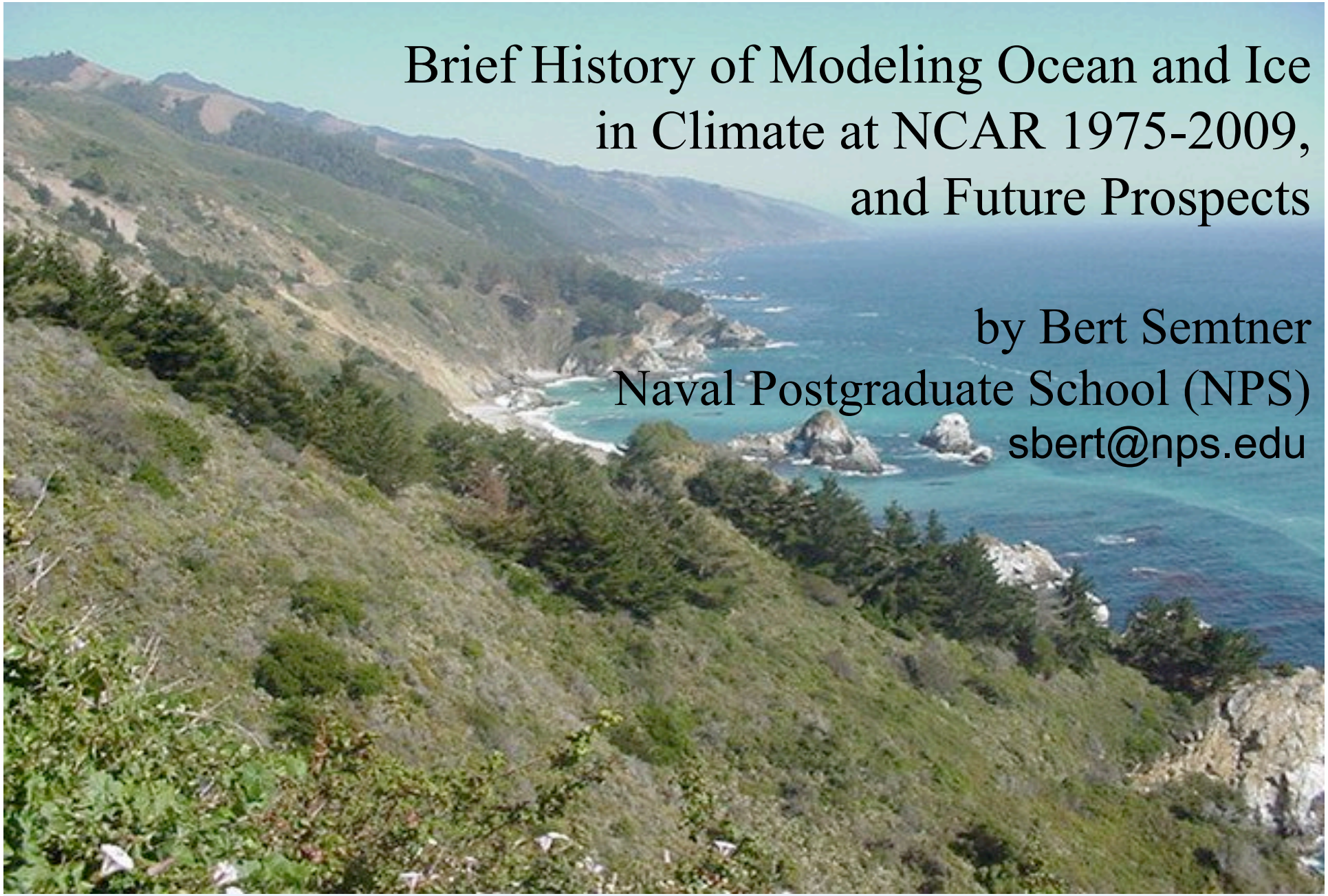


Brief History of Modeling Ocean and Ice in Climate at NCAR 1975-2009, and Future Prospects

by Bert Semtner
Naval Postgraduate School (NPS)
sbert@nps.edu

(based on frequent interactions with Warren Washington over the time period, as an NCAR employee during 1976-1986 and an NCAR Affiliate Scientist thereafter)

Warren's approach

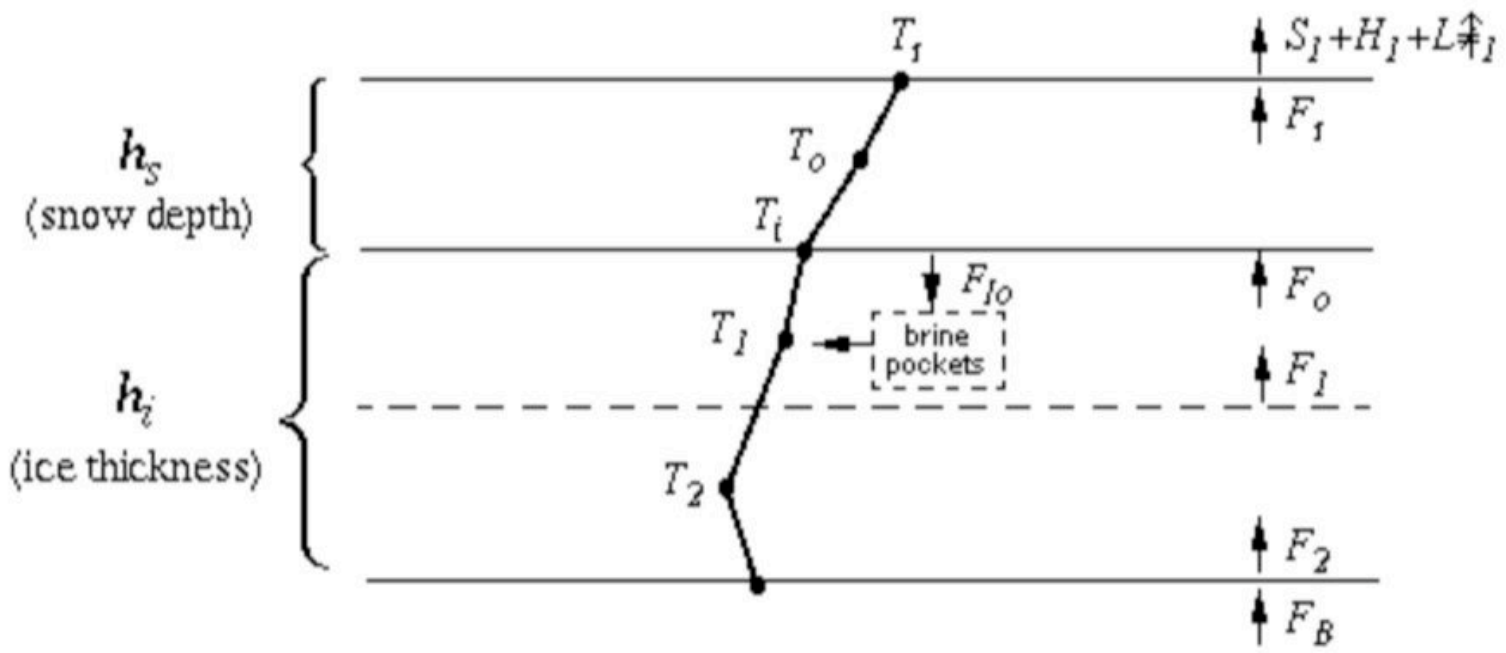
- Warren has had a clear goal over the years of making progress on the foremost scientific and societal problem of modern times, namely the prediction of global climate change.
- His strategy has been to use the best available coupled models and to run them at progressively higher resolution on the fastest available computers in order to better resolve crucial dynamical processes and surface features.
- He has been aided by DOE support from programs under Dave Bader to migrate models onto increasingly parallel computer architectures and to run them with support from him and Jay Fein of NSF on the fastest available NCAR and DOE machines, most recently in the context of CCSM, the Community Climate System Model.

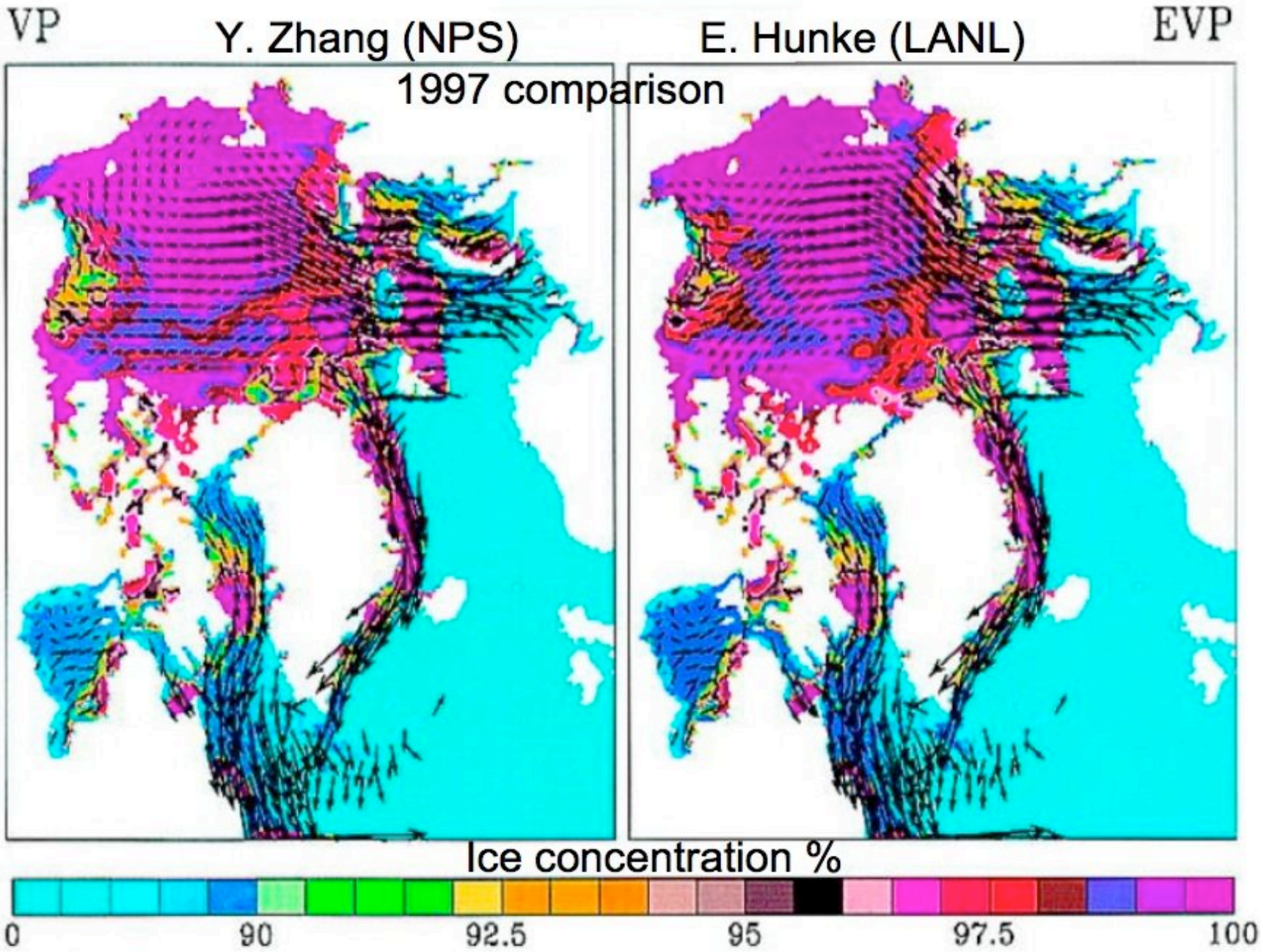
Ice

- The first step involved simplifying a complicated 1969 Maykut-Untersteiner model of sea-ice thermodynamics, which Semtner did in 1975 at the suggestion of Larry Gates. He then interacted with Warren Washington and Warren's PhD student Claire Parkinson, doing simulations on Arctic and Antarctic grids to validate the method geographically; and that formulation has persisted with continuing improvements by others into the latest form of CCSM.
- The dynamics of sea ice by Hibler in 1979 was harder to simplify and was most effectively accomplished by Hunke and Dukowicz in 1997 at Los Alamos by adding elastic waves for efficiency and parallelism while retaining the same yield curve. That approach was adopted by Warren for the DOE Parallel Climate Model in 2000 and now continues in CCSM as the Los Alamos CICE component.
- Recent improvements through 2006 have included having multiple categories of sea ice on grids as fine as 9 km. Glacial ice is now being included in CCSM as well.

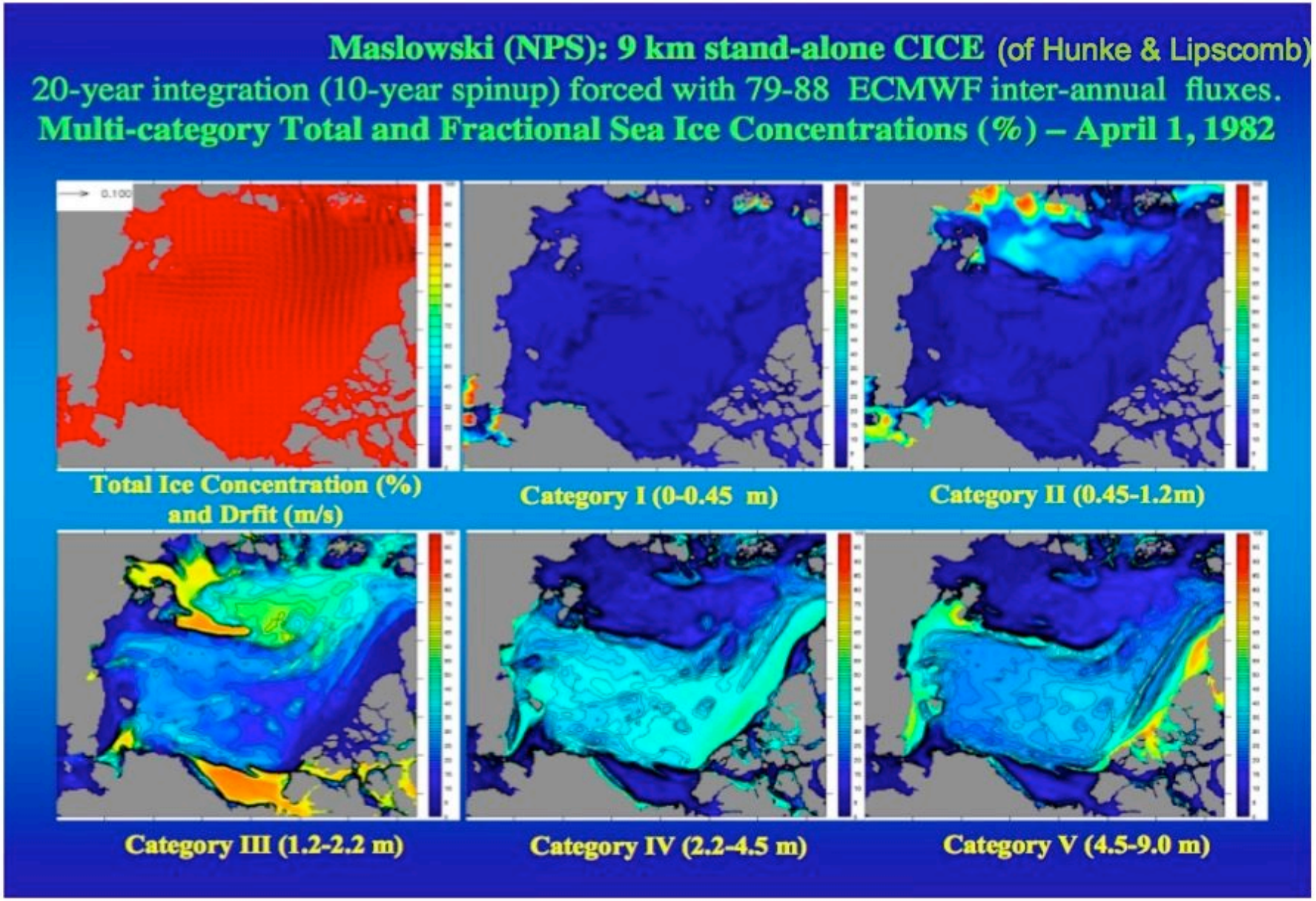
3-Layer Thermodynamic Model

(Semtner, 1976)




VP
Y. Zhang (NPS)
E. Hunke (LANL)
EVP
1997 comparison
Ice concentration %
0
90
92.5
95
97.5
100

A multi-category LANL-NPS ice simulation at ~1/10 degree (2006)



Ocean Climate Modeling -- early years

- *Kirk Bryan and Mike Cox's 1969* pioneering primitive-equation *World Ocean model* was re-designed by Semtner *1974* for upcoming vector machines like GFDL's TI-ASC. In *1984*, Mike Cox modified that code for long vectors required by their new CDC-205.
- *Semtner's vectorized code was adopted* and used on a CRAY-1 by Warren Washington at NCAR in 1977, leading to his *group's first coupled climate model paper in 1980* for a ~500 km grid. *Jerry Meehl became a key player* in both ocean-only and coupled model studies.
- At that time, *NCAR's Oceanography Section was using only quasi-geostrophic box models* with 20 km and 40 km grids to study recently discovered mesoscale eddies, versus using costly primitive-equation models.

Early Papers

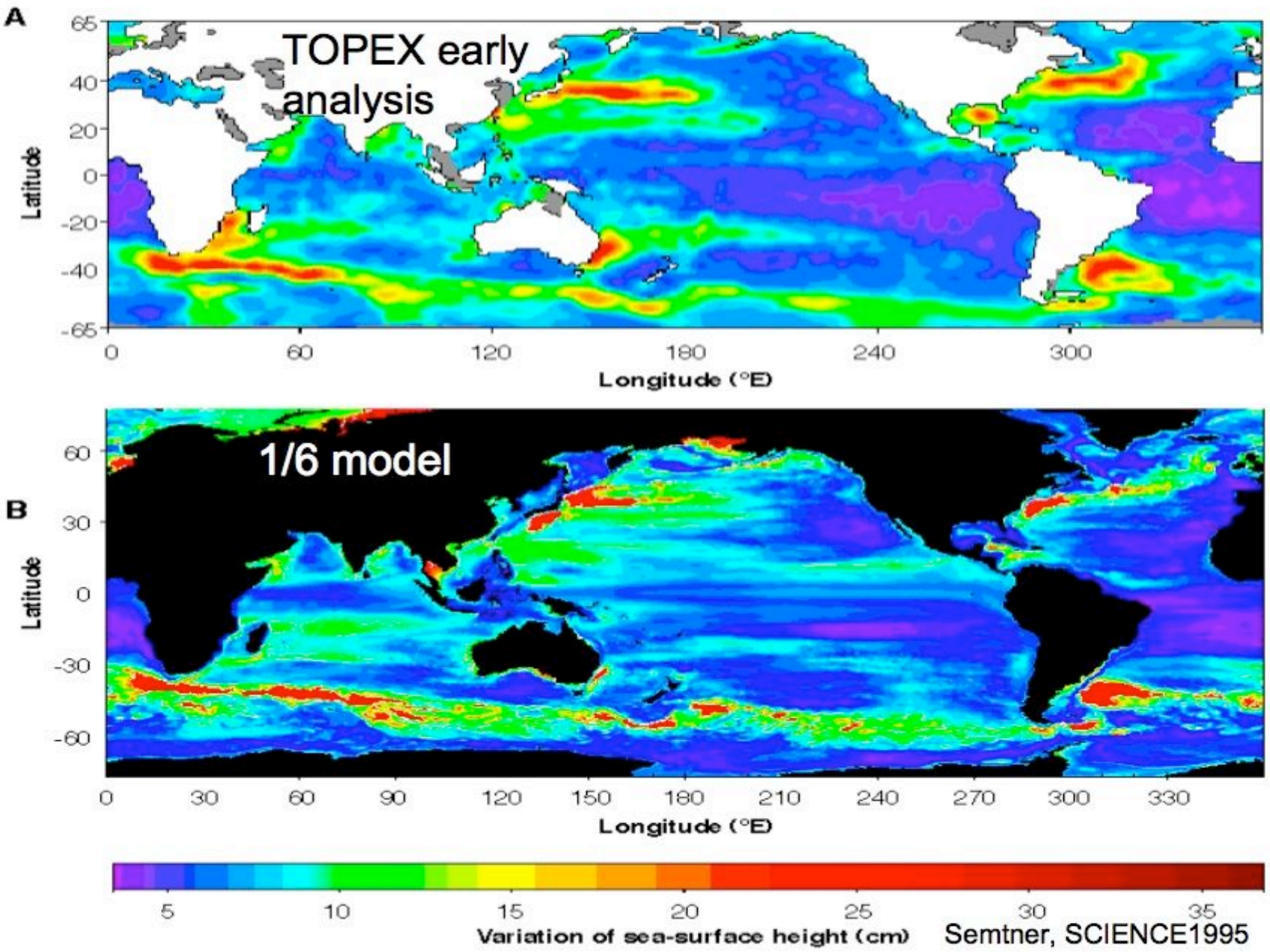
- Washington WM, Semtner AJ Jr, Meehl GA, Knight DJ, Mayer TA (*1980*) A general circulation experiment with a coupled atmosphere, ocean, and sea ice model. Journal of Physical Oceanography 10:1887-1908.

- Meehl GA, Washington WM, Semtner Jr AJ (1982) Experiments with a global ocean model driven by observed atmospheric forcing. Journal of Physical Oceanography 12:301-312.

- Washington, W. M., and G. A. Meehl (*1983*) General circulation model experiments on the *climatic effects due to a doubling and quadrupling of carbon dioxide* concentration. Journal of Geophysical Research, 88:6600-6610.

Ocean -- early studies with eddies for real domains

- *Semtner and Chervin 1988* began decadal integrations of a *parallelized version of Semtner's 1974 code with ~1/2 and ~1/4 degree global grids* (the latter with the help of Robin Tokmakian of NPS) on CRAY XMP, YMP, and C90 machines, utilizing all processors of those machines and a massive solid-state disk. The new code was called the Parallel Ocean Climate Model (*POCM*).
- *Smith, Dukowicz, and Malone 1992* at Los Alamos re-designed POCM for *massively parallel machines* to produce the Parallel Ocean Program (*POP*) under DOE's CHAMMP Program funding.
- Maltrud, Smith, Semtner, and Malone 1993 did a global POP run on a large CM-5 at Los Alamos using a ~1/6 degree grid.
- Bill Holland and Frank Bryan were running CME, a 1/3 degree North Atlantic Cox 1984 Model at NCAR and then a 1/6 degree version over the same time period, without having the multi-processor capability.
- *All the runs resolved mesoscale eddies to some degree*.


A
TOPEX early analysis
Latitude
65
40
20
0
-20
-40
-65
0
60
120
180
240
300
Longitude (°E)
B
1/6 model
Latitude
60
30
0
-30
-60
0
30
60
90
120
150
180
210
240
270
300
330
Longitude (°E)
5
10
15
20
25
30
35
Variation of sea-surface height (cm)
Semtner, SCIENCE1995

Early 1990s NCAR Climate Modeling

Washington and Meehl 1992 progressively advanced their coupled climate modeling studies to include:

- An *atmospheric spectral model of ~3.8 degree* equivalent grid size, *parallelized by Bob Chervin*
- A *parallel-vector 1-degree ocean* using POCM
- 3-layer sea-ice thermodynamics
- *Sea-ice dynamics streamlined to be that of a cavitating fluid* without lateral stresses, following Flato and Hibler 1992.

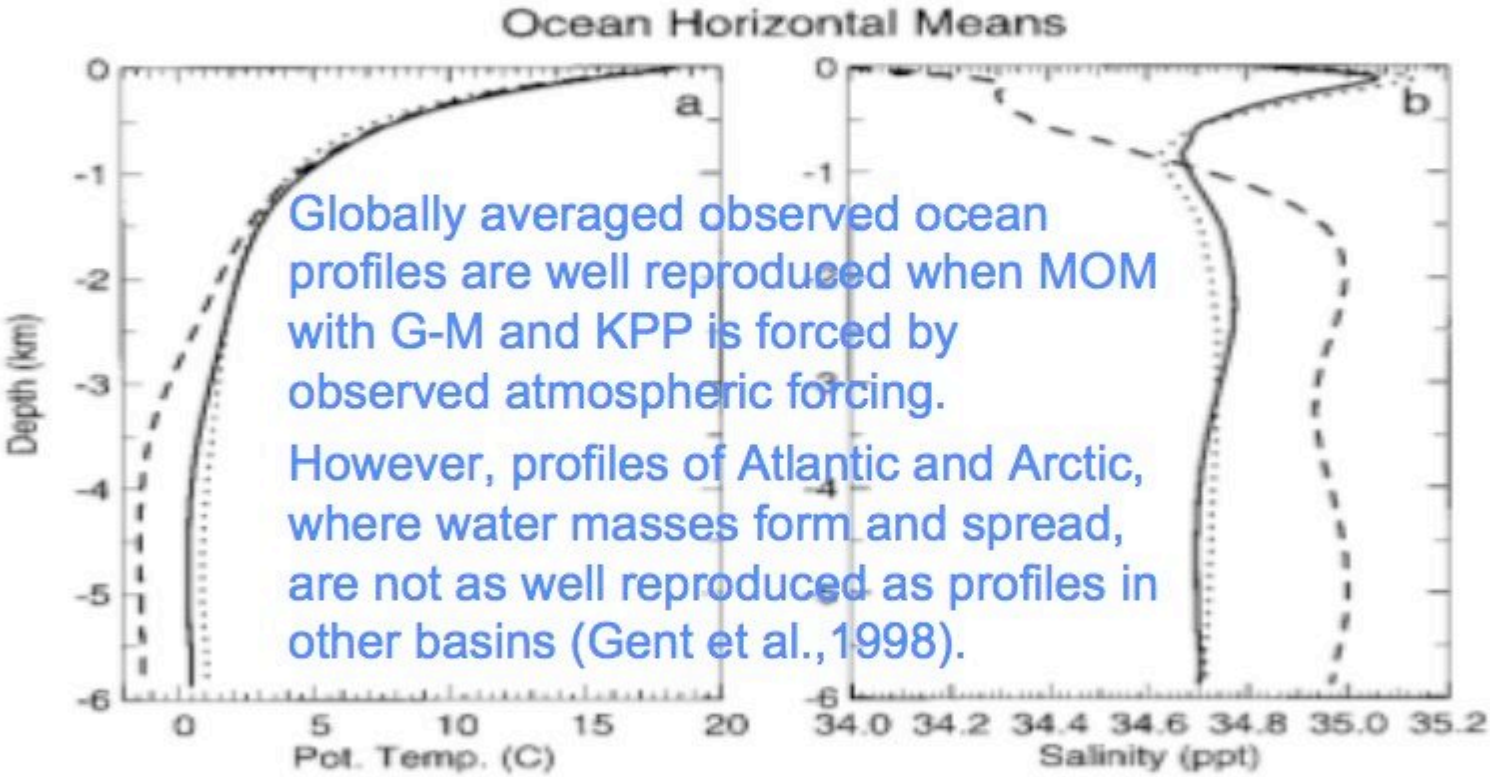
Their early climate-change results were included in the *IPCC Second Assessment Report* (AR2)

Climate with 2.4-deg ocean

- In 1997, Peter Gent and Jim McWilliams's 1990 parameterization of unresolved eddy effects was used for a *separate NCAR Climate System Model (CSM-1) effort using GFDL's well-supported MOM* (Modular Ocean Model) at 2.4 degrees. A K-profile parameterization (KPP) of Large et al. 1994 was also included. CSM-1 integrations were *successful without flux adjustments and included in the IPCC Third Assessment Report*, AR3.
- Not long thereafter, US vector machines became unavailable, and the *G-M eddy parameterization and KPP* were added into POP by Smith and Gent for further CSM modeling.

Vertical Profiles with G-M and KPP

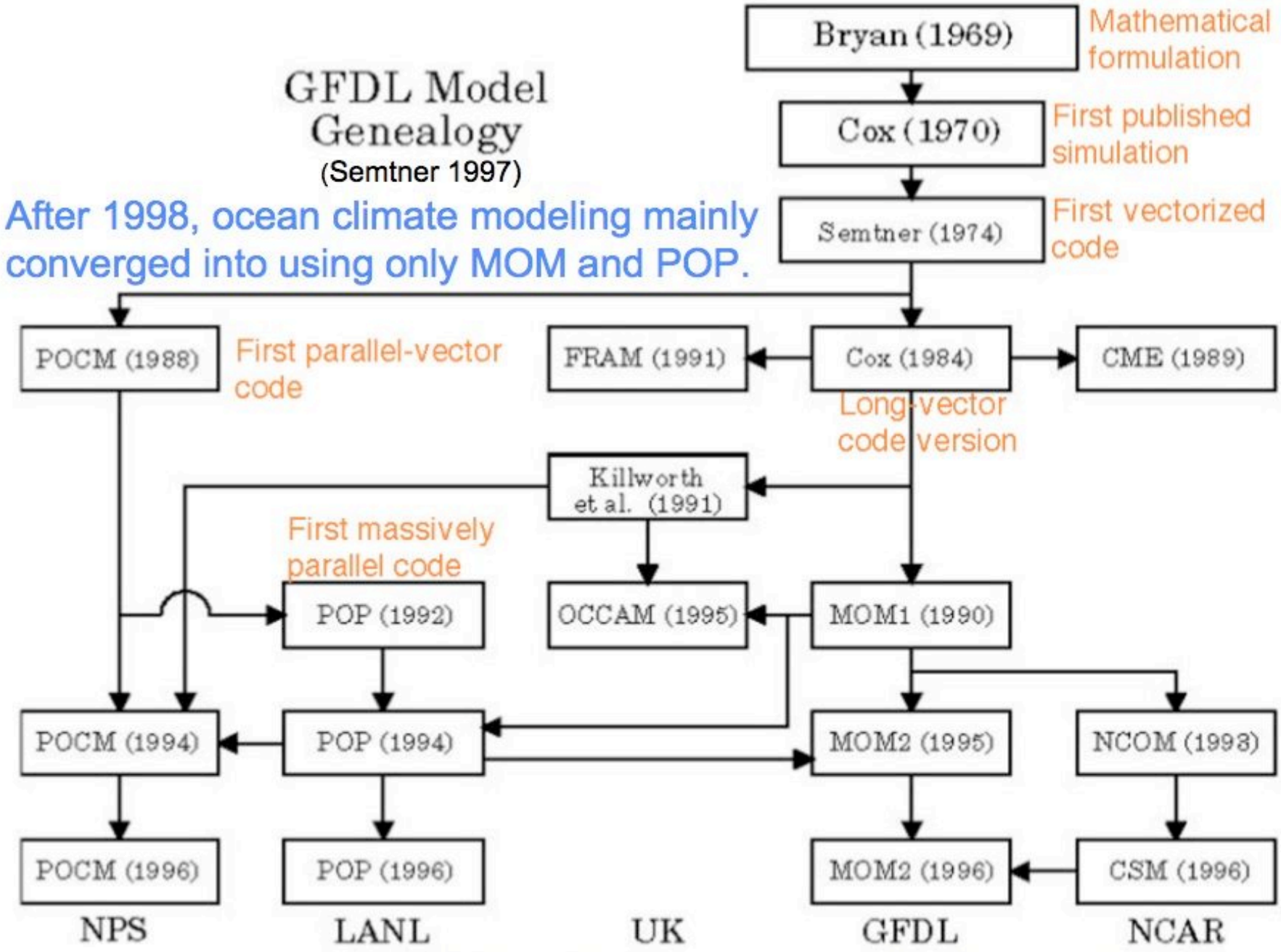
Boville and Gent,1998



Globally averaged observed ocean profiles are well reproduced when MOM with G-M and KPP is forced by observed atmospheric forcing.

However, profiles of Atlantic and Arctic, where water masses form and spread, are not as well reproduced as profiles in other basins (Gent et al.,1998).

FIG. 16. (a) Area-averaged potential temperature and (b) area-averaged salinity plotted against depth. The curves are the Levitus climatology (dotted), uncoupled NCOM equilibrium (solid), and the average of years 250–300 of the fully coupled run (dashed).


GFDL Model Genealogy
(Semtner 1997)
After 1998, ocean climate modeling mainly converged into using only MOM and POP.
Bryan (1969)
Mathematical formulation
Cox (1970)
First published simulation
Semtner (1974)
First vectorized code
POCM (1988)
First parallel-vector code
FRAM (1991)
Cox (1984)
CME (1989)
Long-vector code version
Killworth et al. (1991)
First massively parallel code
POP (1992)
OCCAM (1995)
MOM1 (1990)
POCM (1994)
POP (1994)
MOM2 (1995)
NCOM (1993)
POCM (1996)
POP (1996)
MOM2 (1996)
CSM (1996)
NPS
LANL
UK
GFDL
NCAR

Climate with 2/3-deg ocean

- Washington et al. 1998 produced the *Parallel Climate Model* for Massively Parallel Processors via an *NCAR, LANL, NPS collaboration* and conducted extensive PCM climate change simulations, with 2.8-degree NCAR atmosphere, *~2/3 degree POP, and 27-km CICE*, under continuing *DOE sponsorship*.
- The PCM model and its output were widely distributed and analyzed; and *it contributed to both the 3rd and 4th IPCC Assessments*. Time evolution and spatial patterns of climate change were consistent with results from other major models.

---

* Washington, W. M., J. M. Weatherly, G. A. Meehl, A. J. Semtner, Jr., T. W. Bettge, A. P. Craig, W. G. Strand, Jr., J. M. Arblaster, V. B. Wayland, R. James, Y. Zhang, 2000: Parallel Climate Model (PCM) control and transient simulations. *Clim. Dyn.*, **16**, 755-774

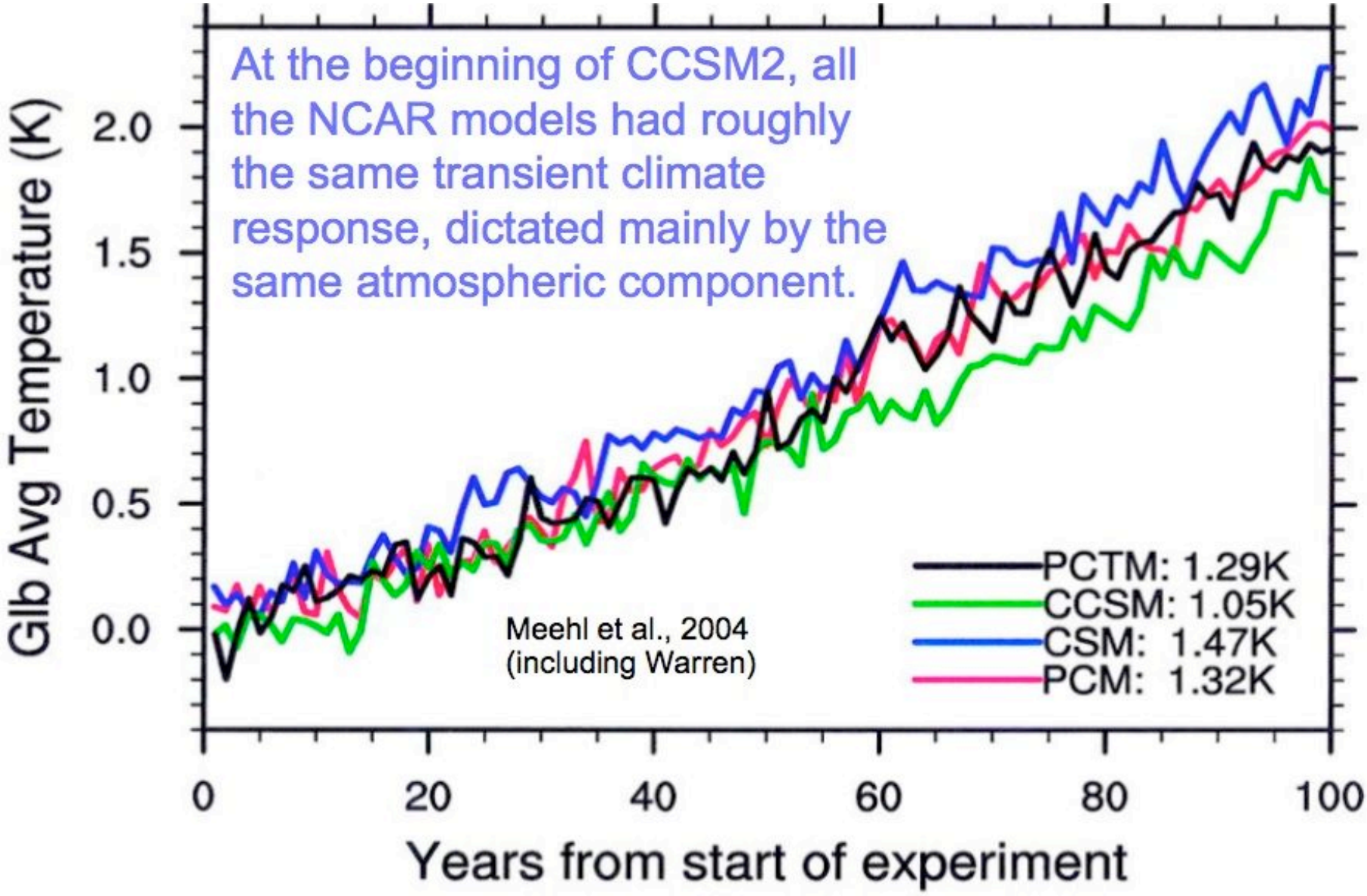
Analysis of the High-resolution Ocean Output

Detection of Anthropogenic Climate Change in the World's Oceans
Tim P. Barnett et al., SCIENCE, 2001

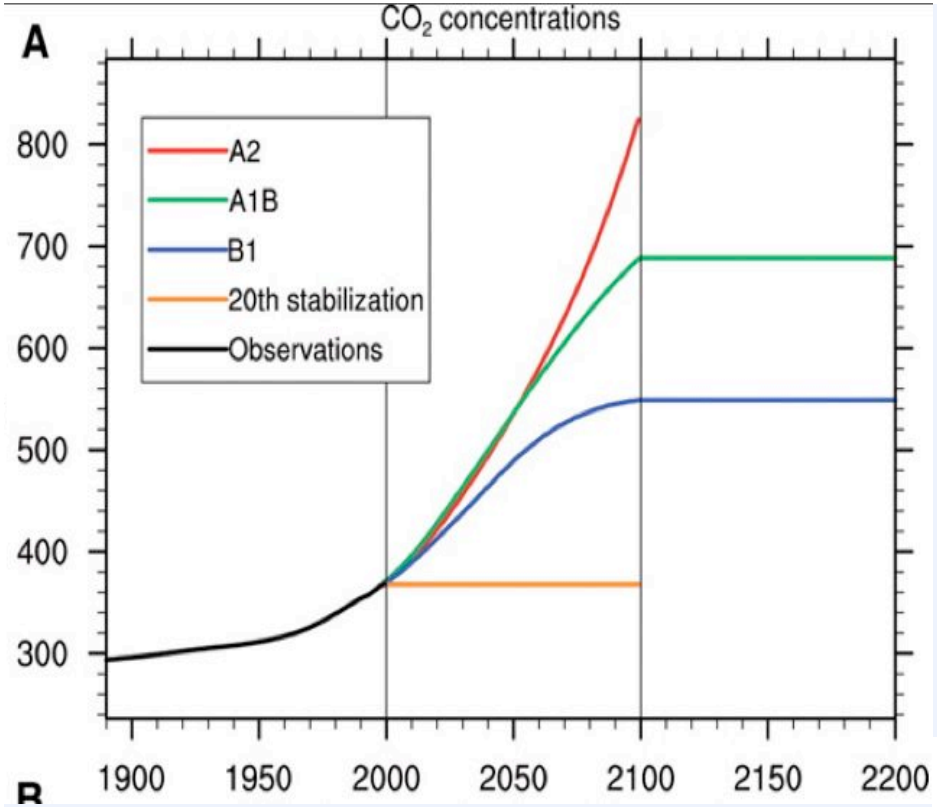
- "*Large-scale increases in the heat content of the world's oceans* have been observed to occur *over the last 45 years*. The horizontal and temporal character of these changes has been closely replicated by the state-of-the-art Parallel Climate Model (PCM) forced by observed and estimated anthropogenic gases."
- "Application of optimal detection methodology shows that *the model-produced signals are indistinguishable from the observations at the 0.05 confidence level*."
- "This suggests that the observed ocean heat-content changes are consistent with those expected from anthropogenic forcing, which *broadens the basis for claims that an anthropogenic signal has been detected in the global climate system*."

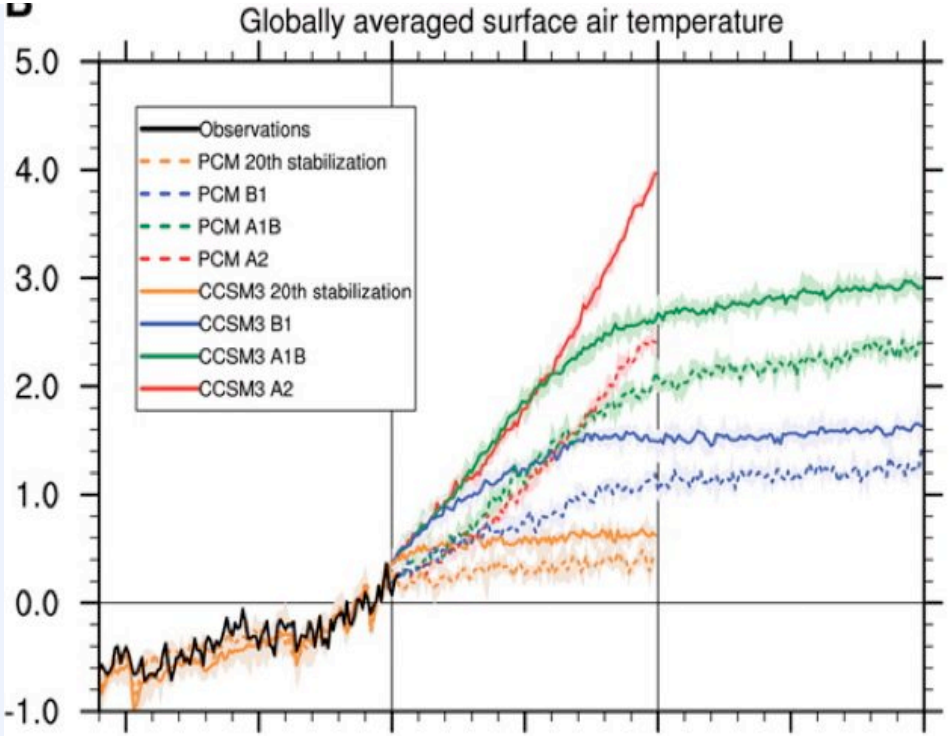
Community Modeling

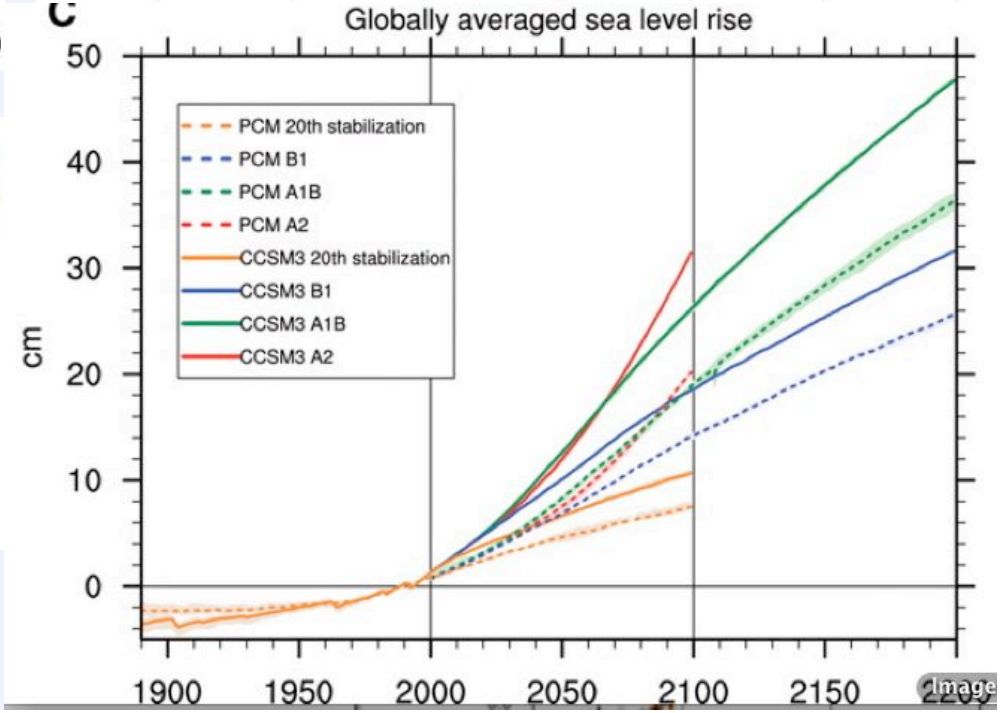
- *In 2000, Warren's effort joined with the CSM effort in a newly constituted CCSM*, in order to pool the collective expertise and more thoroughly explore aspects of climate and climate change.
- The atmosphere was an updated CSM component, whereas the *ocean was an updated POP and the ice was an updated CICE*.
- Warren Washington and Jerry Meehl became co-chairs of a new CCSM2 *Climate Change Working Group*.
- For IPCC AR4, CCSM3 integrations 2005 totaled 10,800 yrs with a *1.4-deg (T85) atmosphere, ~1-deg. ocean*.
- Continuing global ocean refinements are now mainly the joint responsibility of the NCAR Oceanography Section and the LANL ocean group through the Ocean Model Working Group of CCSM.



For 1% annual CO2 increase, all the models occasionally experience decreases of a few tenths of a degree lasting up to a decade; and such events must be expected in the real climate system.







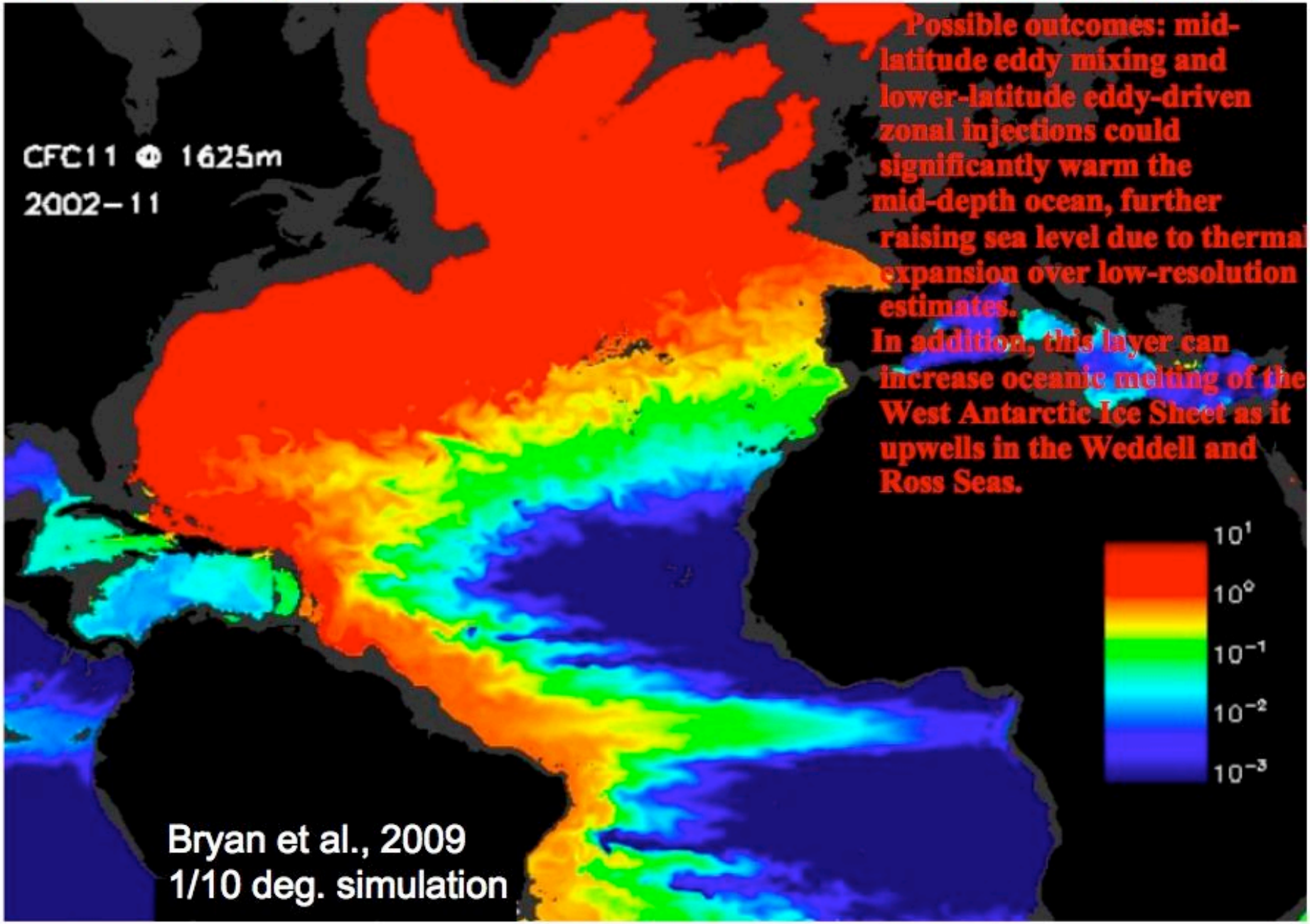
Some key results for IPCC

(Meehl et al., 2005: How much more warming and sea level rise? *Science*, **307**, 1769—1772) (including Warren)

Future Prospects

- Recent *global ocean modeling at NCAR on a 1/10 degree grid* by Bryan (NCAR), McClean (NPS-SIO-LLNL), and Maltrud (LANL) shows excellent eddy resolution of processes important to accurate climate simulation. Promising 1/10 global POP runs were made by those investigators on the Japanese Earth Simulator in 2003.
- *The 1/10 POP ocean model is coupled to an improved atmospheric model having ~ 50 km grid in CCSM4* for decadal studies in support of IPCC AR5. The coupled model has already been run for hundreds of simulated years in an NSF PetaApps simulation 2009.
- The CCSM4 configuration can migrate onto emerging NSF and DOE petaflop computers; and Warren and his colleagues will then want to examine how longer-term ensemble climate projections are affected.

Freon spreading at depth suggests pathways for human-induced warming!



Summary of NCAR developments over the course of Warren's career

- **Historical Sea-Ice Progression**: *efficient thermodynamics* => free drift => implicit VP => cavitating fluid => *explicit parallel EVP dynamics* => grids as fine as 9 km and multi-category ice
- **Historical Ocean Climate Progression**: global ocean-only models: no eddies => somewhat resolved => well resolved at 0.1 deg; *atmosphere* / ocean models: *5.0* / 5.0 deg. => 3.8 / 1.0 => 2.8 / 2.4 => 2.8 / 0.67 => 1.4 / 1.0 => *0.5* / 0.1 deg.*)*

CSM PCM CCSM3 CCSM4

Impressive increases in resolution since CSM in 1997 are mainly due to massive parallelism and the pioneering efforts of Warren and his sponsors and collaborators to take advantage of growing numbers of processors.