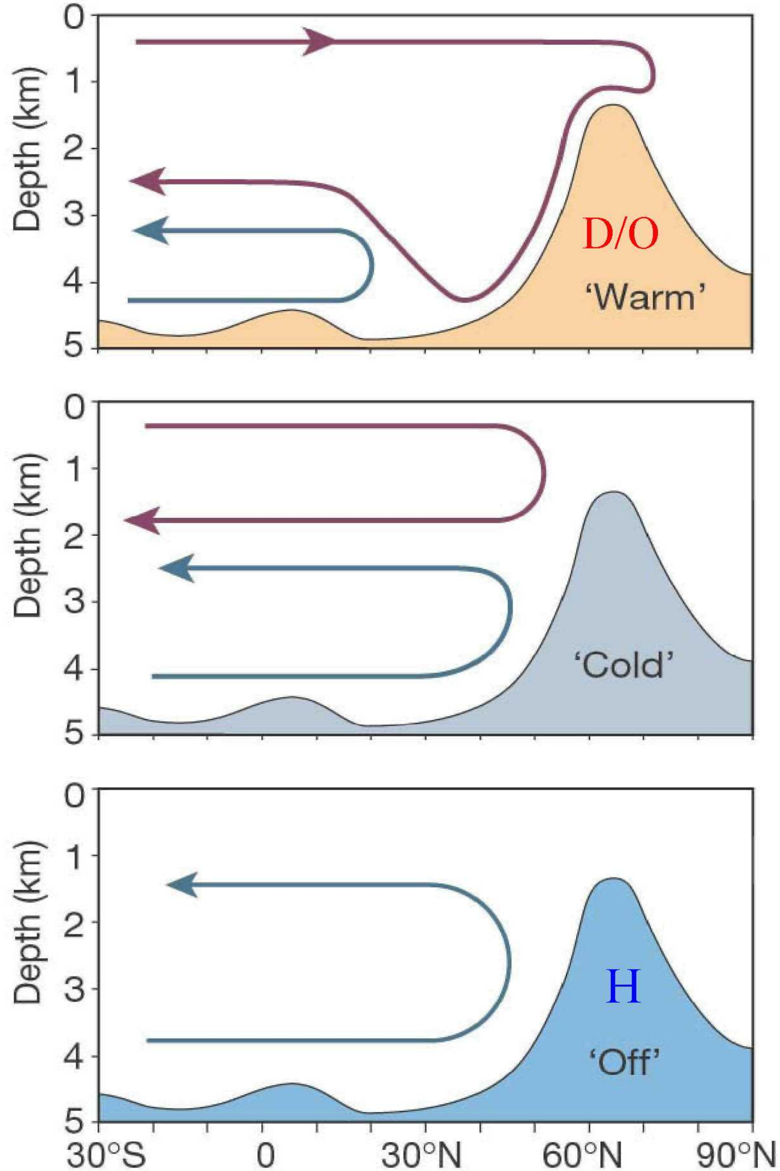




3 Modes of Ocean Circulation During the Last Glacial Period?

Rahmstorf (2002)

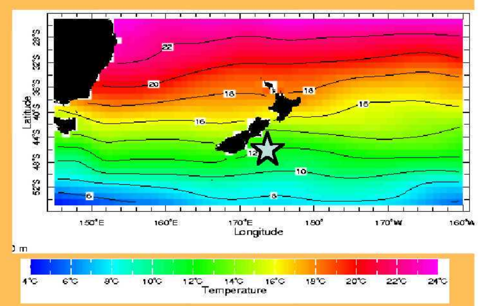




Expression of H-events SE of New Zealand

- High algal productivity
- Warm SSTs

MD97-2120
46°S, 175°E
1210 m

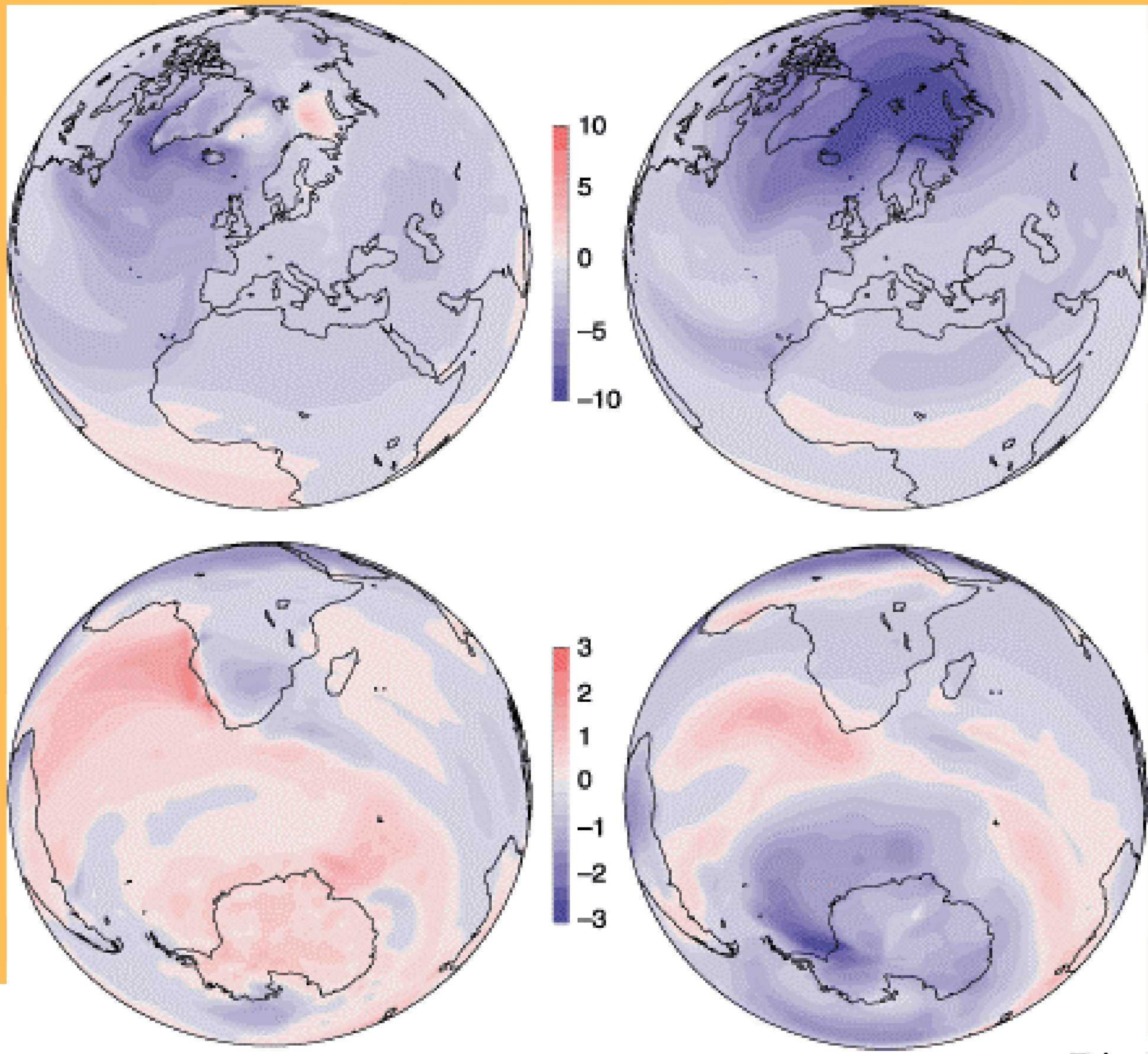


$\delta^{18}O$: K. Pahnke (in prep.). HE Ages: van Kreveld et al. (2000) & Rashid et al. (in press)

Cause of Subantarctic SW Pacific Warmth During Heinrich Events

Coupled GCM Evidence for a "Bipolar Seesaw"

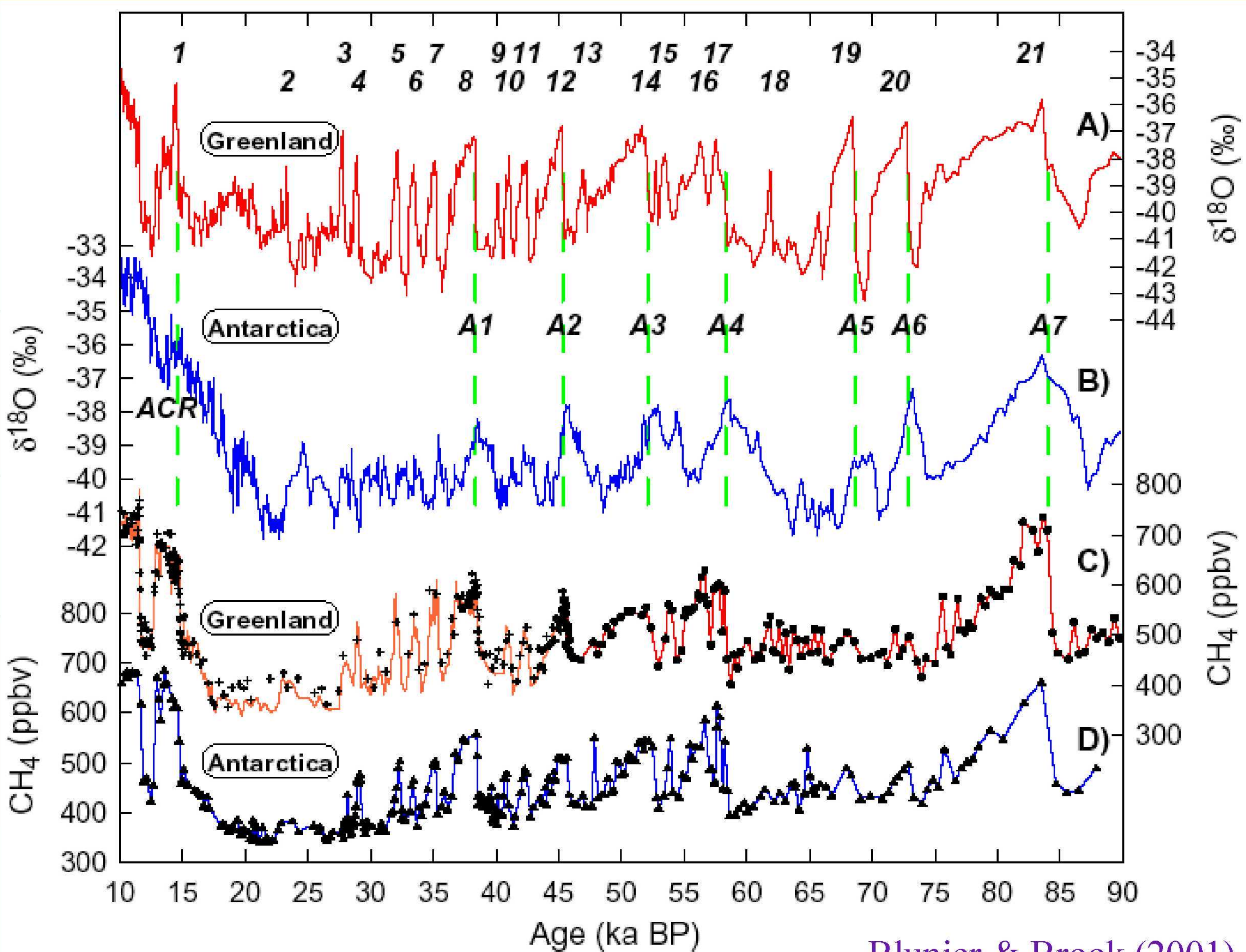
Stocker (2002)



Vellinga & Wood (2002)

Rind et al. (2001)

Asynchrony of Greenland & Antarctic Temperature



Blunier & Brook (2001)

MD97-2120 SST with GISP2 & Byrd T

Cause of High Alkenone Concentrations During Heinrich Events

3 Factors Influencing Alkenone Concentrations in Sediments

- Dilution by other sedimentary components

  ^{230}Th-normalized alkenone fluxes argue against this.

- Alkenone preservation

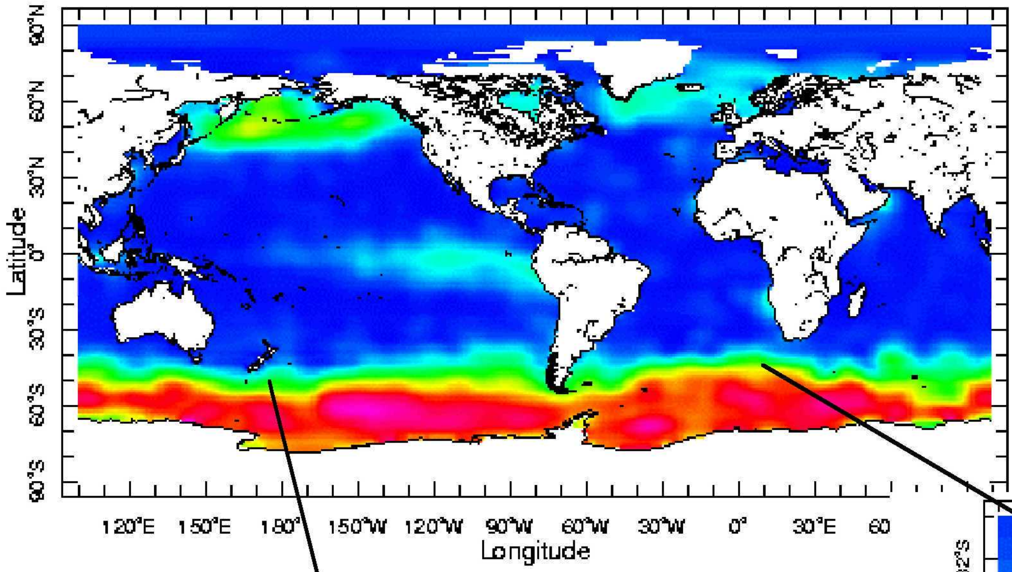
  Co-variation of [alkenone] at 1250 m in subantarctic SW Pacific & 5000 m in subtropical SE Atlantic argue against this.

- Coccolith production

  Most likely cause of [alkenone] maxima during H-events.

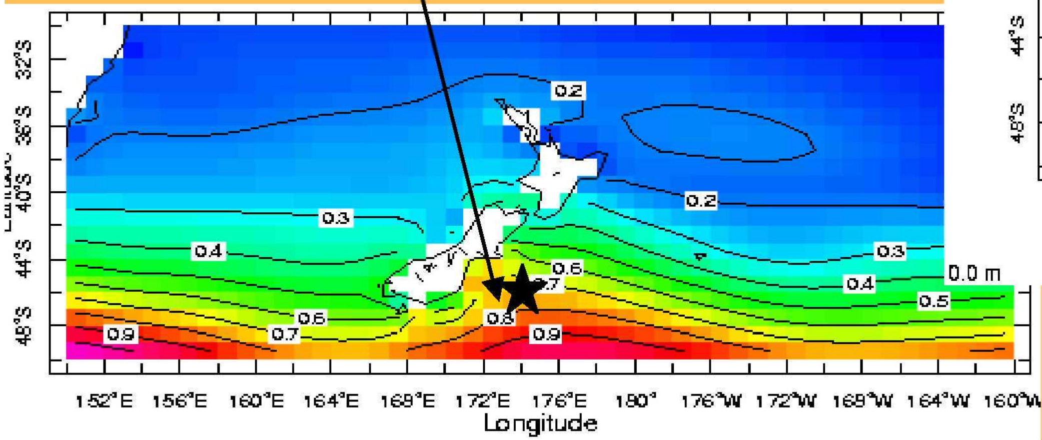
Circum-Hemispheric Productivity Events?

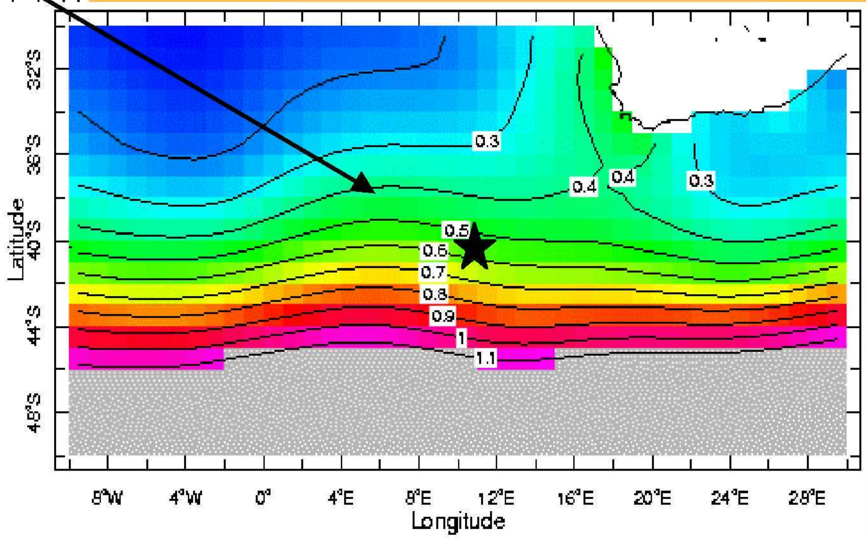
Unlike Most of the Global Ocean, Macronutrients do not Limit Algal Productivity in the S. Ocean

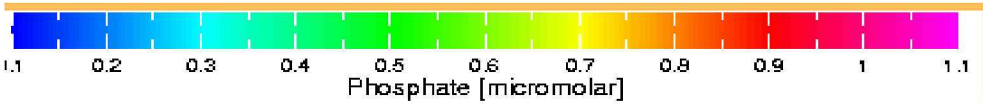


0.0 m

[Phosphate]







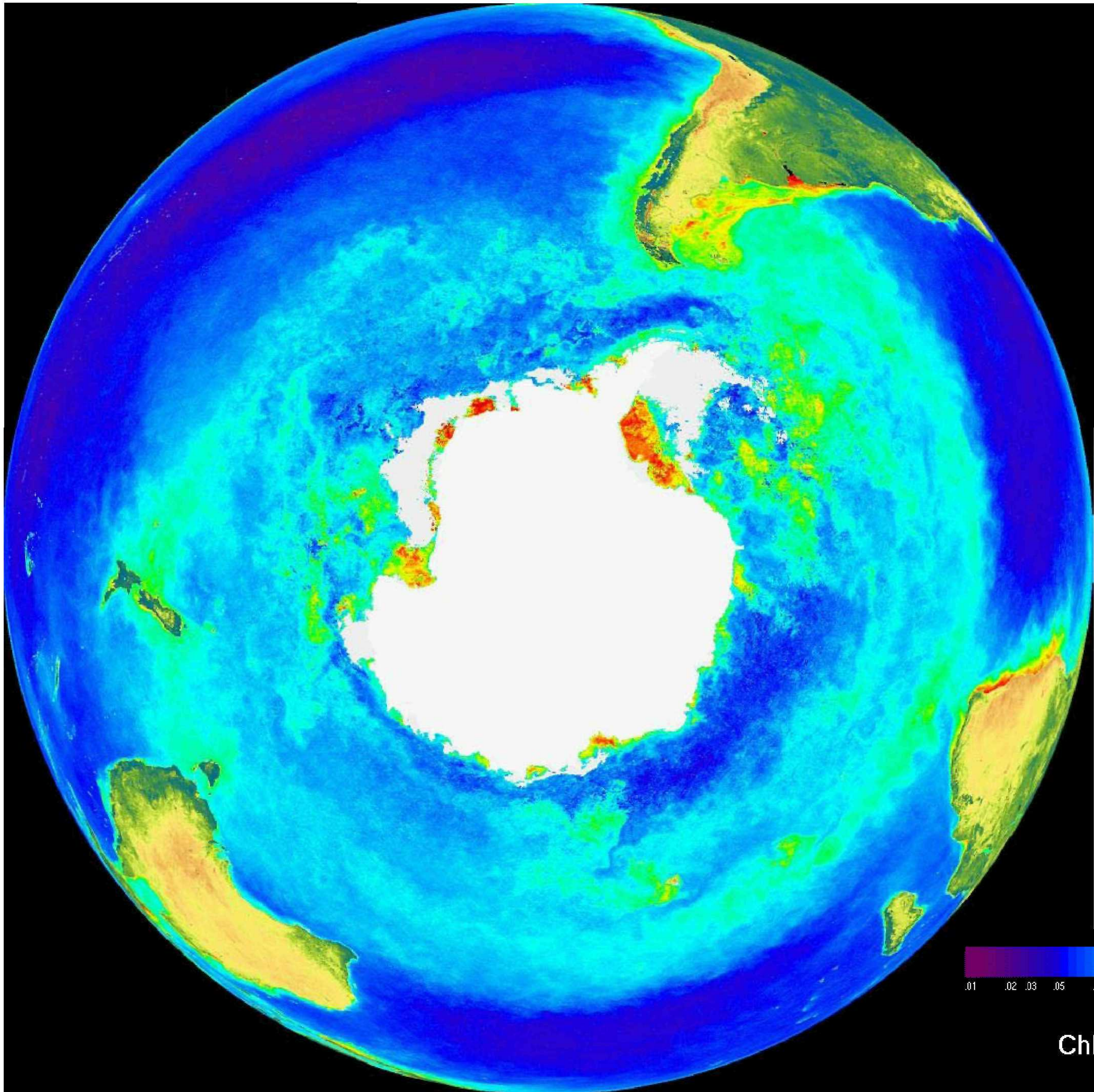
…Instead, iron does (Martin, 1990)

LEVITUS94 ANNUAL Phosphate
World Ocean Atlas CD-ROM, Levitus et al., 1994

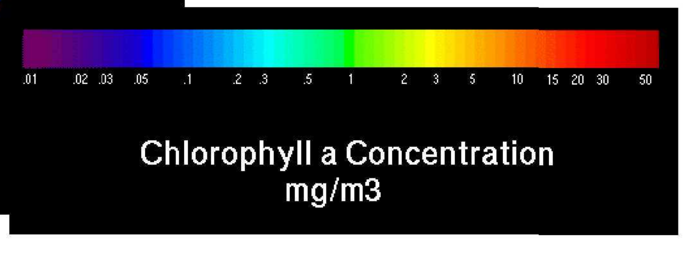
Levitus (1994)

Southern Ocean Primary Production

9/97-8/98



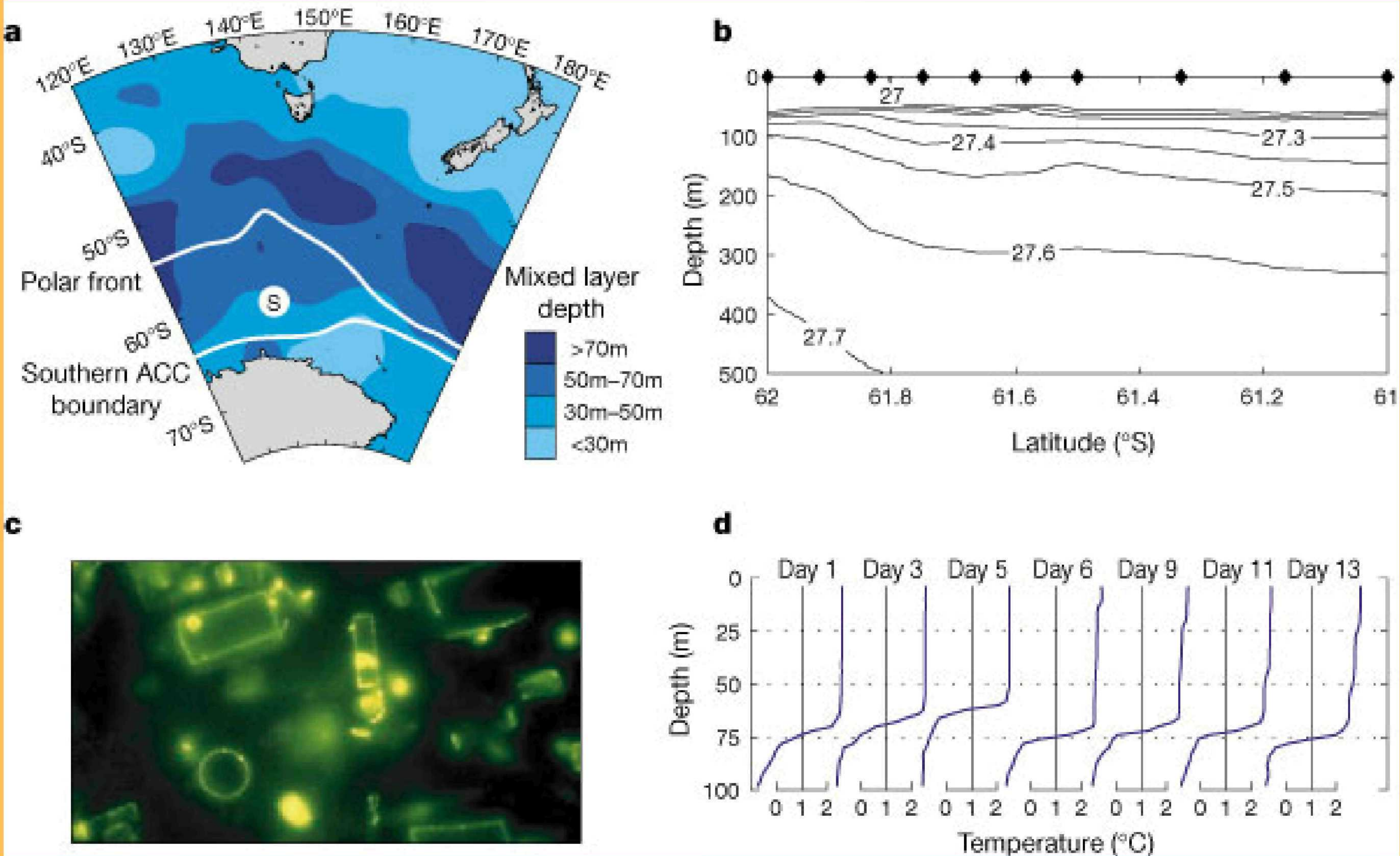
http://seawifs.gsfc.nasa.gov



While S. Ocean [Alkenone] Co-varies with Antarctic Air Temp., Not Likely Causal…

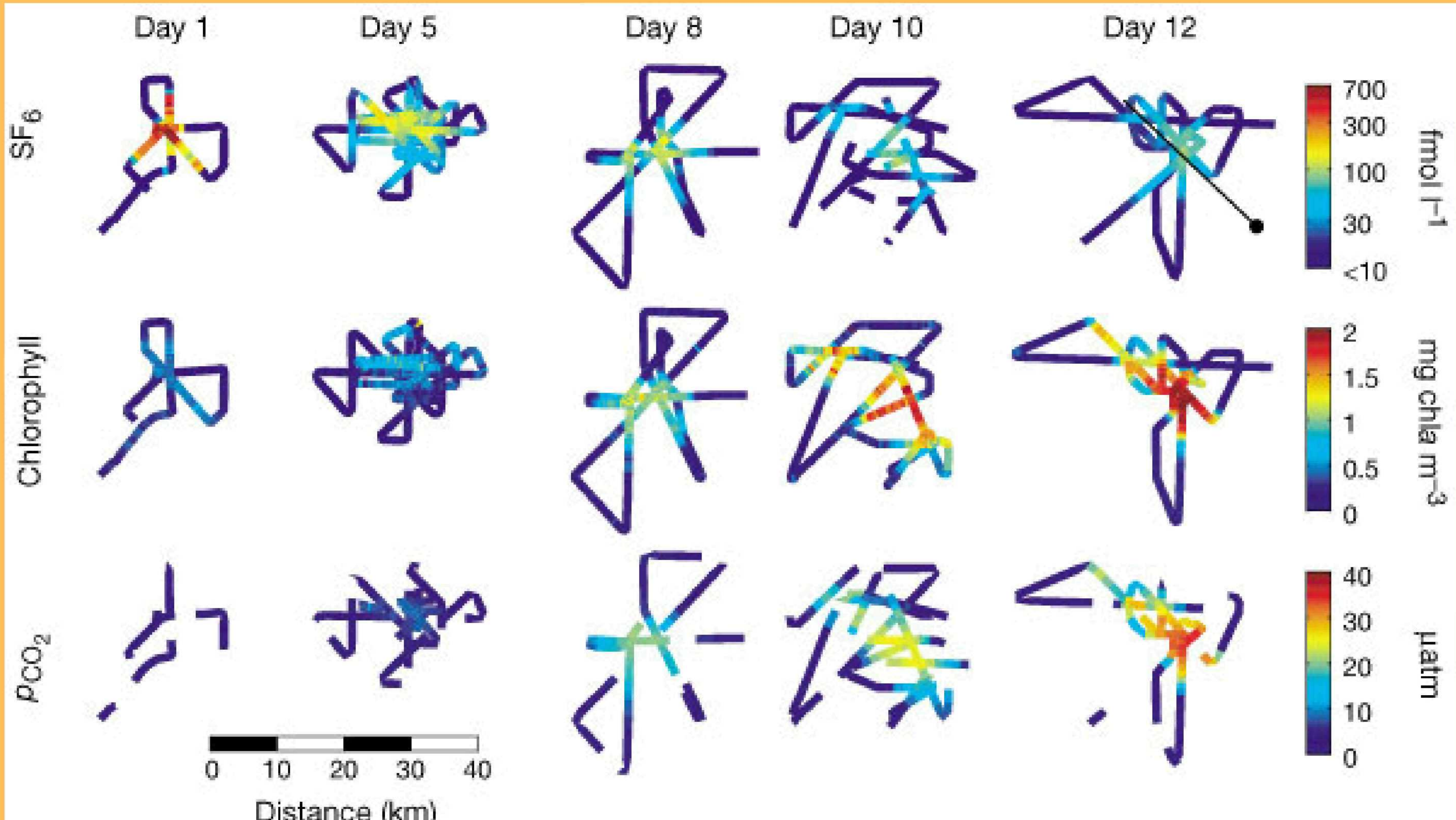
Evidence for Iron-Limitation of Algal Growth in Southern Ocean Water

S. Ocean 1° Production Limited by Fe: SOIREE-1



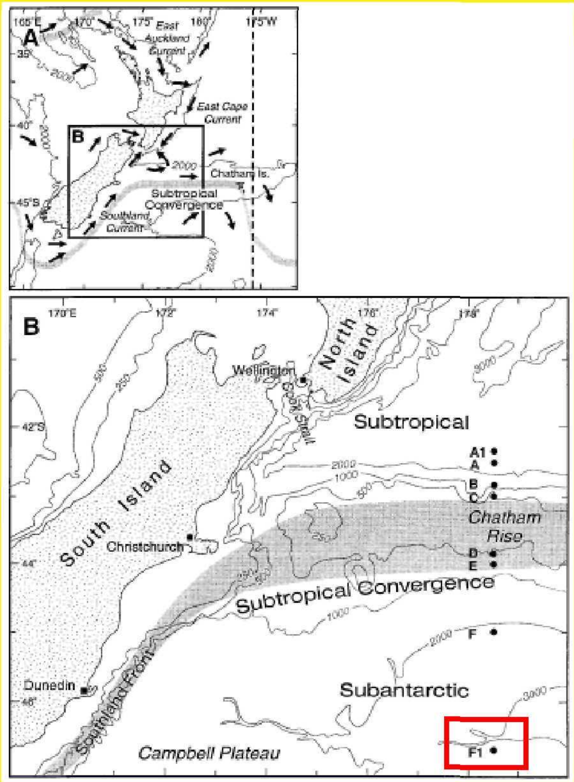
Boyd et al. (2000) *Nature*, Vol. 407: 695-701

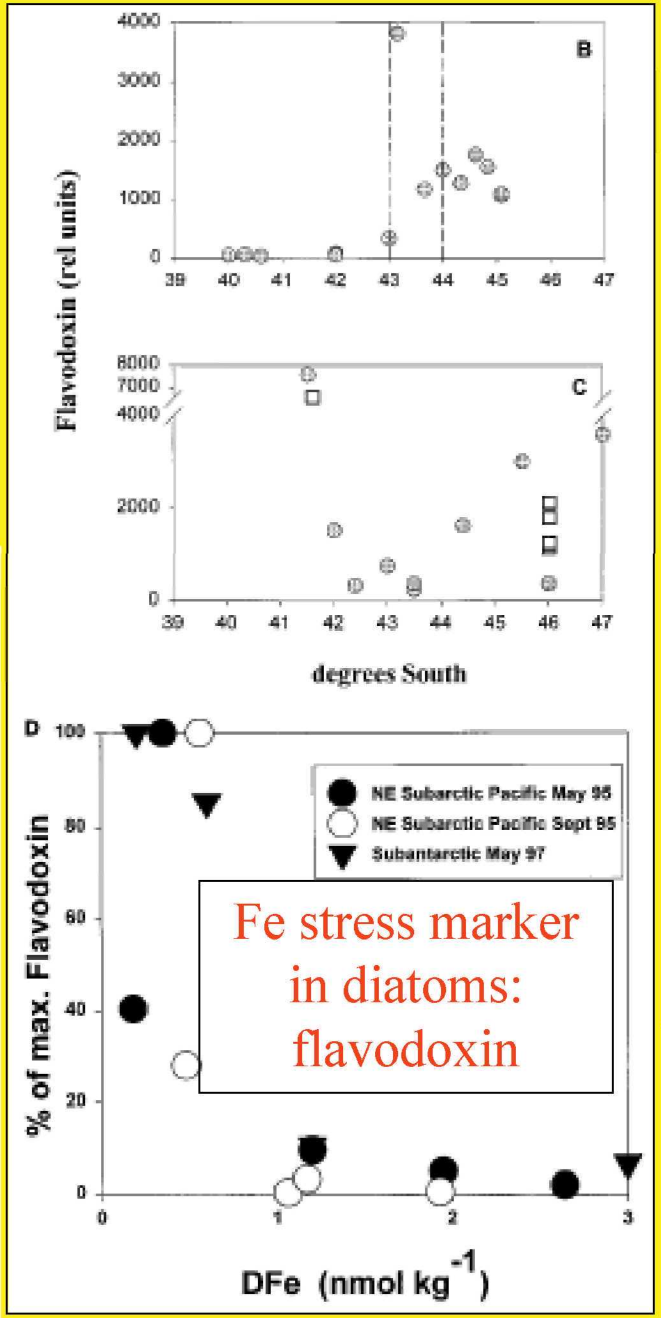
S. Ocean 1° Production Limited by Fe: SOIREE-2

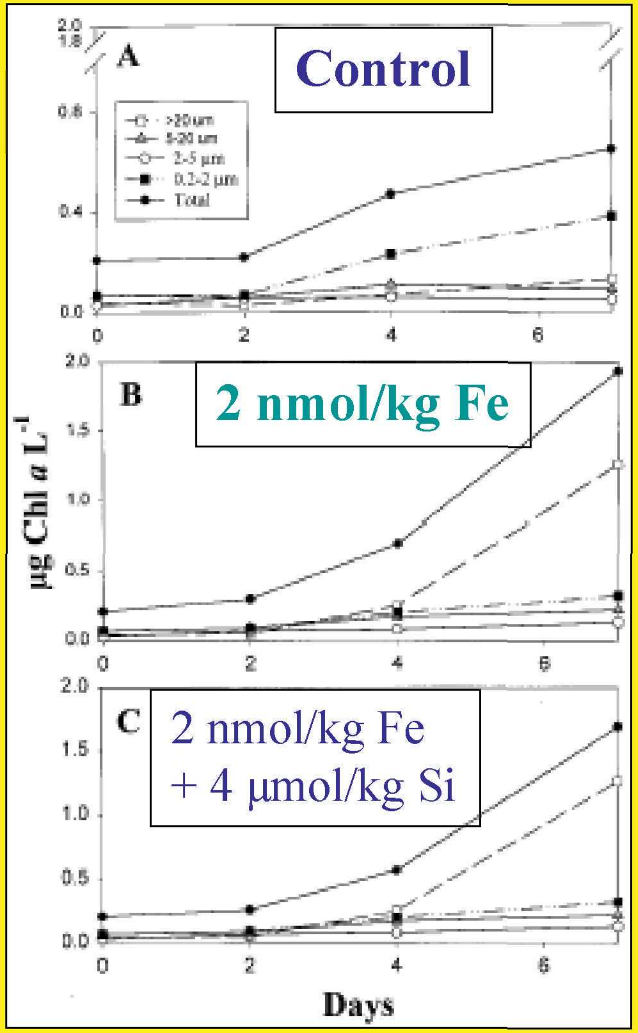


Boyd et al. (2000) *Nature*, Vol. 407: 695-701

In vitro Fe-Addition Experiment October, 1997 Subantarctic Water (F1)

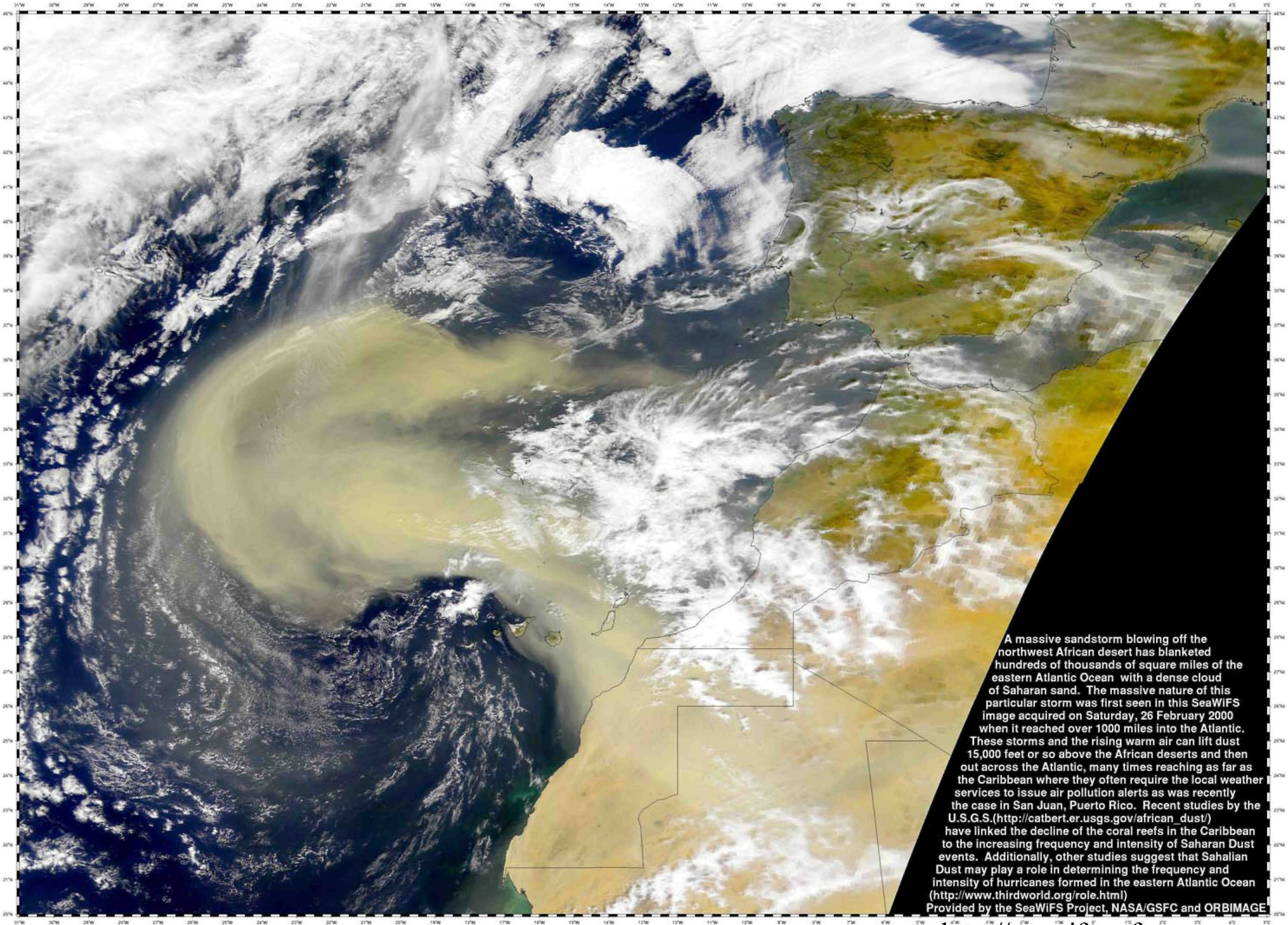






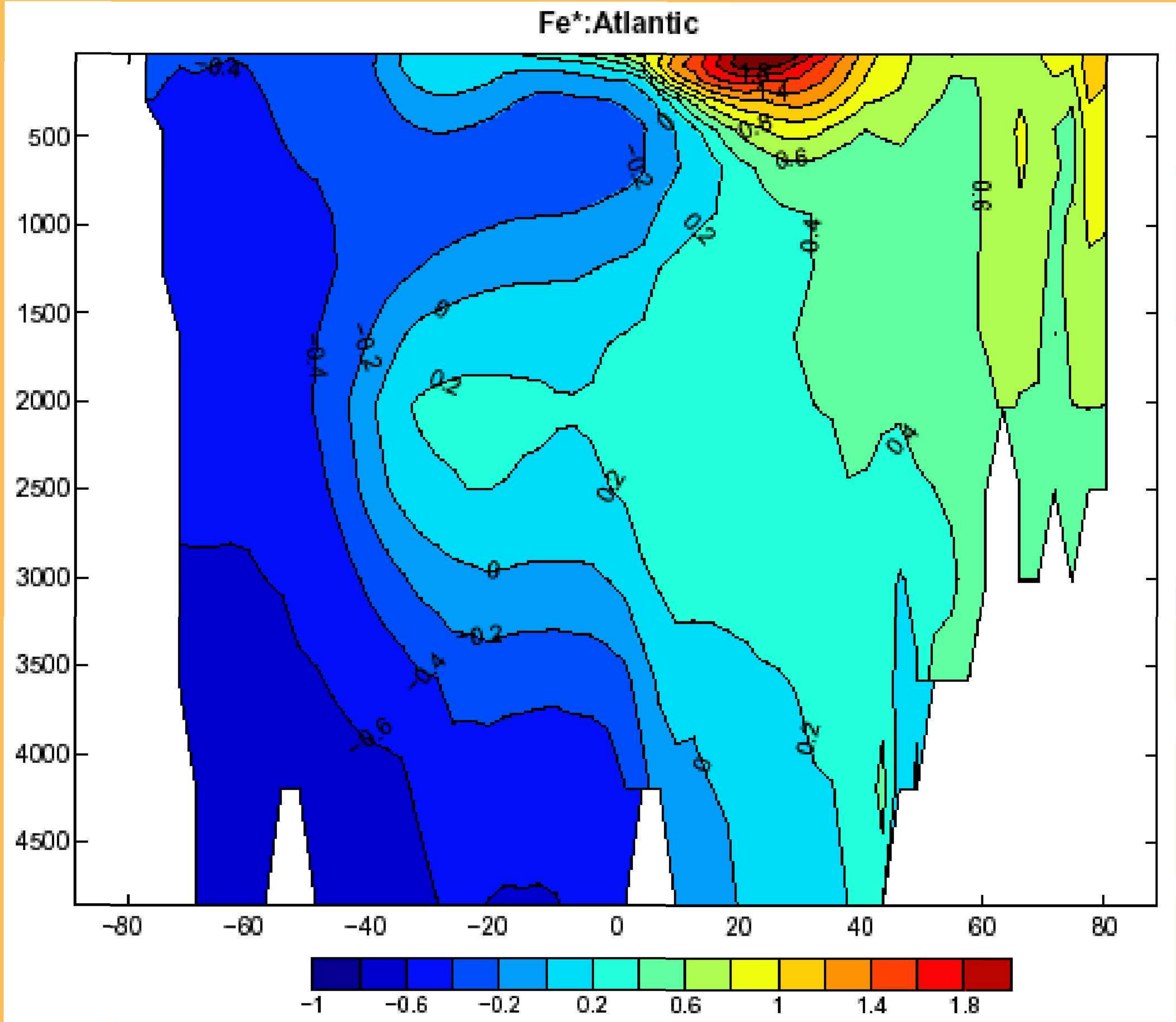
Fe-Limitation of 1° Production in Subantarctic water SE of New Zealand

Boyd et al (1999) *JGR*, 104(C6): 13,395-13,408



http://seawifs.gsfc.nasa.gov

N. Atlantic Deep Water Supplies Fe to the S.Ocean



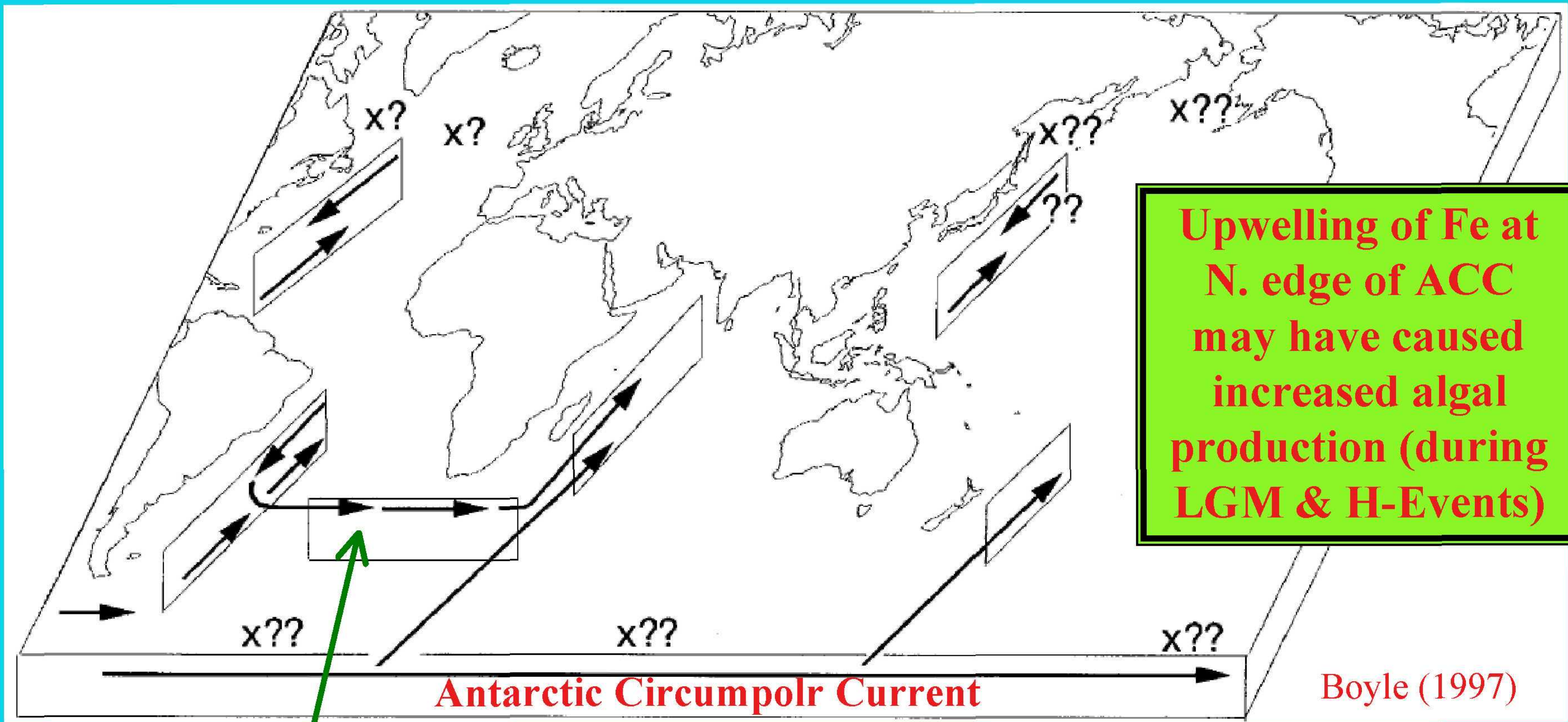
Fe* = Fe deficit (relative to PO_4^{3-})

$Fe^{*} = Fe - R_{Fe}PO_4$
$R_{fe} = Fe/PO_4$

Fe/C = 4μmol/mol
C/P = 117 mol/mol
Fe/P = 0.47 mmol/mol

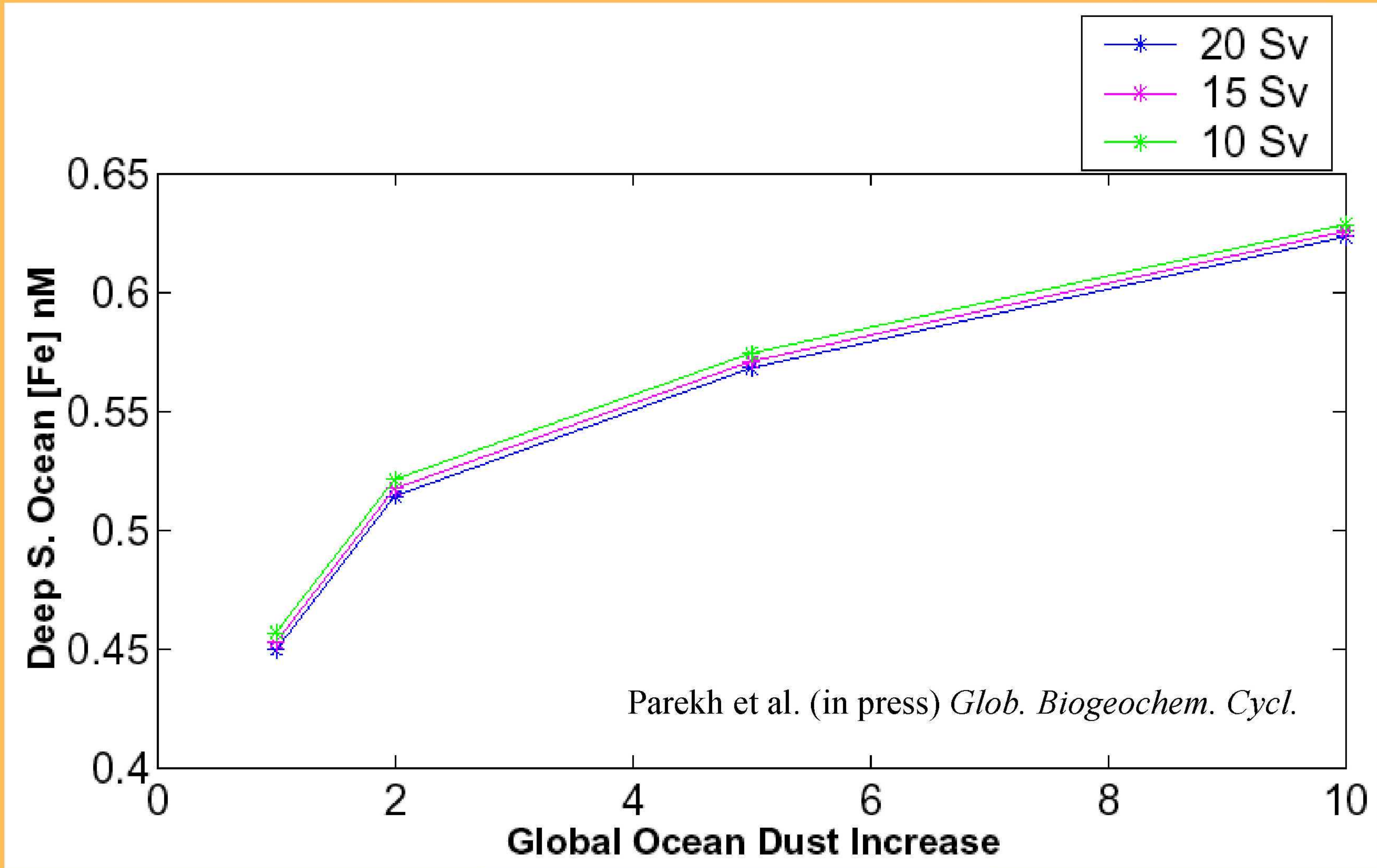
Payal Parekh (2003) Ph.D. Thesis, MIT-WHOI.

Possible LGM Deepwater Circulation



"A shallower variety of North Atlantic deep water will have a more difficult time reaching high latitudes of the Southern Ocean where it can be recycled into the bottom water. . . . Instead, any high-^{13}C water emerging beyond the tip of Africa might simply flow eastward into the Indian and Pacific basins, bypassing the Antarctic entirely." (Imbrie et al., 1992)

Irrespective of the style of N. Atl. Deep / Intermediate Water, S. Ocean [Fe] Likely increased w/ global dust flux during cold periods



Part II: Conclusions

Massive Iceberg Discharge Events in N Atlantic (Heinrich Events) Were Likely Associated With:

- Large productivity increases in Southern Ocean
  - May have been caused by increased [Fe]
- Warming of subantarctic SW Pacific
- Additional & longer SST records needed to determine spatial extent & evaluate causal links

Acknowledgements

Discussions
Ed Boyle (MIT)
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ODP (Bremen)

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Maria Shriver MIT)
Bridgette Therriault (MIT)
Zach Gazak (MIT)