Ocean reanalysis for Climate reconstruction: SODA

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- Water masses & basic dynamics
- Simple Ocean Data Assimilation construction
- A few results

Atlantic water masses

Temperature

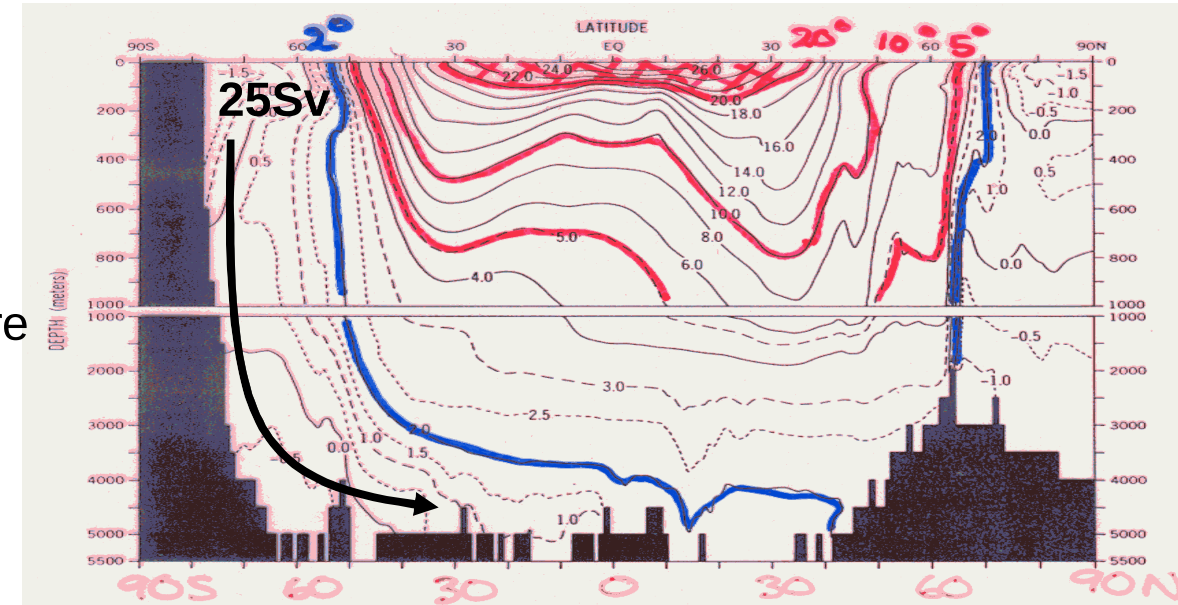


Figure 110.—Annual mean Atlantic zonal average (by one-degree squares) of potential temperature (°C).

Salinity

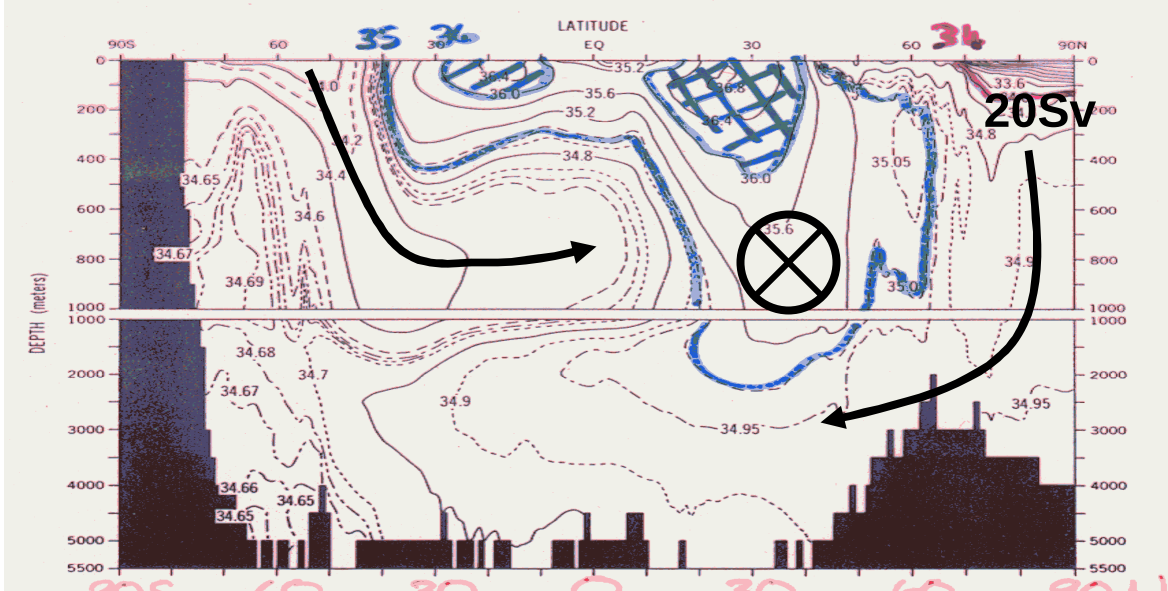


Figure 111.—Annual mean Atlantic zonal average (by one-degree squares) of salinity (°/..).

1Sv = 10^6 m^3/s

Conservation of T/S

Atlantic O_2 concentration

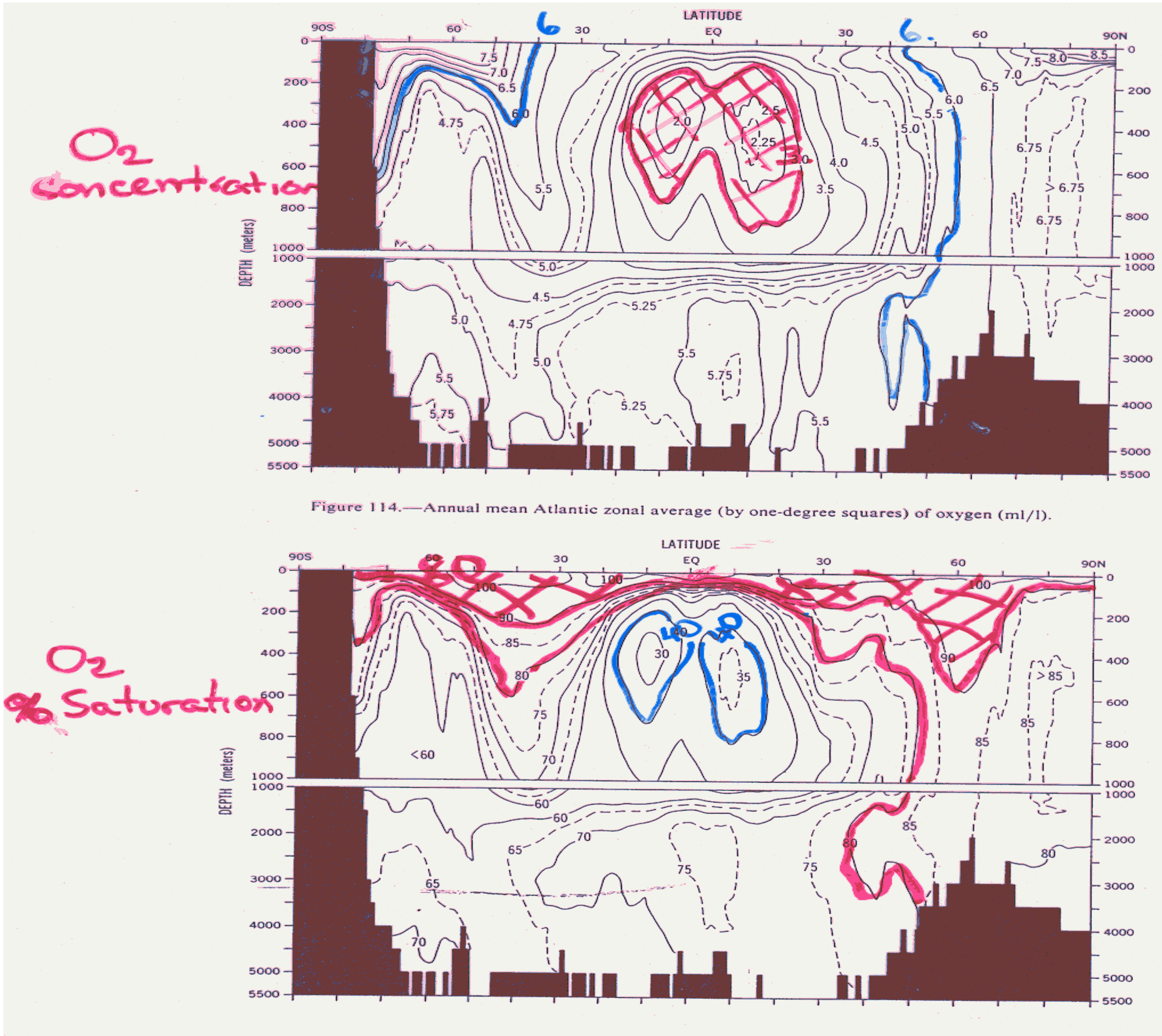
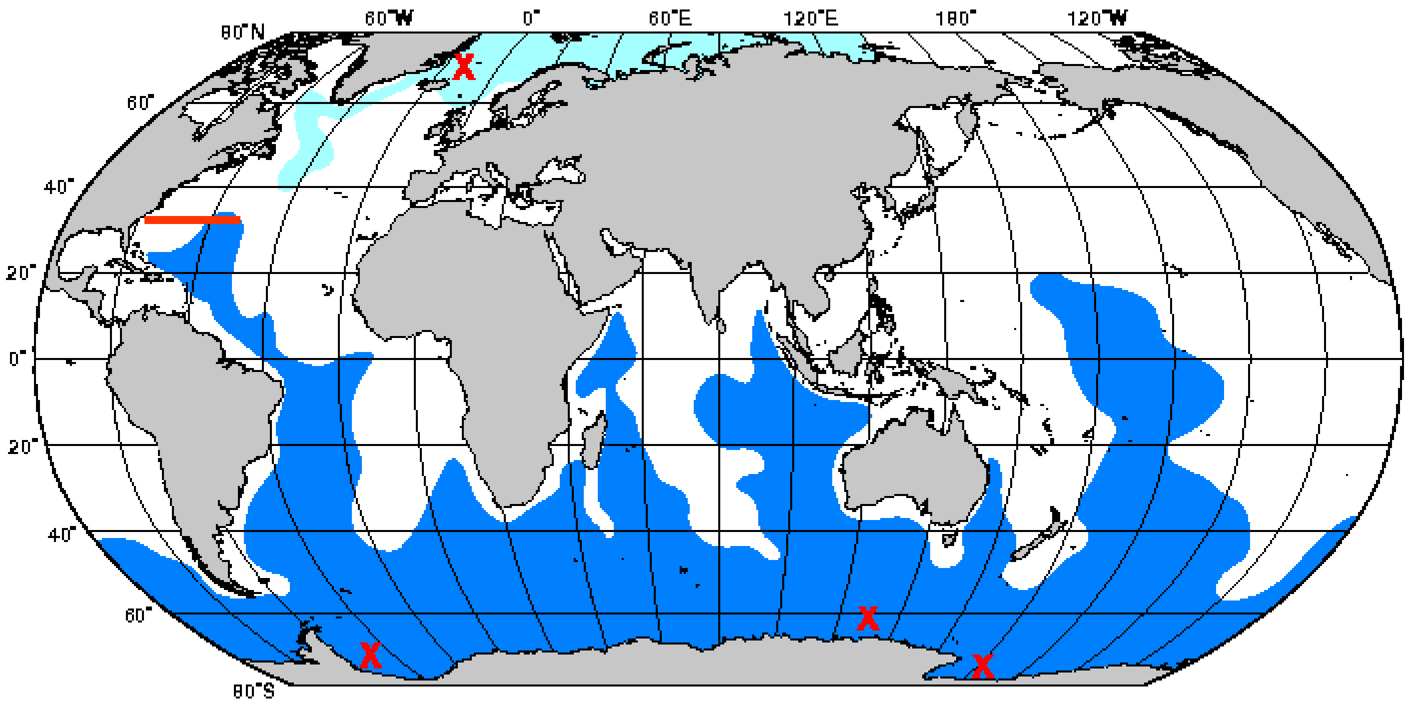


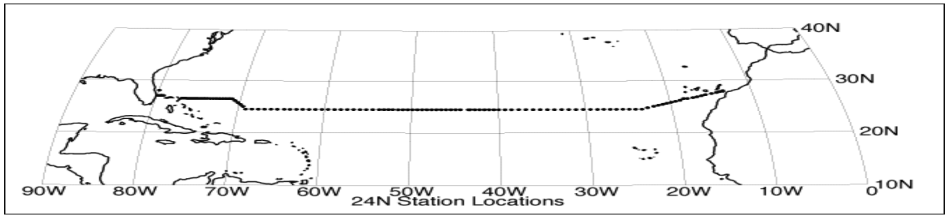
Figure 114.—Annual mean Atlantic zonal average (by one-degree squares) of oxygen (ml/l).

Penetration of bottom water into World Ocean (Lynne Talley, SIO)



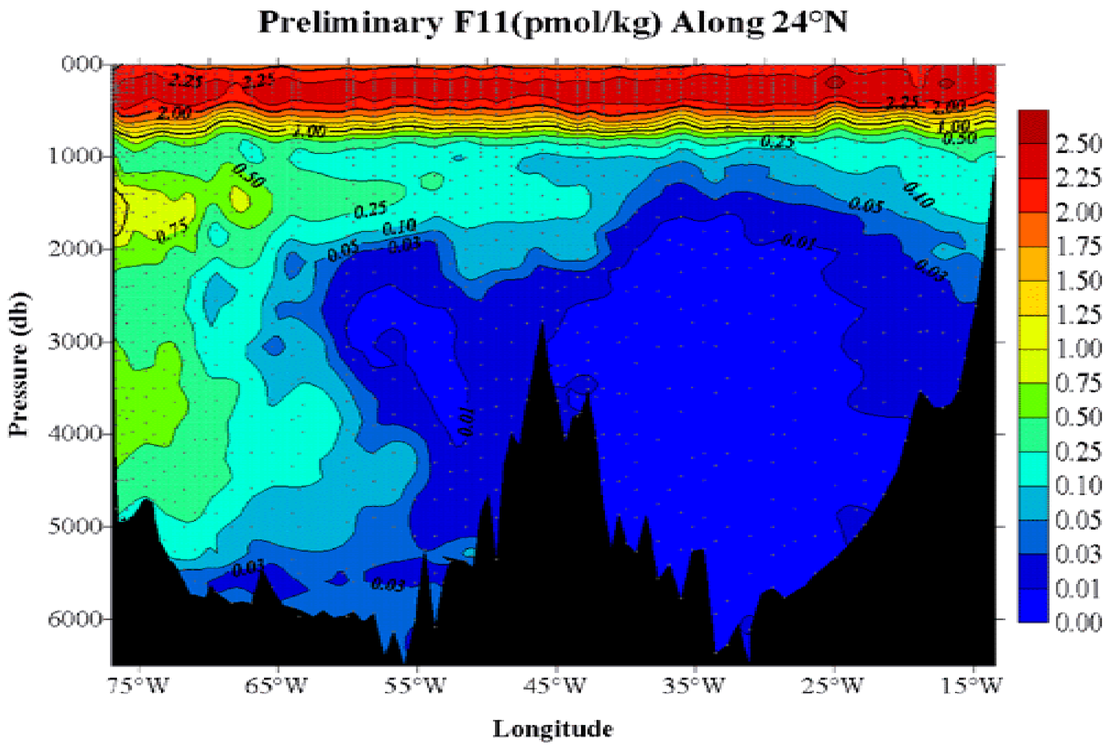
CFCs along 24N

Note North Atlantic Deep Water moving southward along western boundary

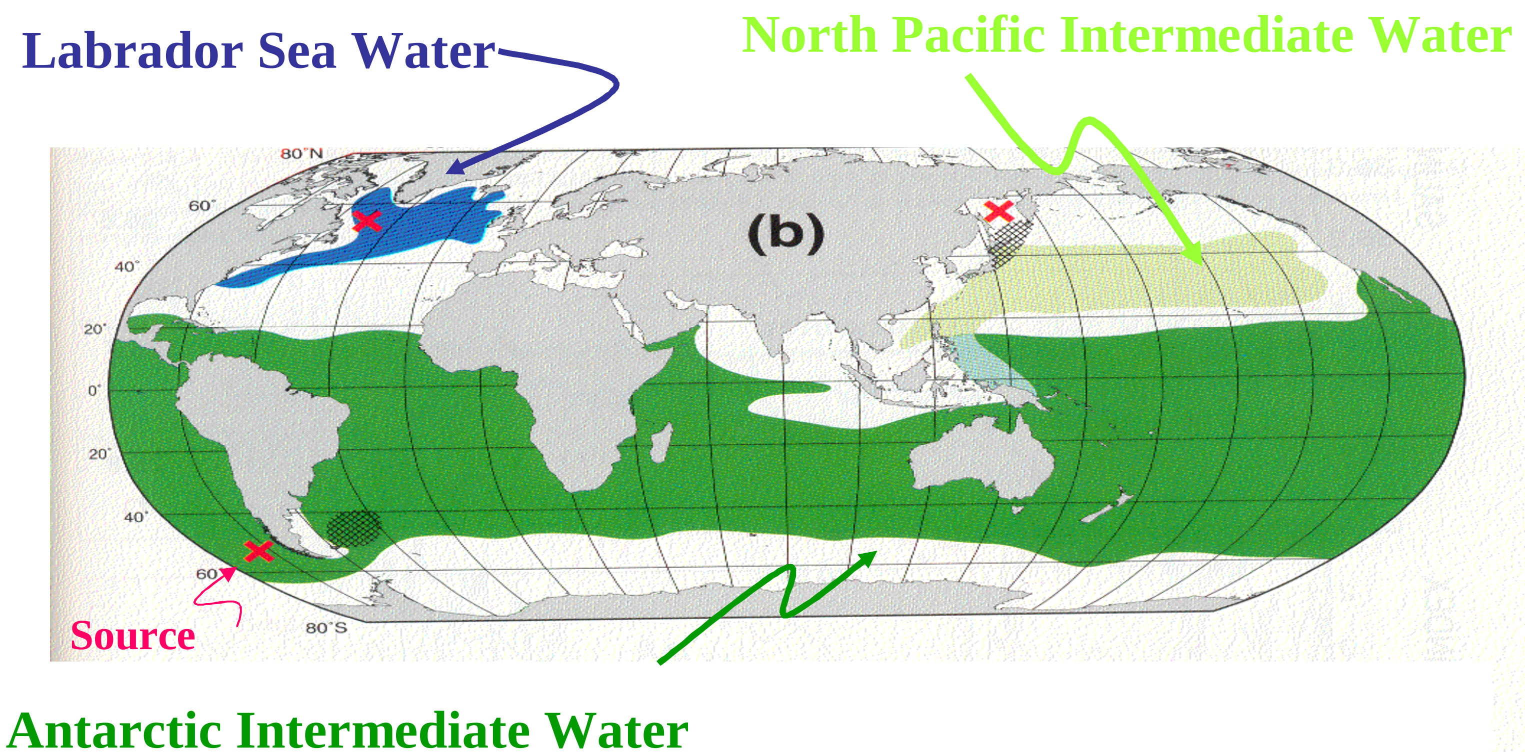


UNADW

LNADW



Penetration of intermediate water masses

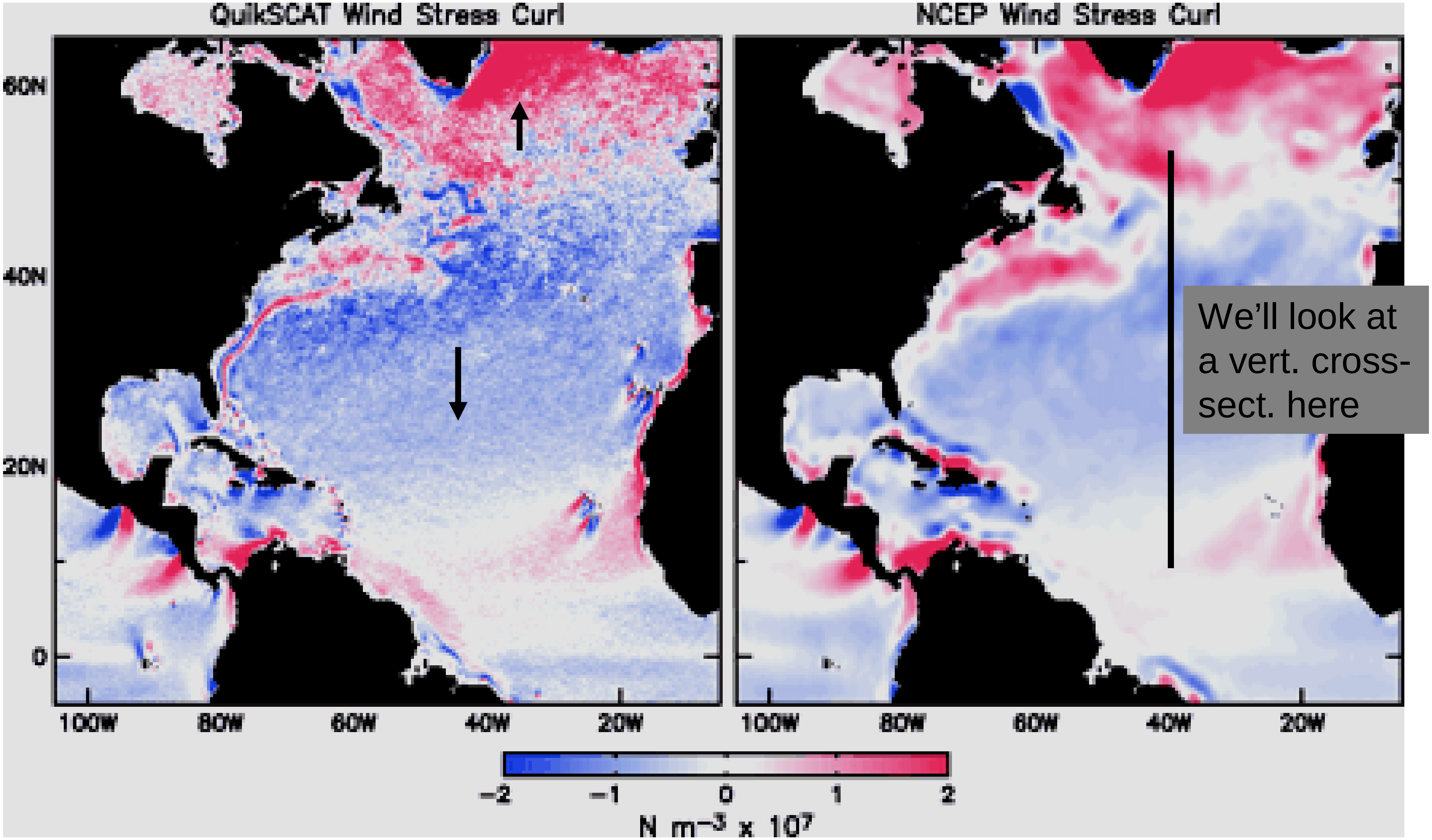


(Talley, 1999)

PV-conserving dynamics in the upper ocean

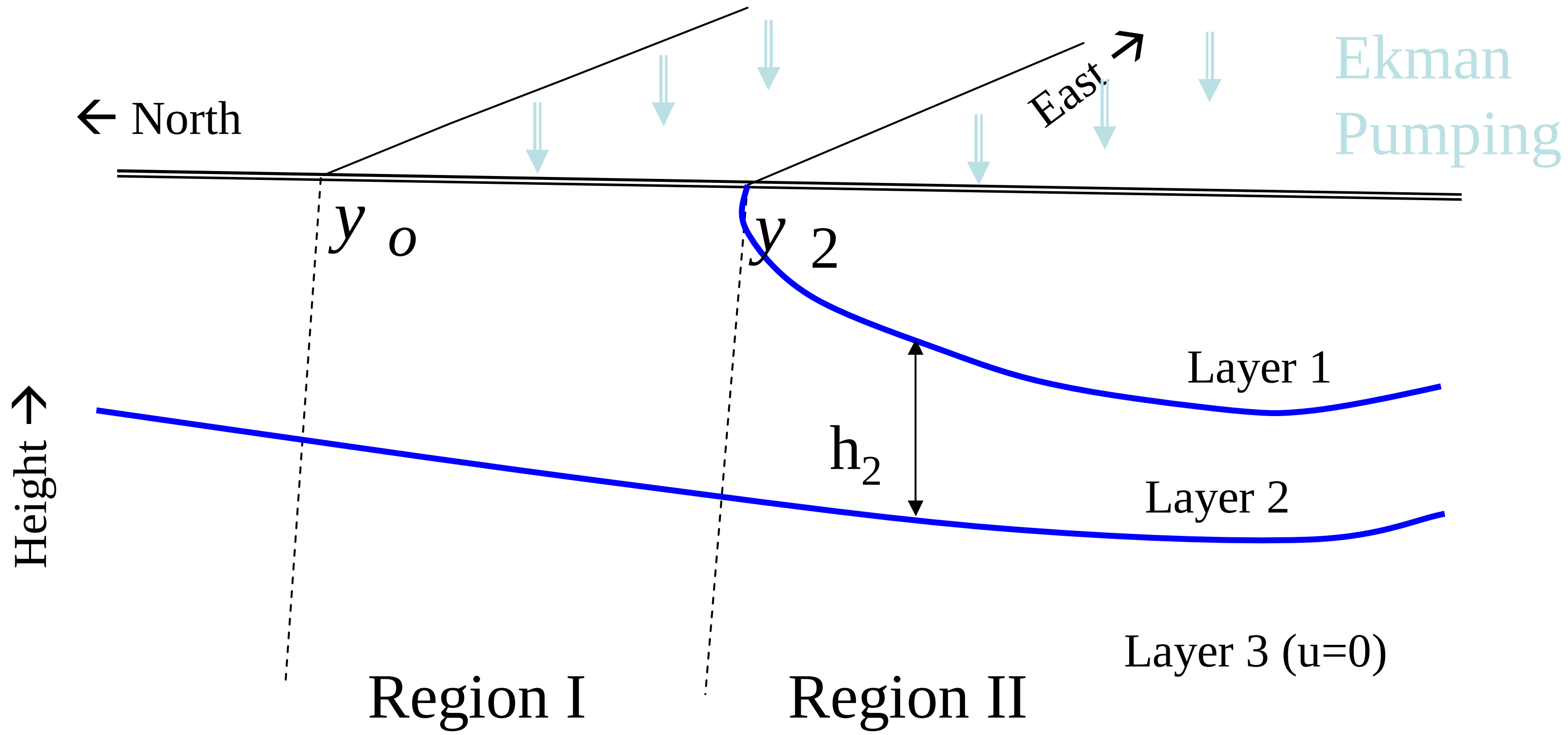
$$\frac{\partial \varsigma}{\partial t} + f\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + \beta v = curl(\tau)$$

Near-surface vorticity source: wind stress curl



Chelton et al., Science, 2004 http://www.sciencemag.org/cgi/content/full/303/5660/978/FIG2

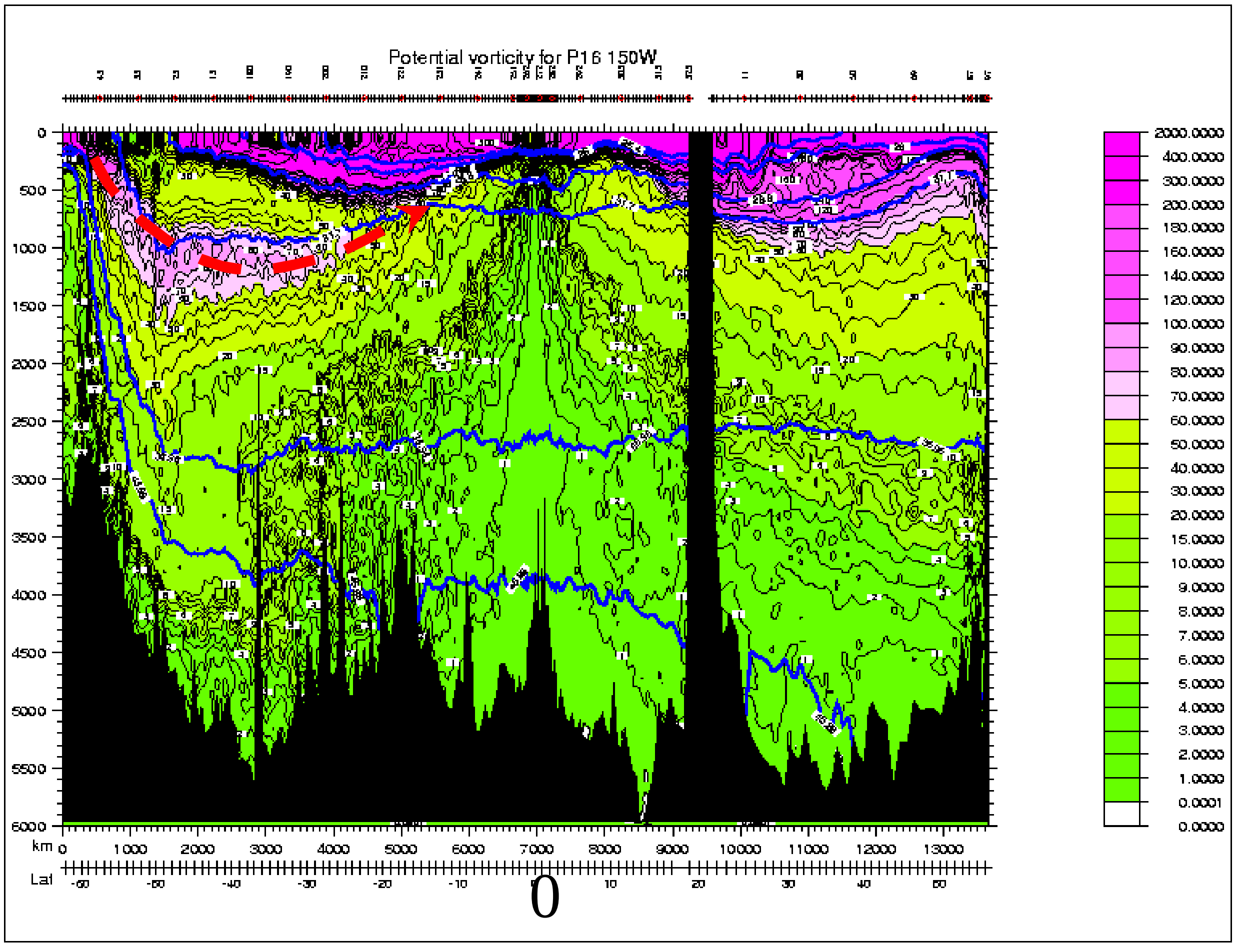
Two Layer model



Potential vorticity: $q=f/h_2$

Potential vorticity evaluated along a meridional transect through the Pacific

$$(\varsigma + f) - f\int \frac{\partial w}{\partial z} dt$$



Depth →

Latitude →

Simple Ocean Data Assimilation
a reanalysis for 1958-2006

The model

$$\frac{D\vec{U}}{Dt} + \underbrace{2\vec{\Omega} \times \vec{U} = -\frac{\nabla p}{\rho_o}}_{\textbf{Geostrophy}} + \kappa \nabla^2 \vec{U} + \upsilon \frac{\partial^2 \vec{U}}{\partial z^2} - g\hat{k}$$

$$\upsilon \frac{\partial \vec{U}}{\partial z}(z=0) = winds$$

$$\nabla \cdot \vec{U} + \frac{\partial w}{\partial z} = 0$$

$$\frac{DT}{Dt} = \kappa \nabla^2 T + \upsilon \frac{\partial^2 T}{\partial z^2} + heating$$

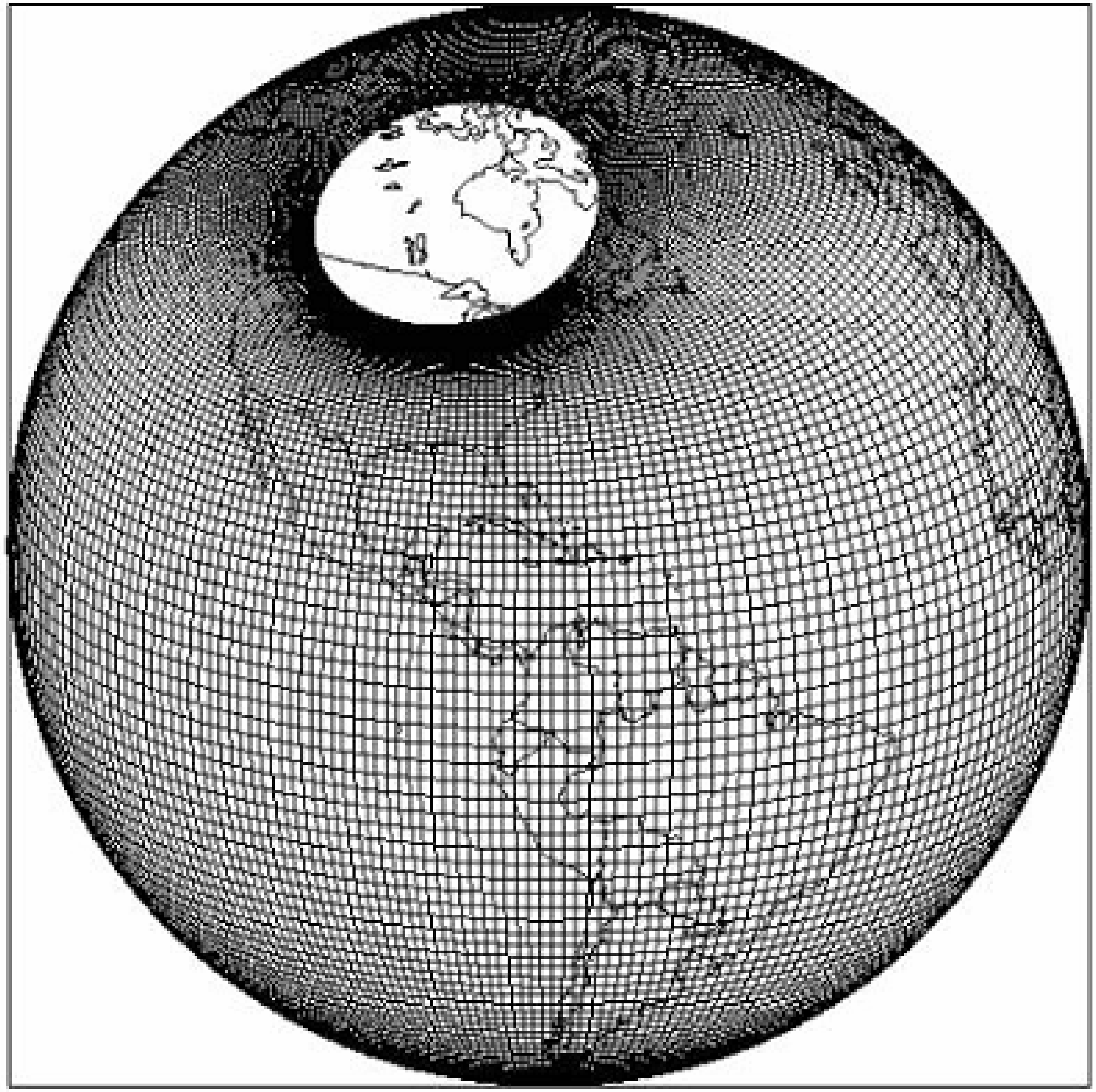
$$\frac{DS}{Dt} = \kappa \nabla^2 S + \upsilon \frac{\partial^2 S}{\partial z^2} + salt\,flux$$

Displaced pole horizontal grid

900x720x40 =
25M grid points

State Variables:
u, v, T, S, …

Time step:
20min (26K ts/yr)

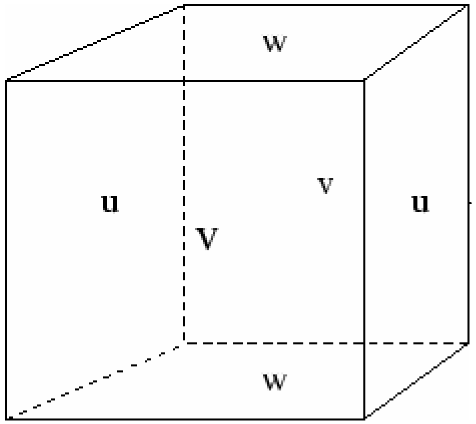


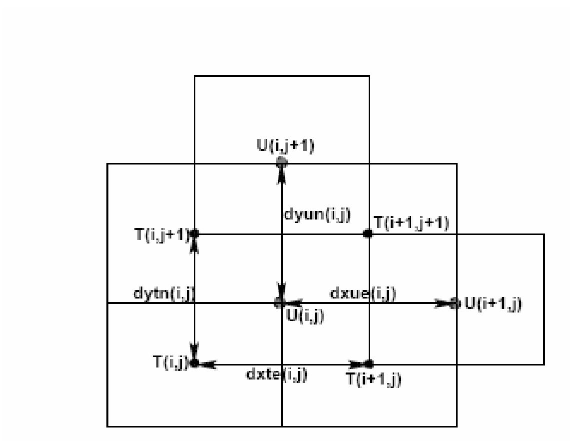
http://climate.lanl.gov/Models/POP/

Numerics

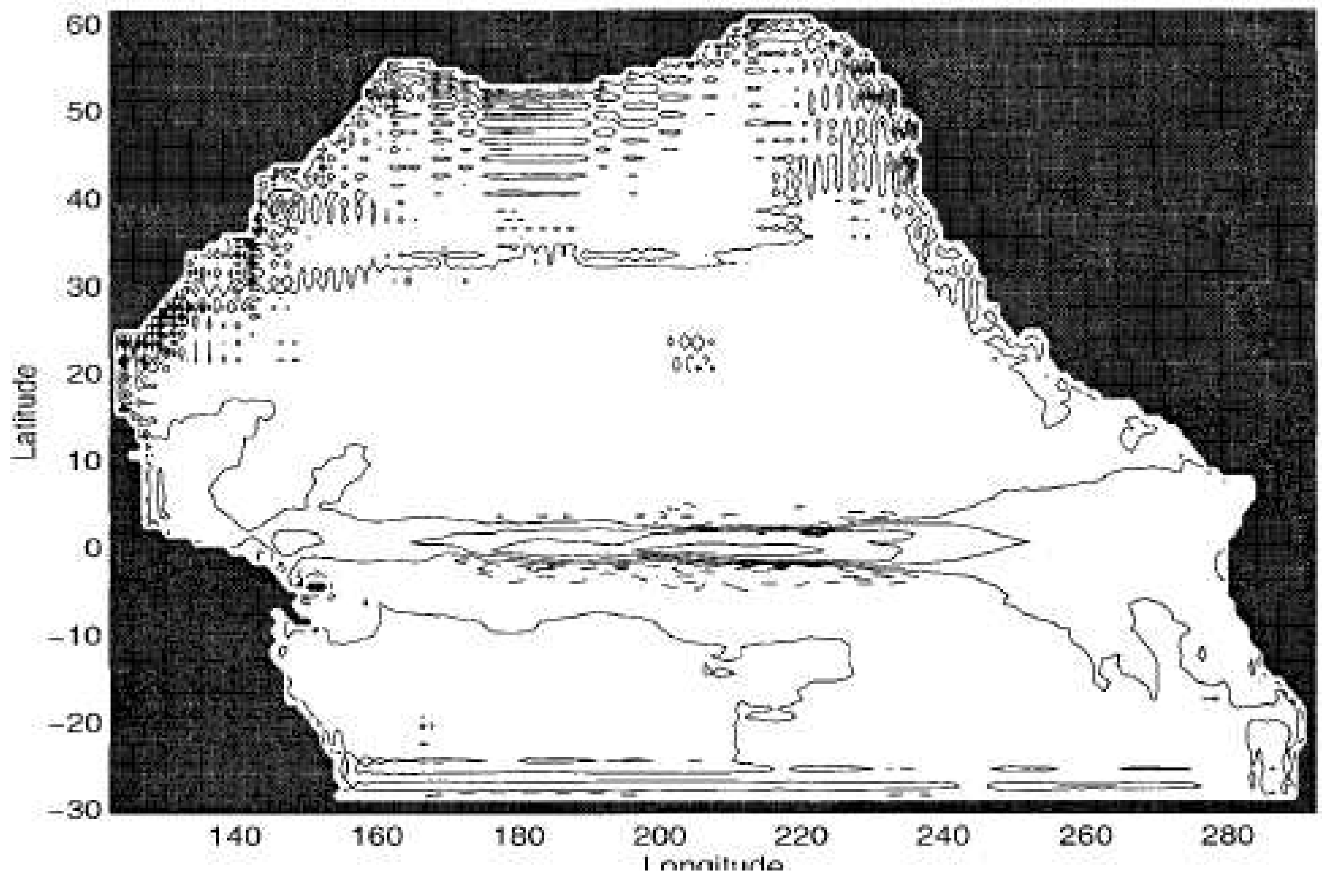
- Upstream advection
- Leap frog time differencing
- Separate internal and external modes
- MPI, shared memory
- Output is in netcdf

•Arakawa-C grid in horizontal



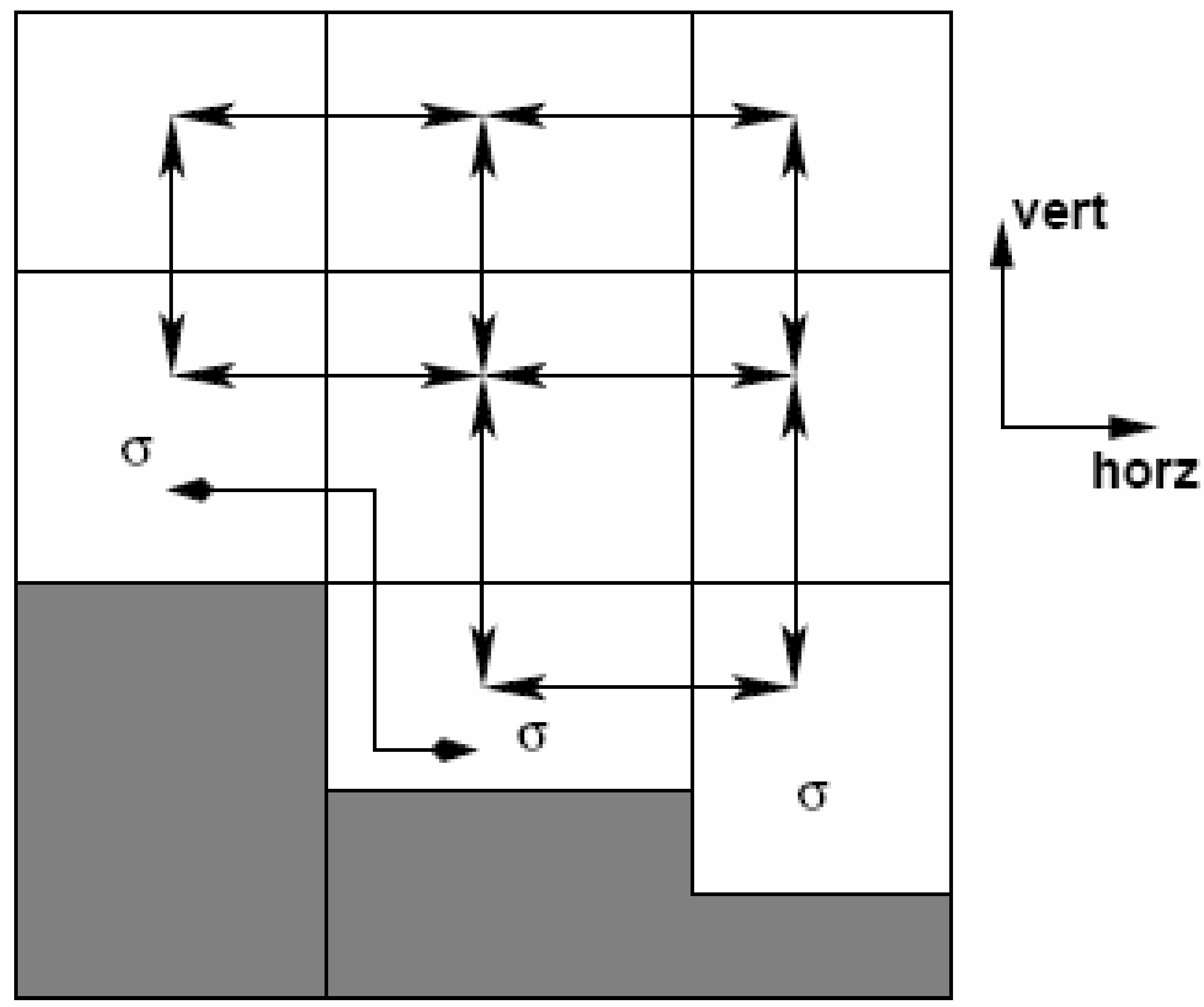


Noise introduced with Arakawa c-grid due to insufficient resolution



Adcroft et al, MWR, 1999

Sigma coordinate transport



Model details

- **Mixing**
  - KPP, bi-harmonic
- **Winds**
  - **ERA40 daily stress**
  - **QuikSCAT**
- **Topography**
  - Sandwell and Smith (etopo30) with McClean modifications for some passages
- **Freshwater flux**
  - GPCP precipitation when avail., bulk formula evaporation, seasonal river discharge. Relaxation to clim. salinity under ice.
- **Heat flux**
  - Bulk formula
- **Sea ice**
  - Observed monthly cover 1979-
- **Tracers** → CFCs, …

Performance on two architectures

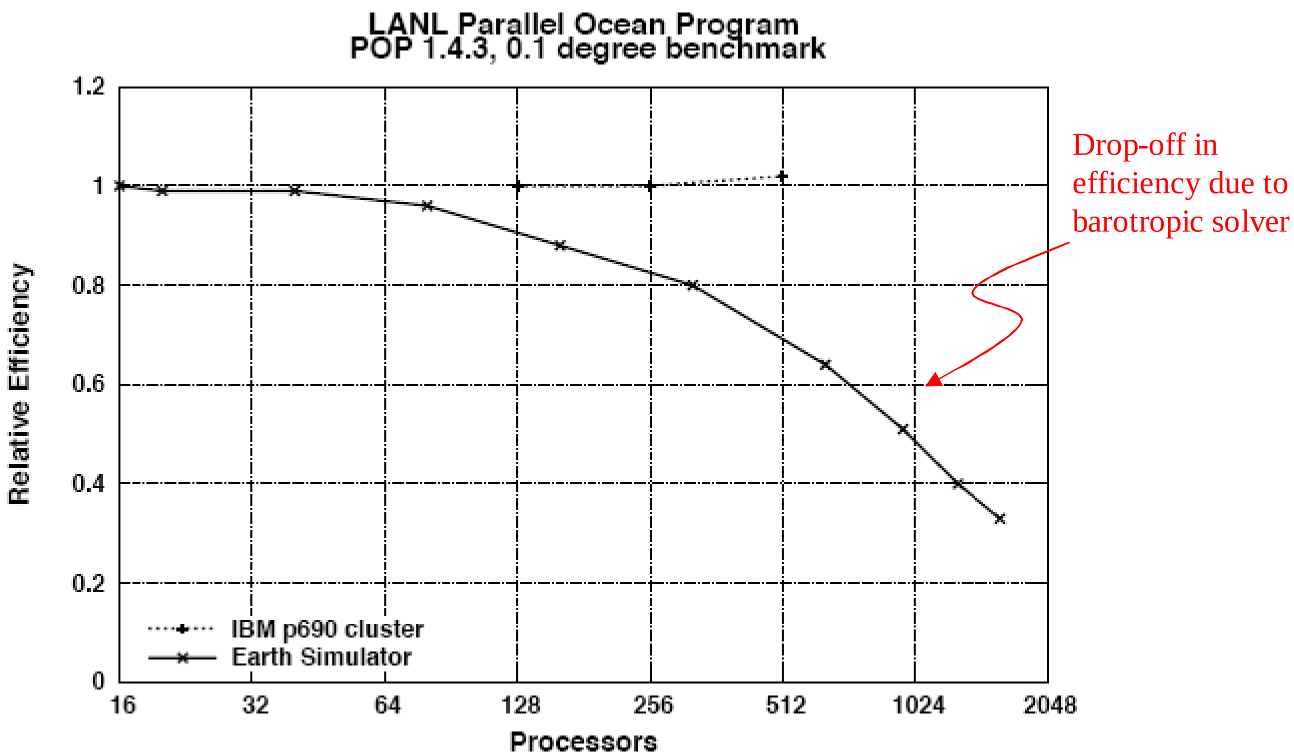


Figure 6. Parallel efficiency for the Earth Simulator relative to 16 processors and for the p690 relative to 128 processors in the 0.1 configuration

Absolute performance

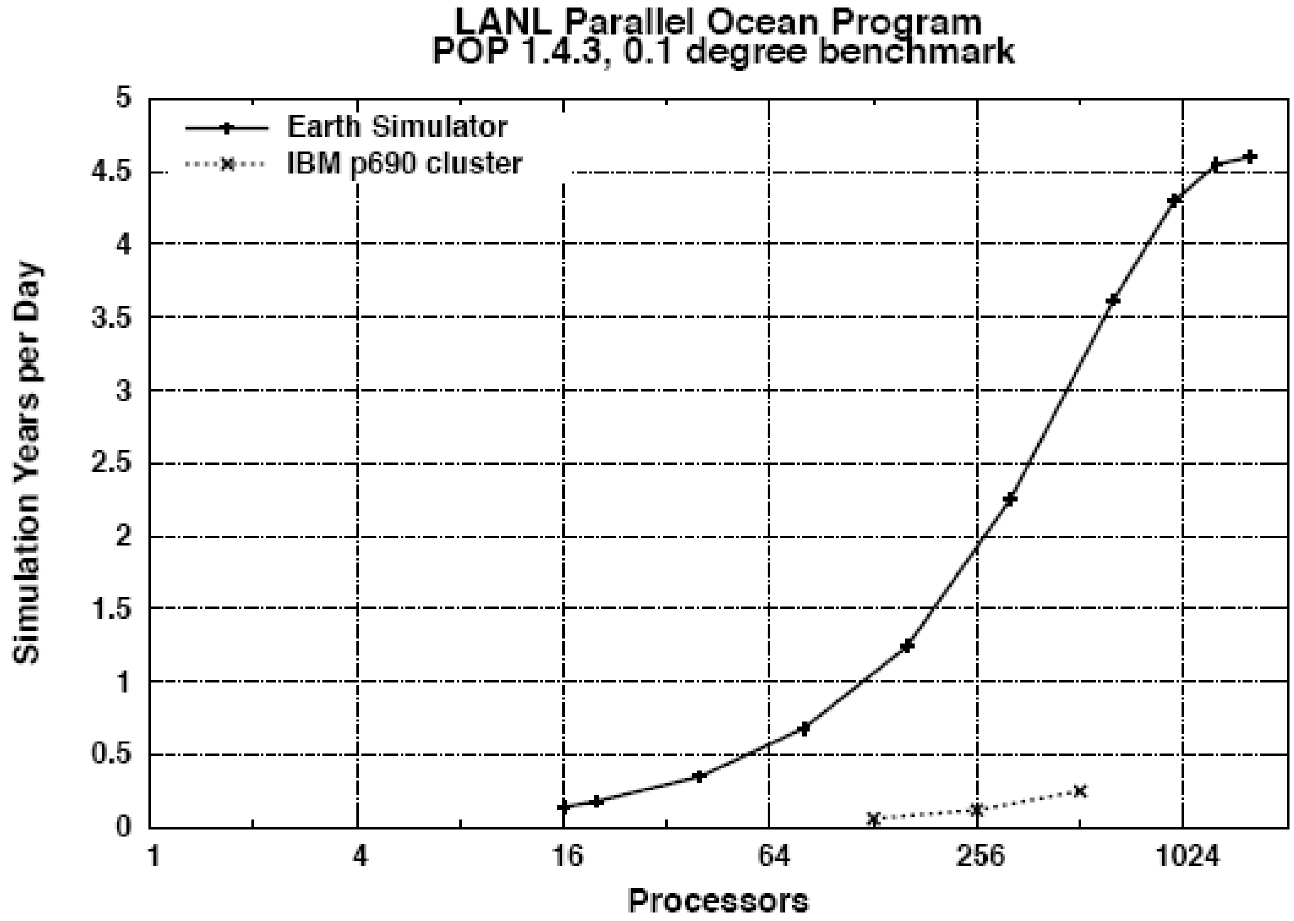


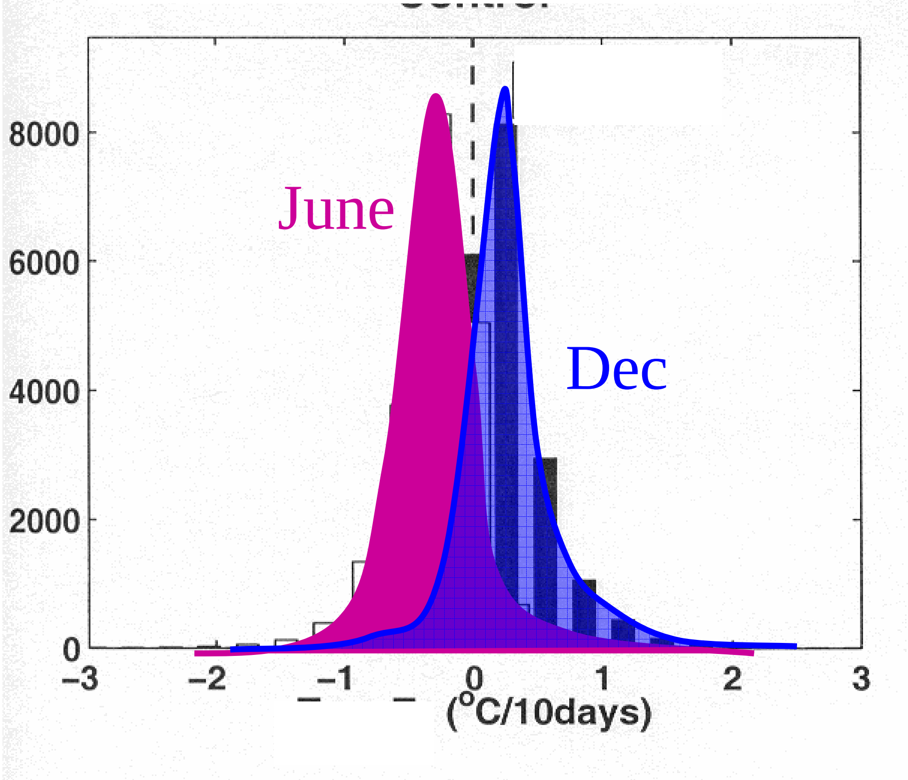
Figure 5. Performance in model years per CPU day as a function of processor count for the 0.1 configuration

Assimilation details (I)

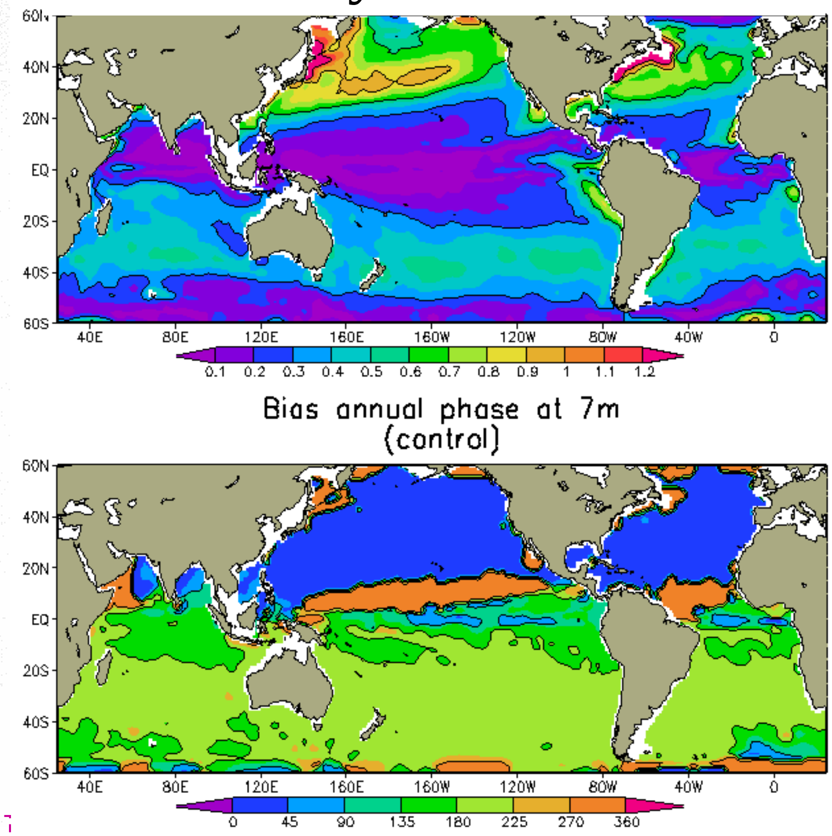
- Multivariate two-stage sequential updating algorithm
  - Stage I correct bias $\beta^a = \beta^f - \mathbf{L}\left[\omega^o - \mathbf{H}(\omega^f - \beta^f)\right]$
  - Stage II correct state $\omega^a = \tilde{\omega}^f + \mathbf{K}\left[\omega^o - \mathbf{H}\tilde{\omega}^f\right]$
- Time increment
  - 10dy IUA {a digital filter}

SODA annual cycle bias in the mixed layer (without bias correction algorithm)

Histogram of $<\mathbf{w}^f - \mathbf{w}^o>$
In the North Pacific



Annual cycle of ML bias

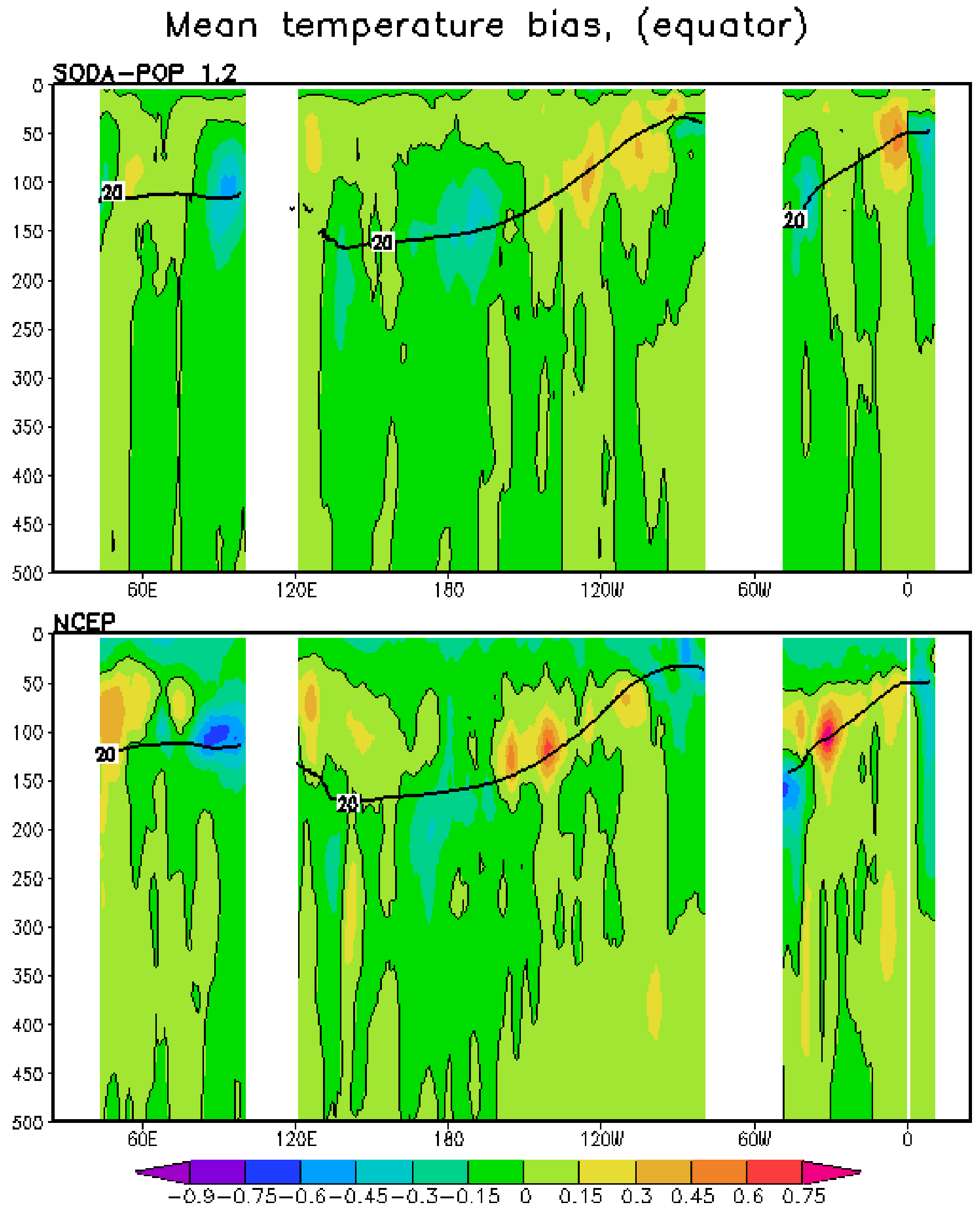


amp

phase

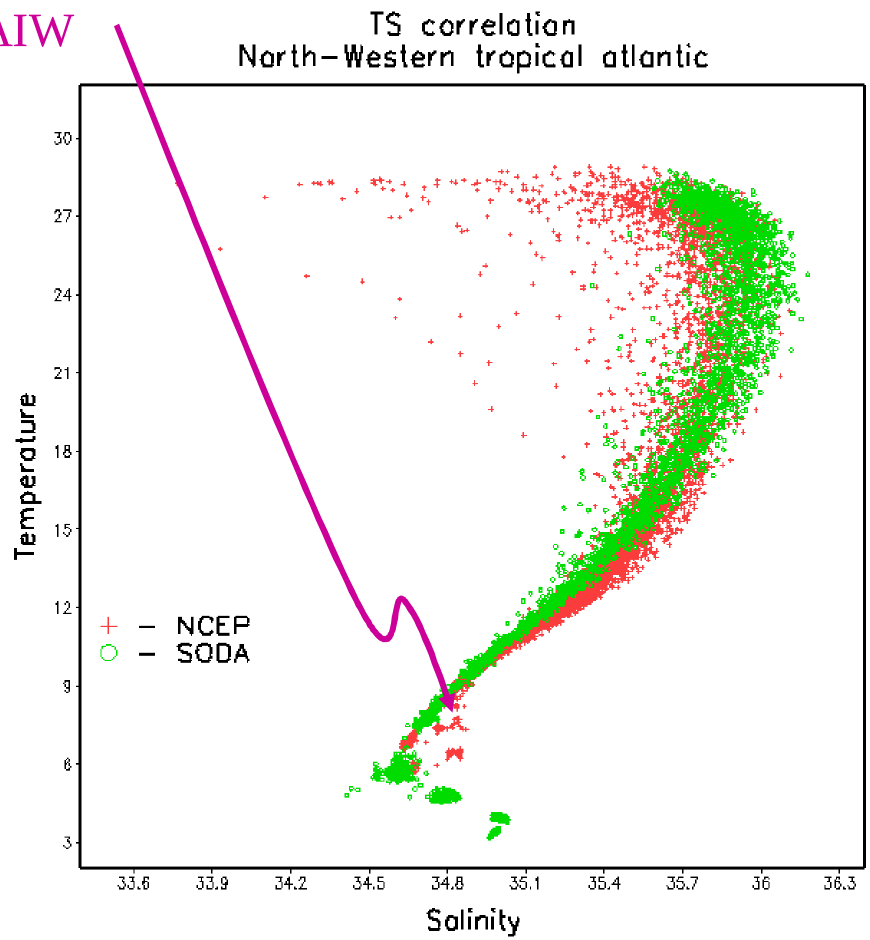
"The summer mixed layer is too cold, the winter mixed layer is too warm"

Mean temperature forecast - obs

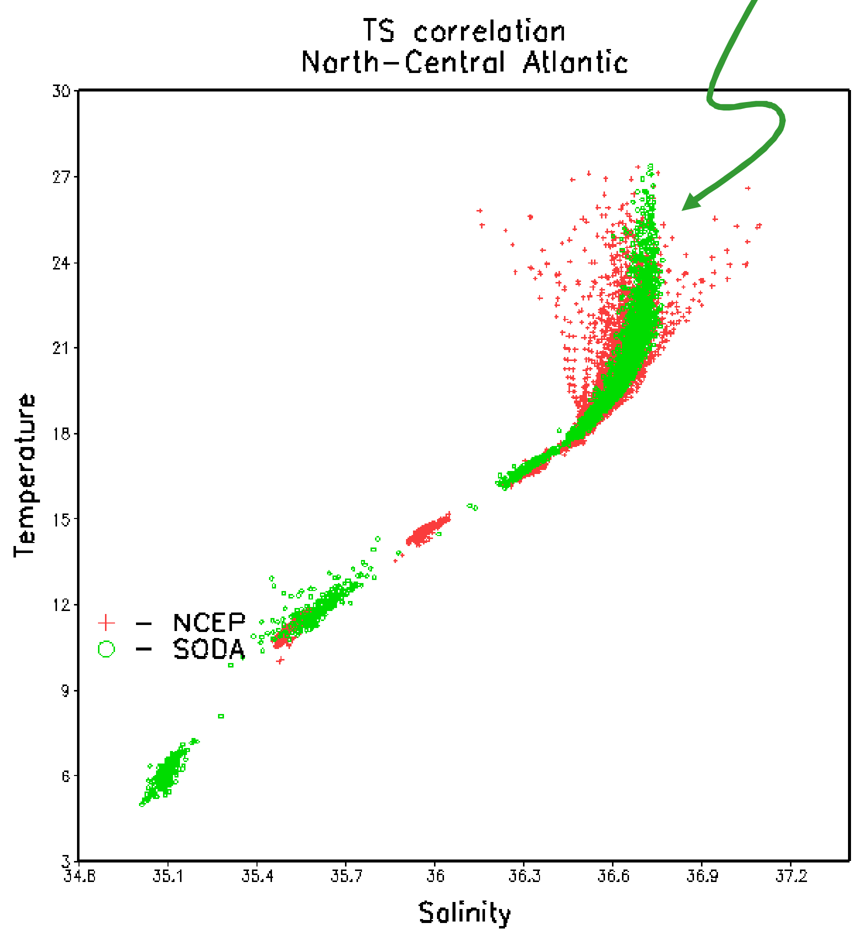


Temperature – salinity characteristics

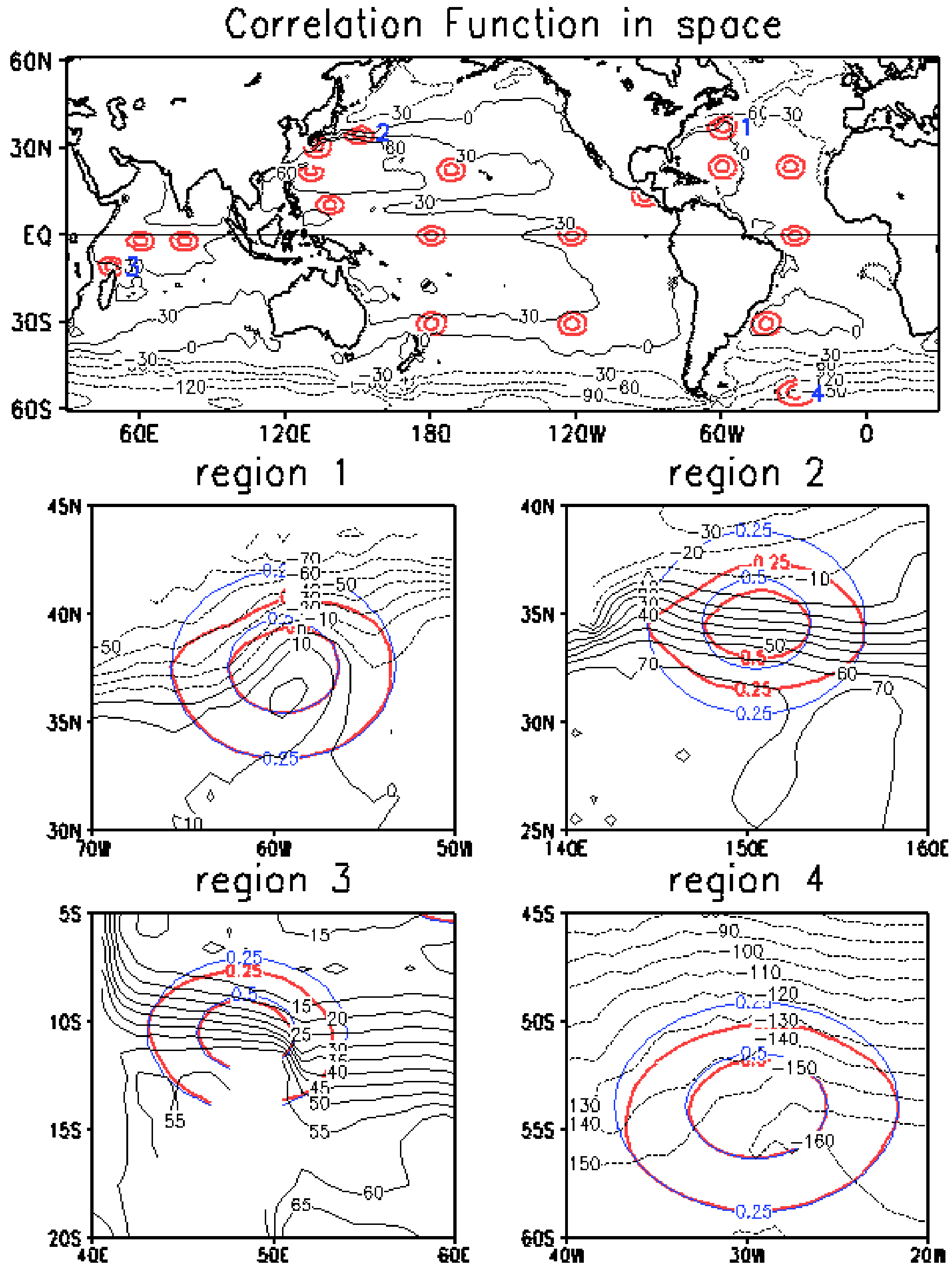
NCEP may have some problems with AAIW



SODA lacks precip



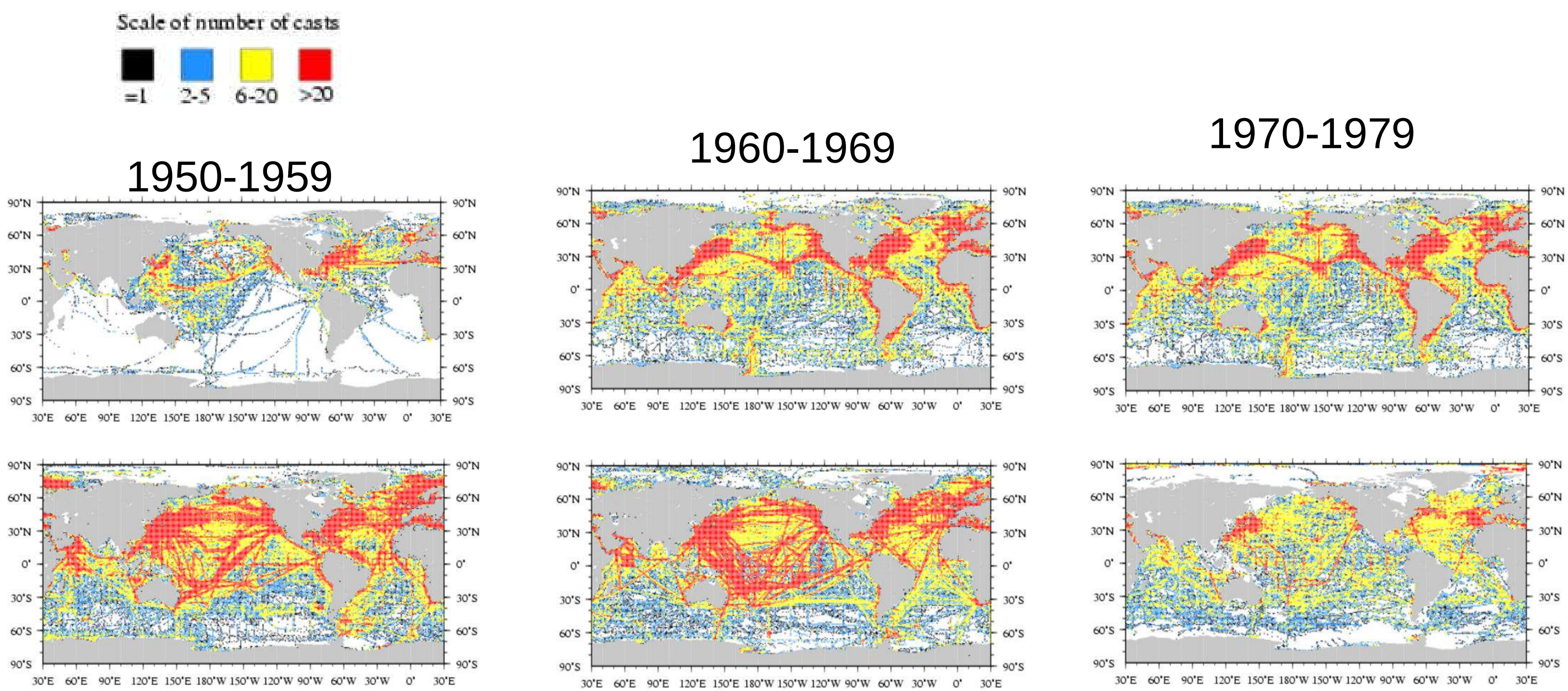
SODA flow-dependent background error



Assimilation details (II)

- Error covariances:
  - Flow-dependent, anisotropic, latitude/depth-dependent
- Bias model
  - Empirical, including time-mean, annual and basin-scale components
- Data
  - Hydrography (Levitus 2001 MBTs, XBTs, CTDs, floats, moored thermistor chains, ARGO, etc.)
  - In situ and satellite SST
  - Altimetry
- Available: monthly 1958-2001 a 0.5^{o}X0.5^{o} grid http://apdrc.soest.hawaii.edu
  - 5-day averages at the surface
  - 5 day averages from 5S to 5N (T, S, u, v)

Profile network



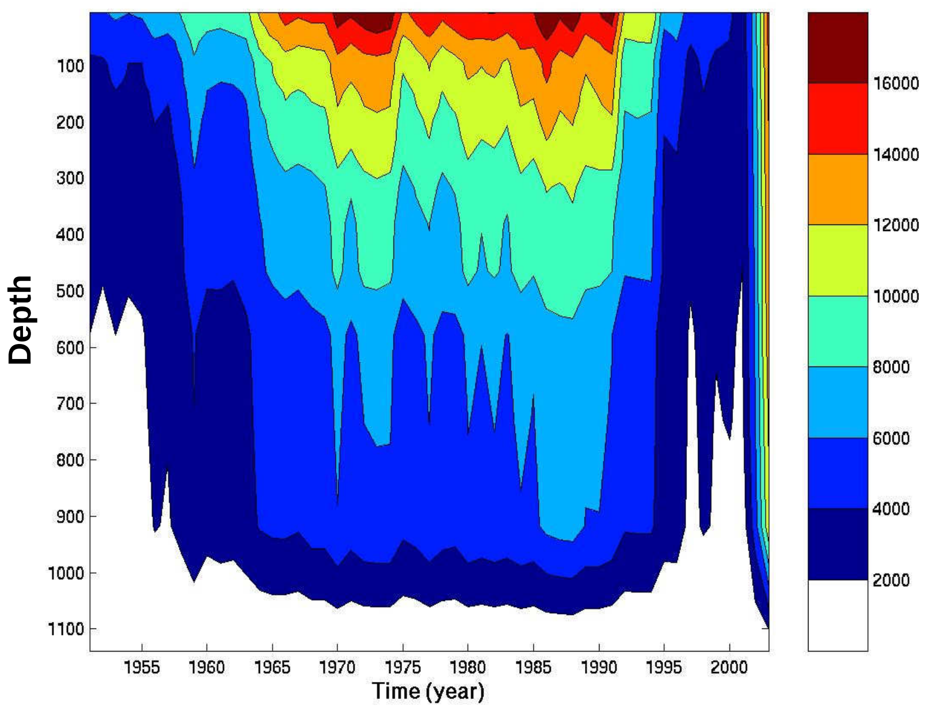
Global hydrographic observations vs depth

How do we handle changes in the data types? Data cleaning (droprate errors)?

Altimetry

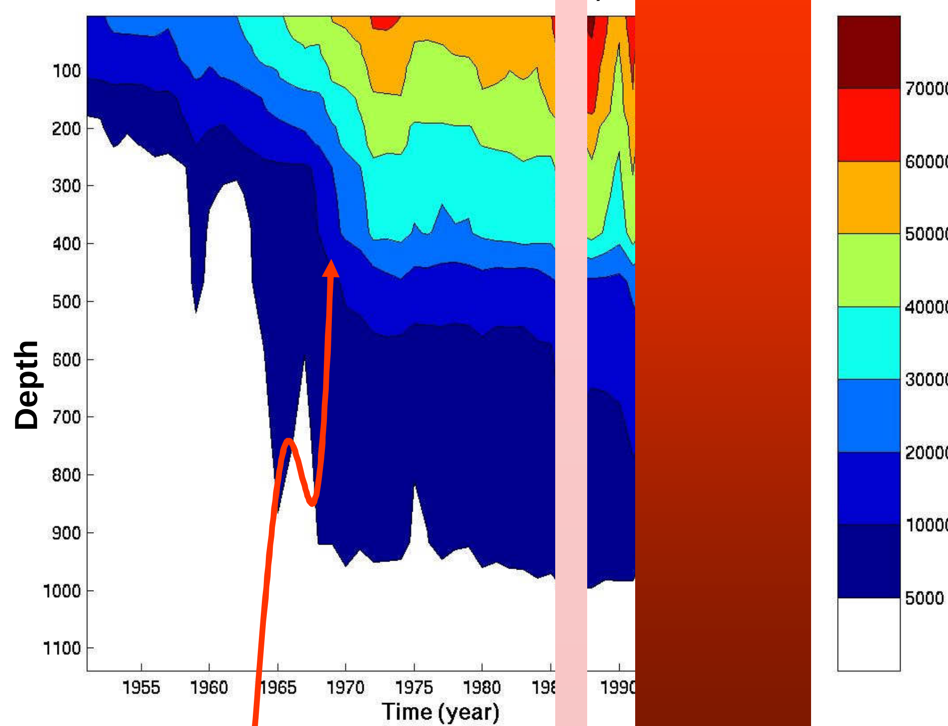
Salinity

16,000



Temper tu

),00

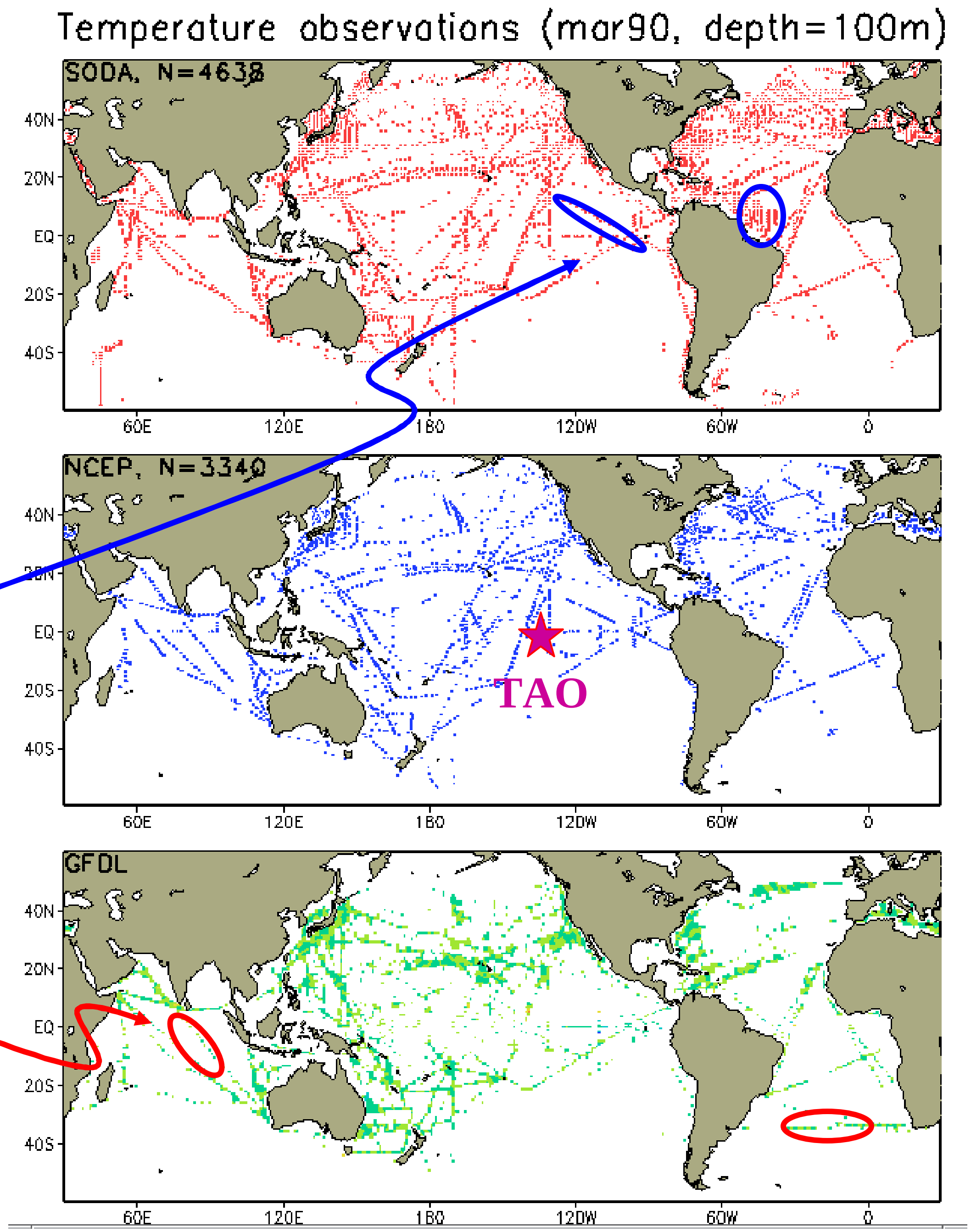


Change in data coverage

Data coverage differences

Data missing from GFDL

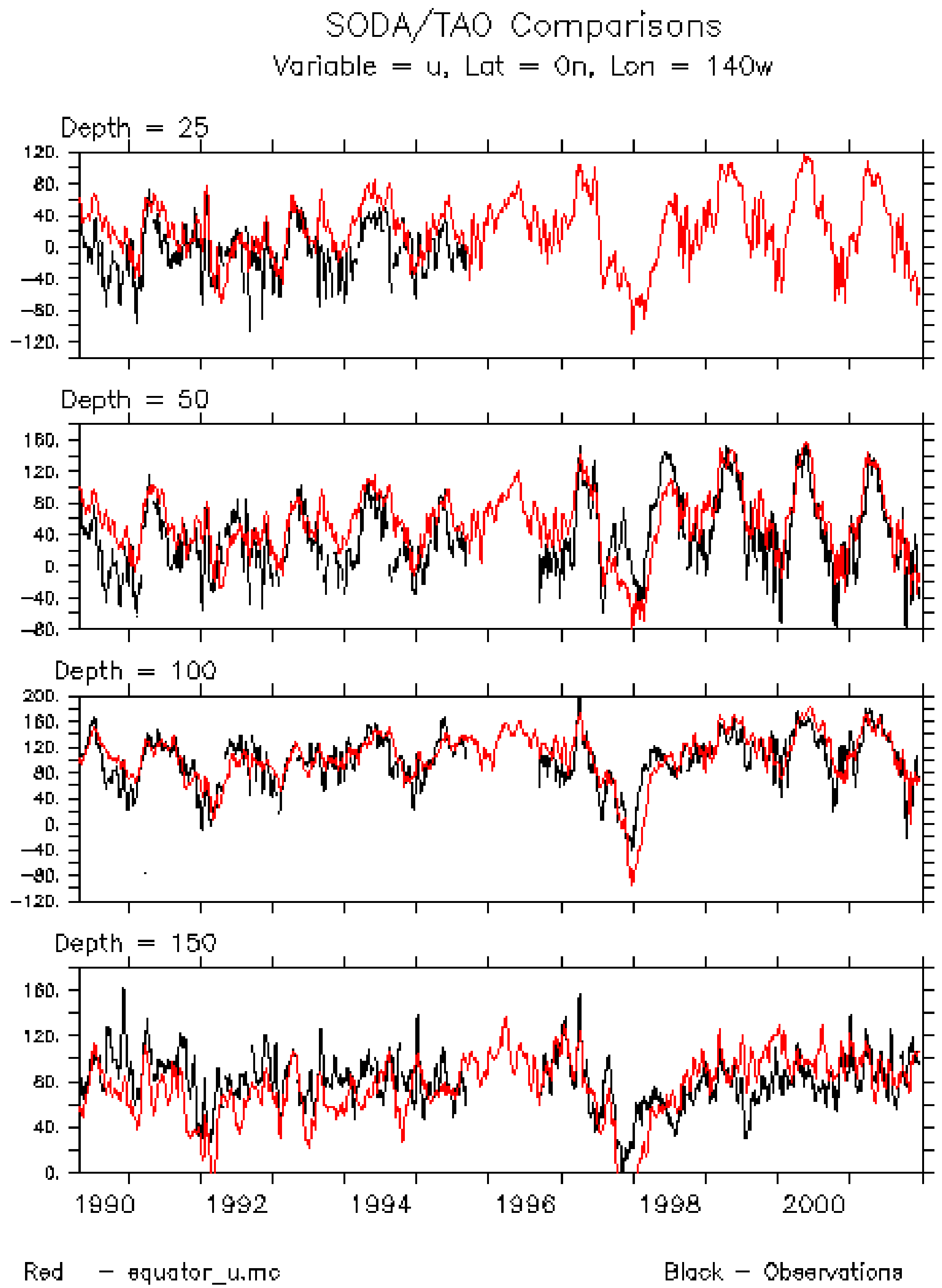
Data missing from SODA



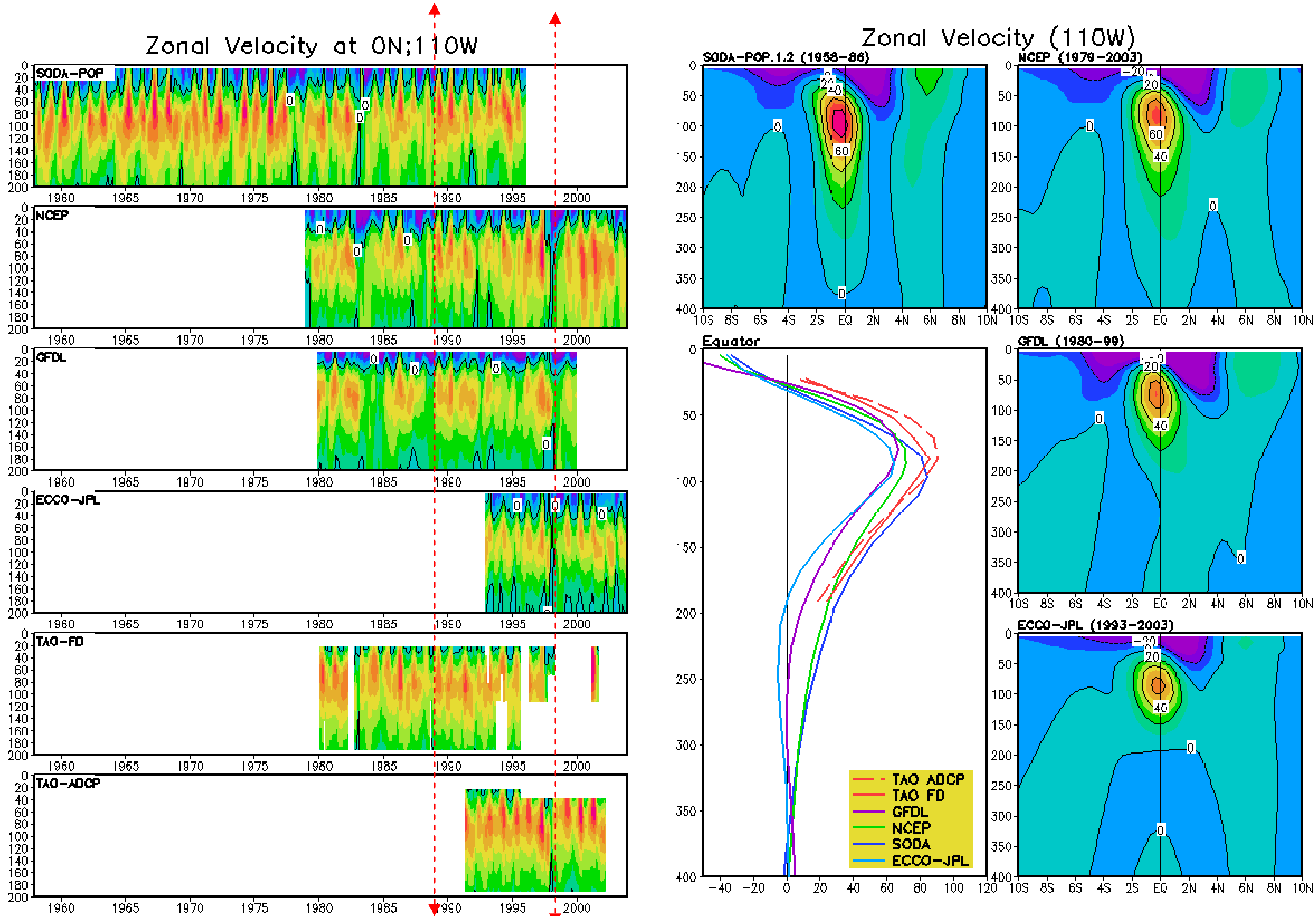
Some Comparison data

- Tracers
- Velocity
  - Drifters
  - Time series
  - ADCP cruise tracks
- Cryospheric data:
  - sea ice distribution consistent with the winds
  - Information about heat/freshwater and/or SST/S
- Color

Comparison to independent observations

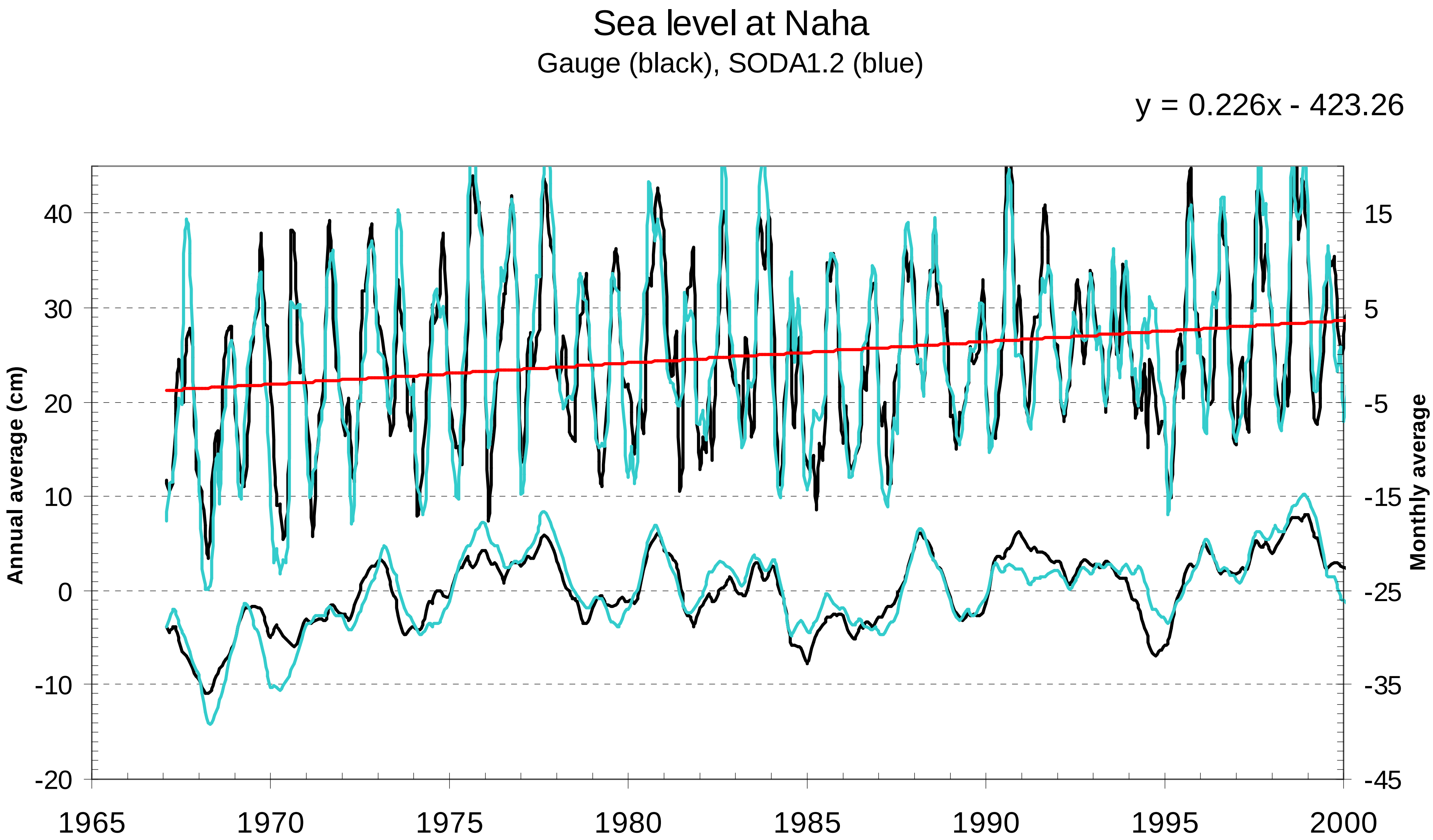


Zonal velocity 0N, 110W



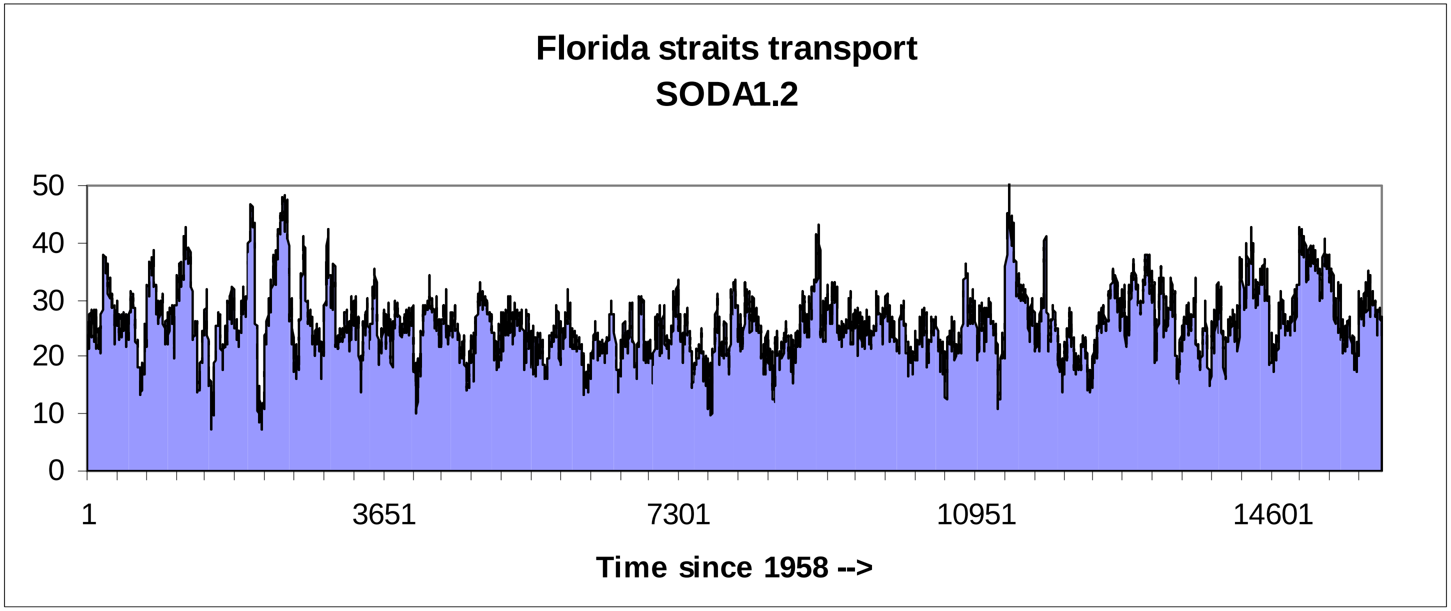
old

Comparison of observed and analysis sea level at Naha, Japan

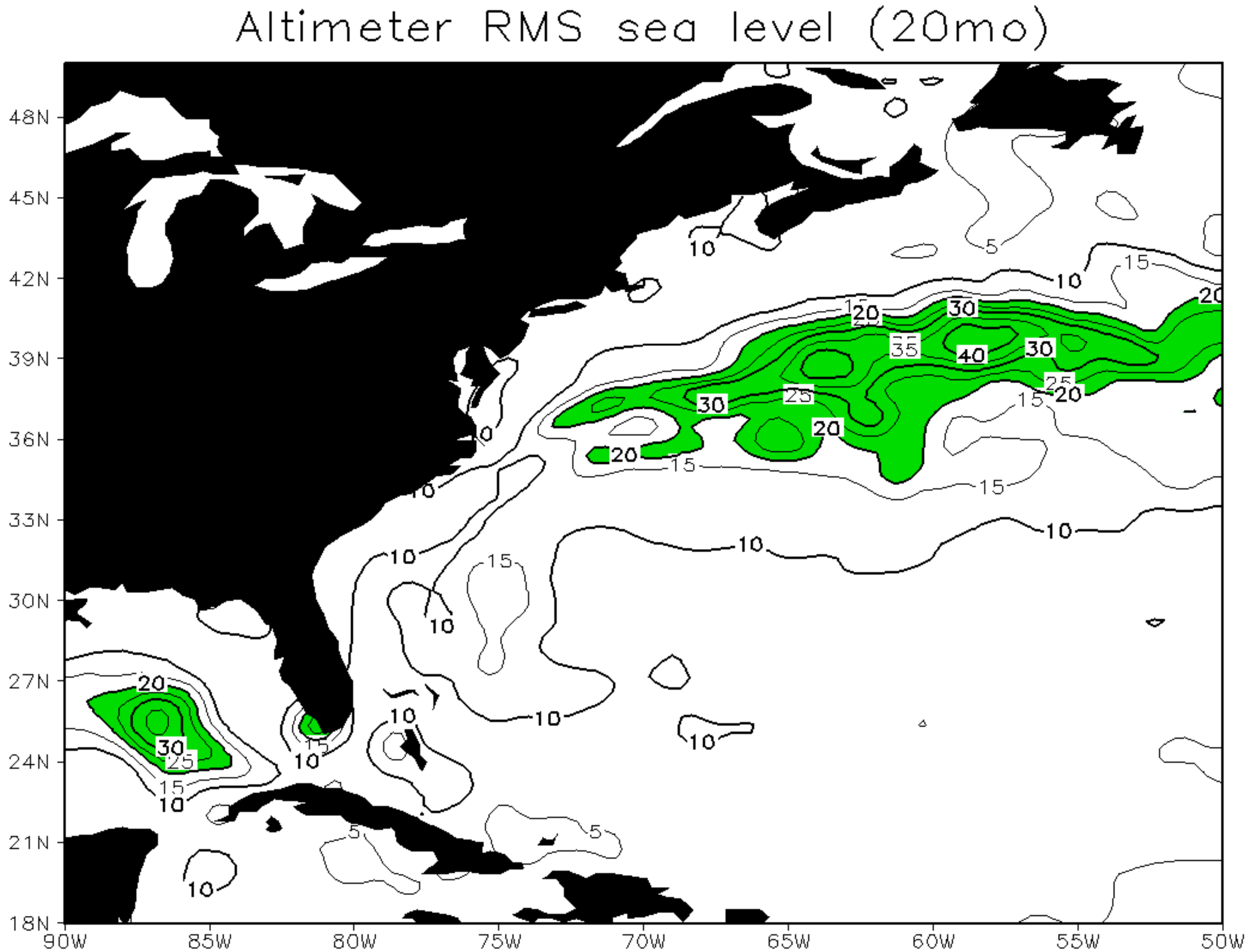


Mean Volume Transport

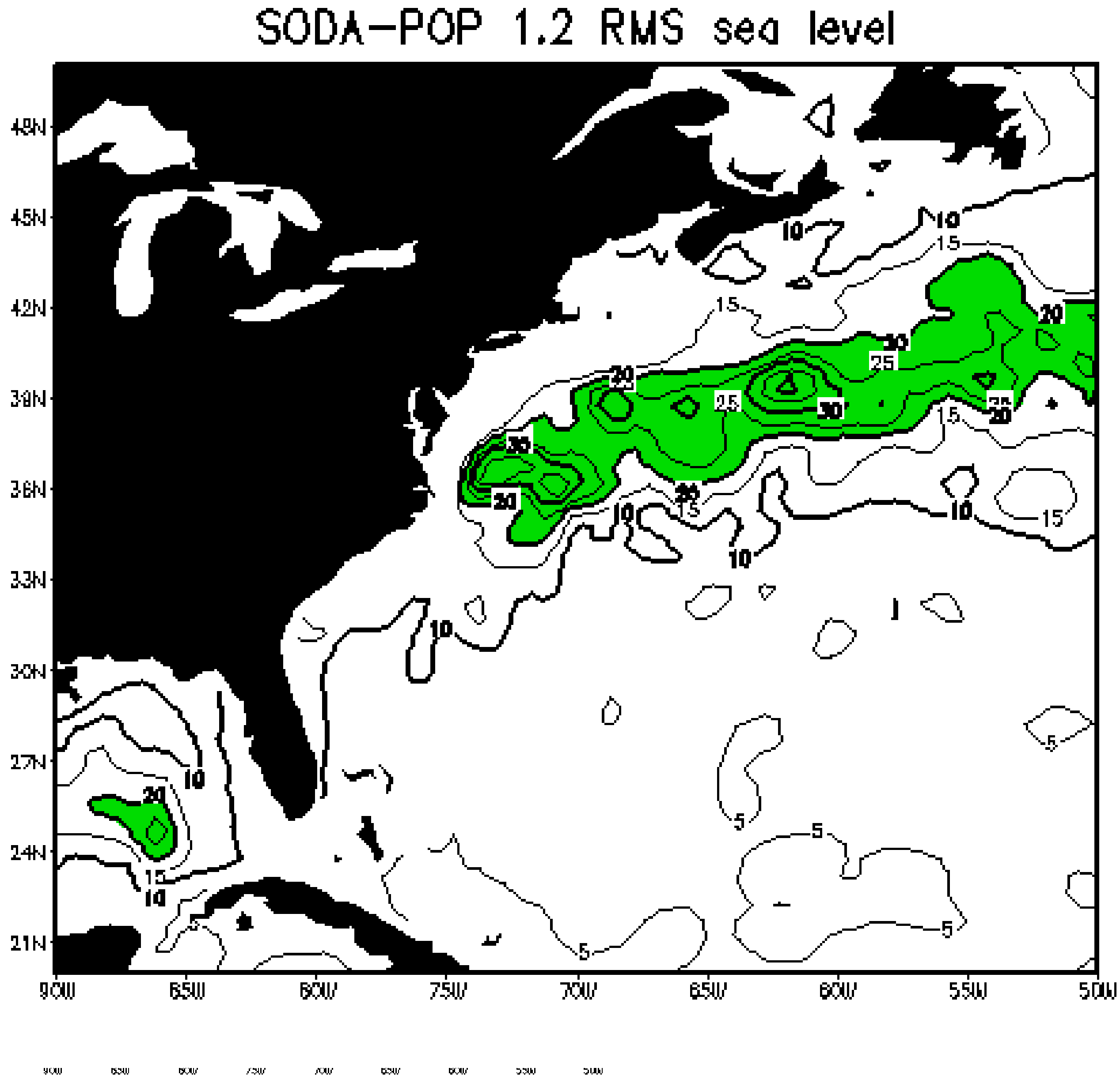
Passage	Obs	SODA1.2	SODA1.0
ACC-Drake (Peterson, 1988)	**123+-15**	**155**	144
Kuroshio (Wimbush, 1999)	**63**	**40**	41
Gulf Stream at Hatteras (Hogg, 1992)	**45**	**48**	48
Florida Straits (Leaman et al., 1987)	**31+-3**	**26**	26
Agulhas (Bryden et al. 2003)	**70+-4**	**68**	69
Indonesian Throughflow (Meyers, 1995)	**12**	**15**	13
Denmark Straits		**4.9**	6
Antilles (Wilson and Johns, 1997)	**9.5+-3**	**19**	18



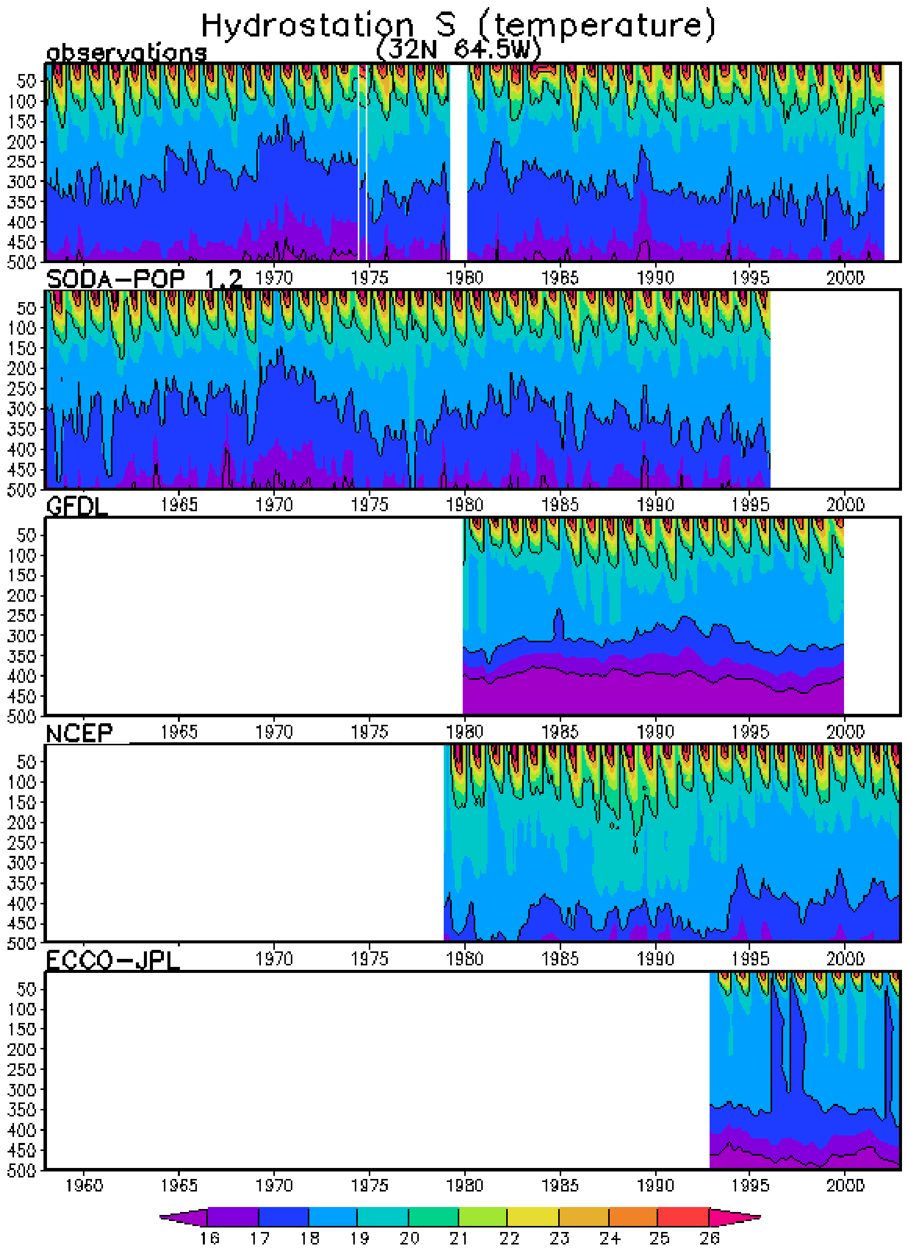
AVISO combined altimeter sea level

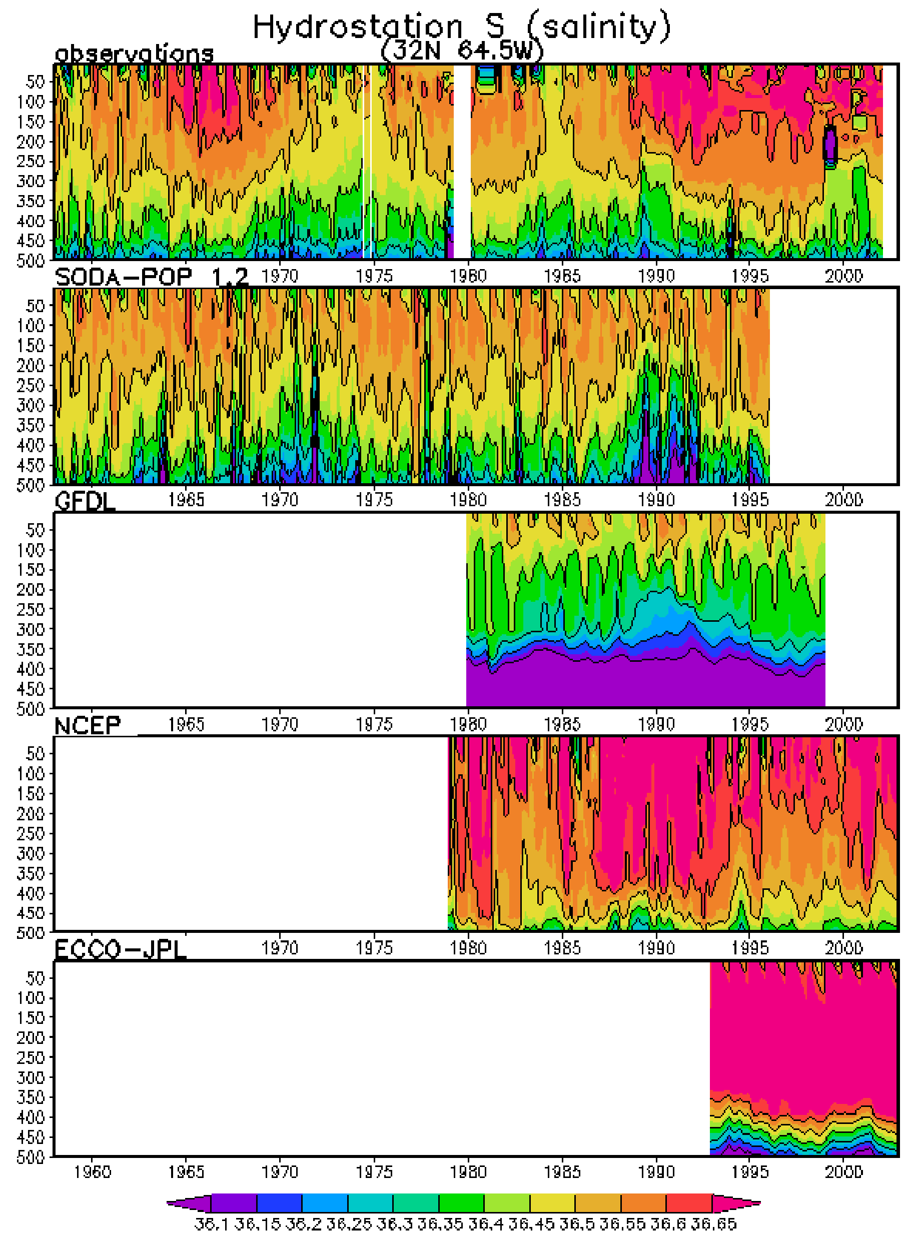


Reanalysis sea level

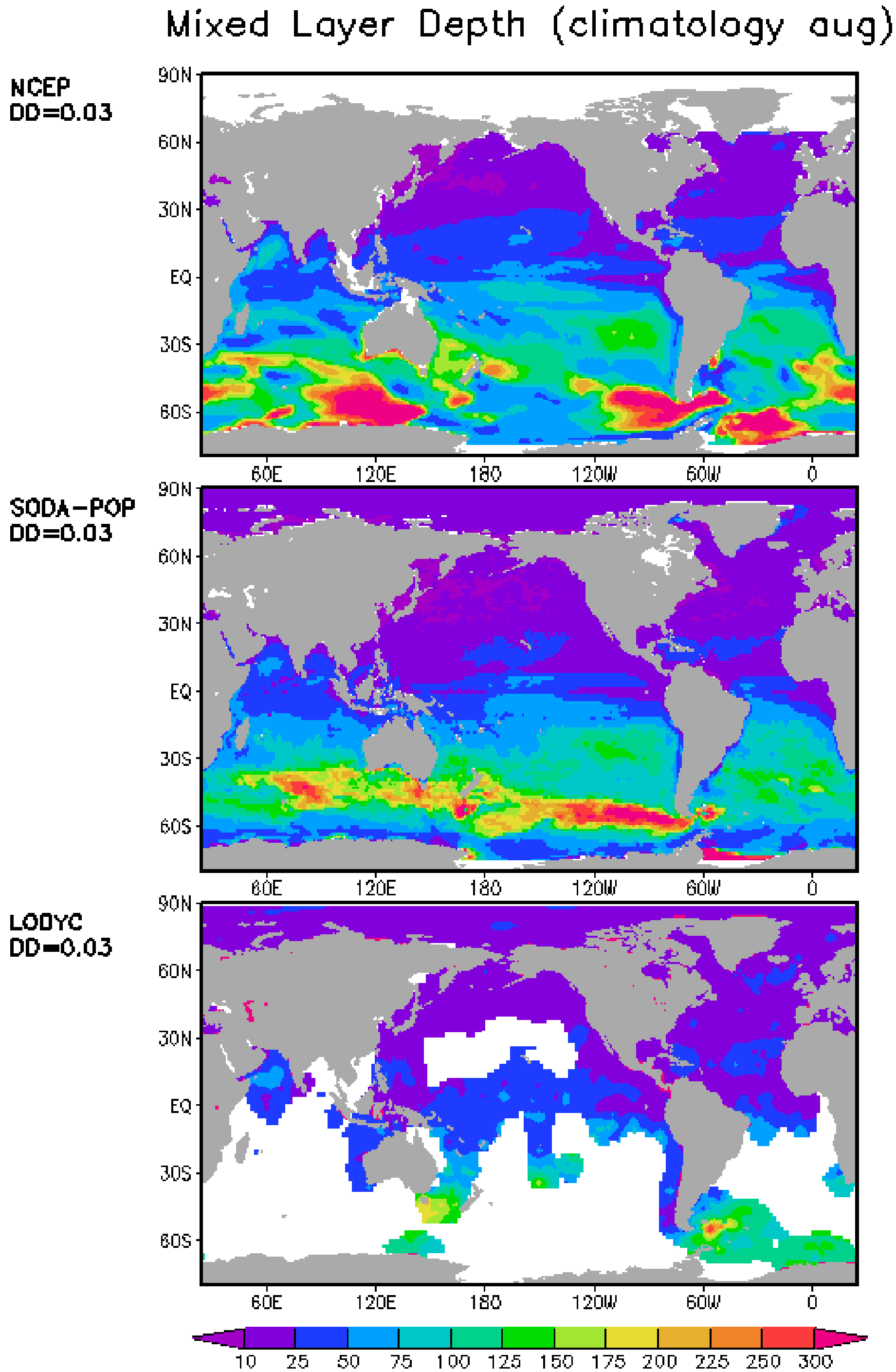


Bermuda Atlantic Time series





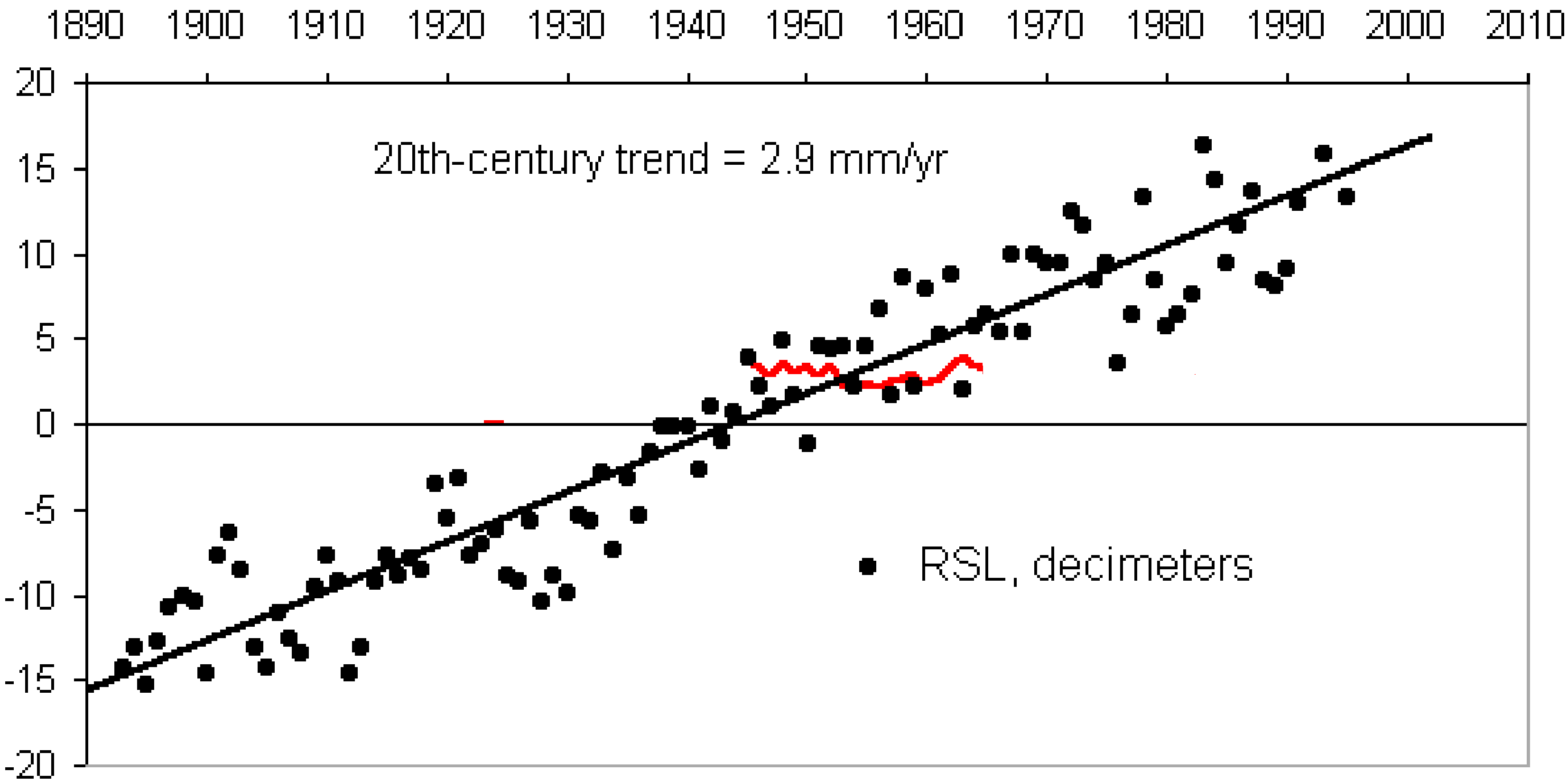
Seasonal MLD



Variability of the ocean’s climate

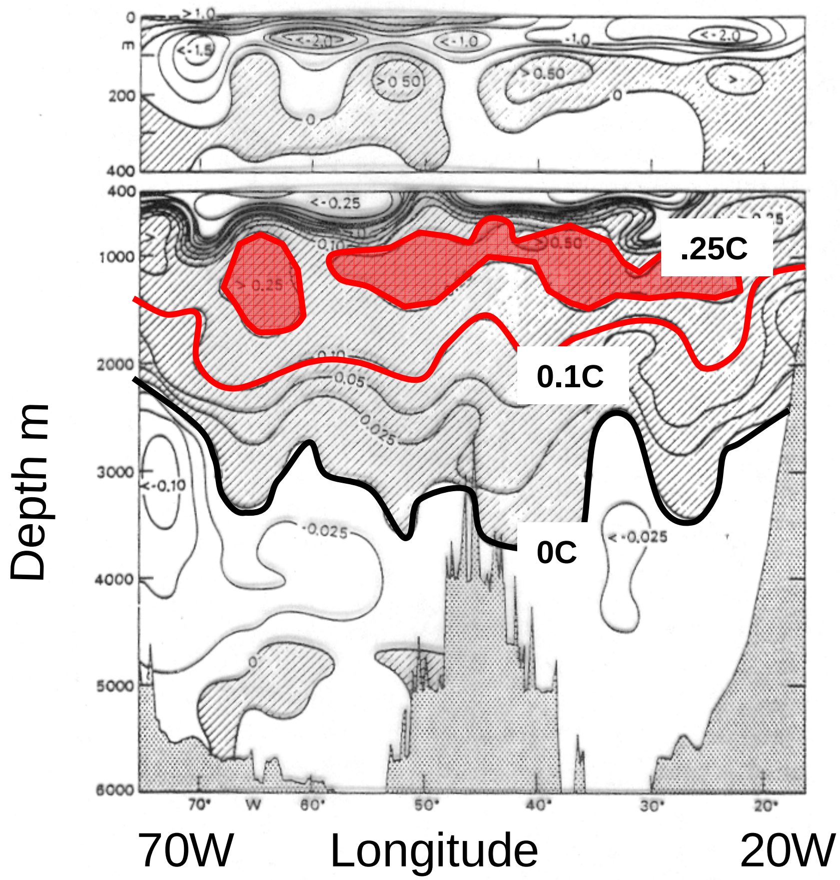
- Focus on warming signal in the ocean

Relative Sea Level Rise at New York City



Observed warming of Atlantic along 24N

Temp(1992) – Temp (1957)



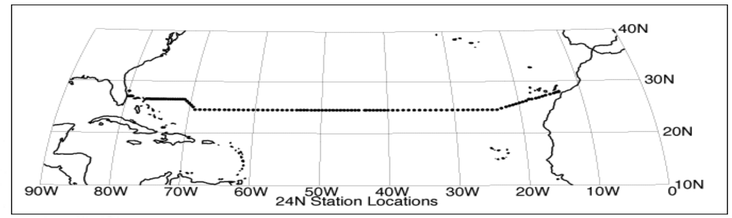
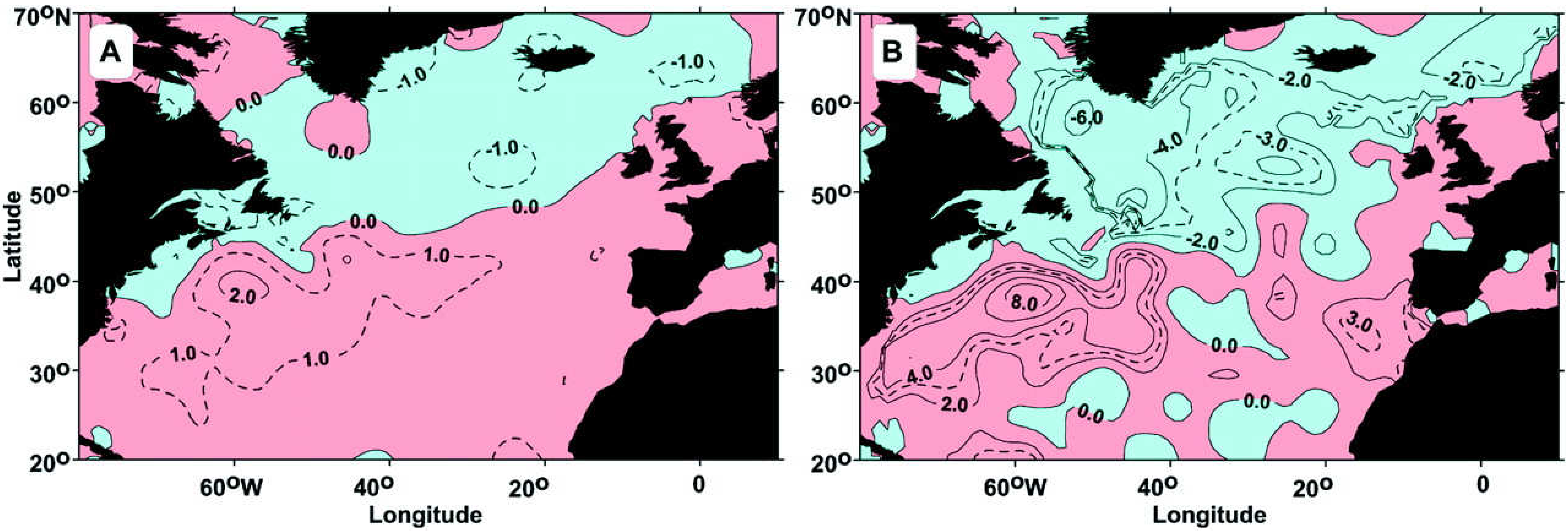


Figure 3.5 - (a) Temperature difference across 24°N between cruises in 1957 (as part of IGY) and 1992 (WOCE line A5). The data show considerable warming across the mid-water (800-2700 m) layer and cooling within the surface layers and below 3000 m (Parilla *et al.*, 1994).

Heat storage 1988-92 minus 1970-74 from Levitus et al. (2000) {redone 04}

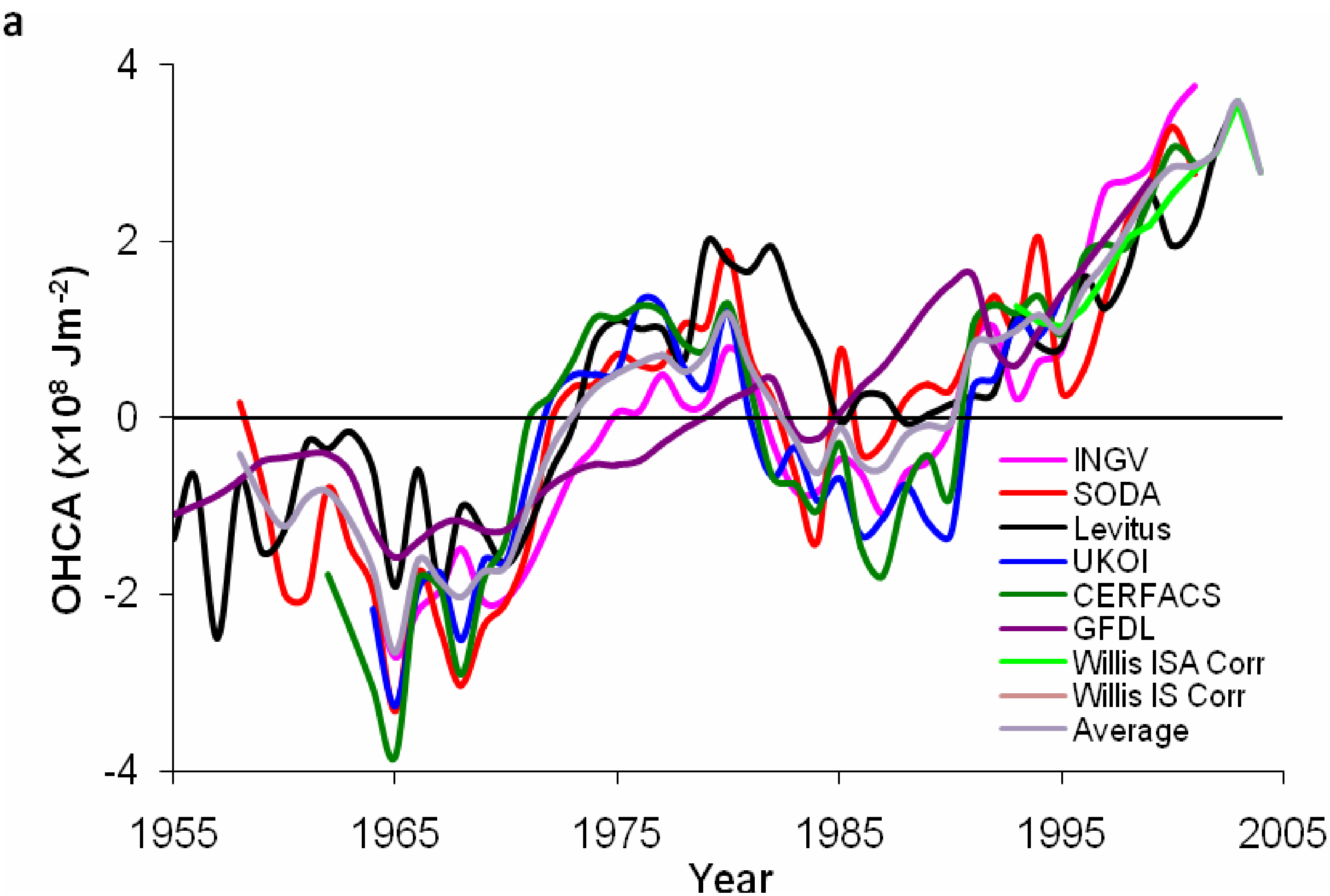


0/ 300m

0/3000m

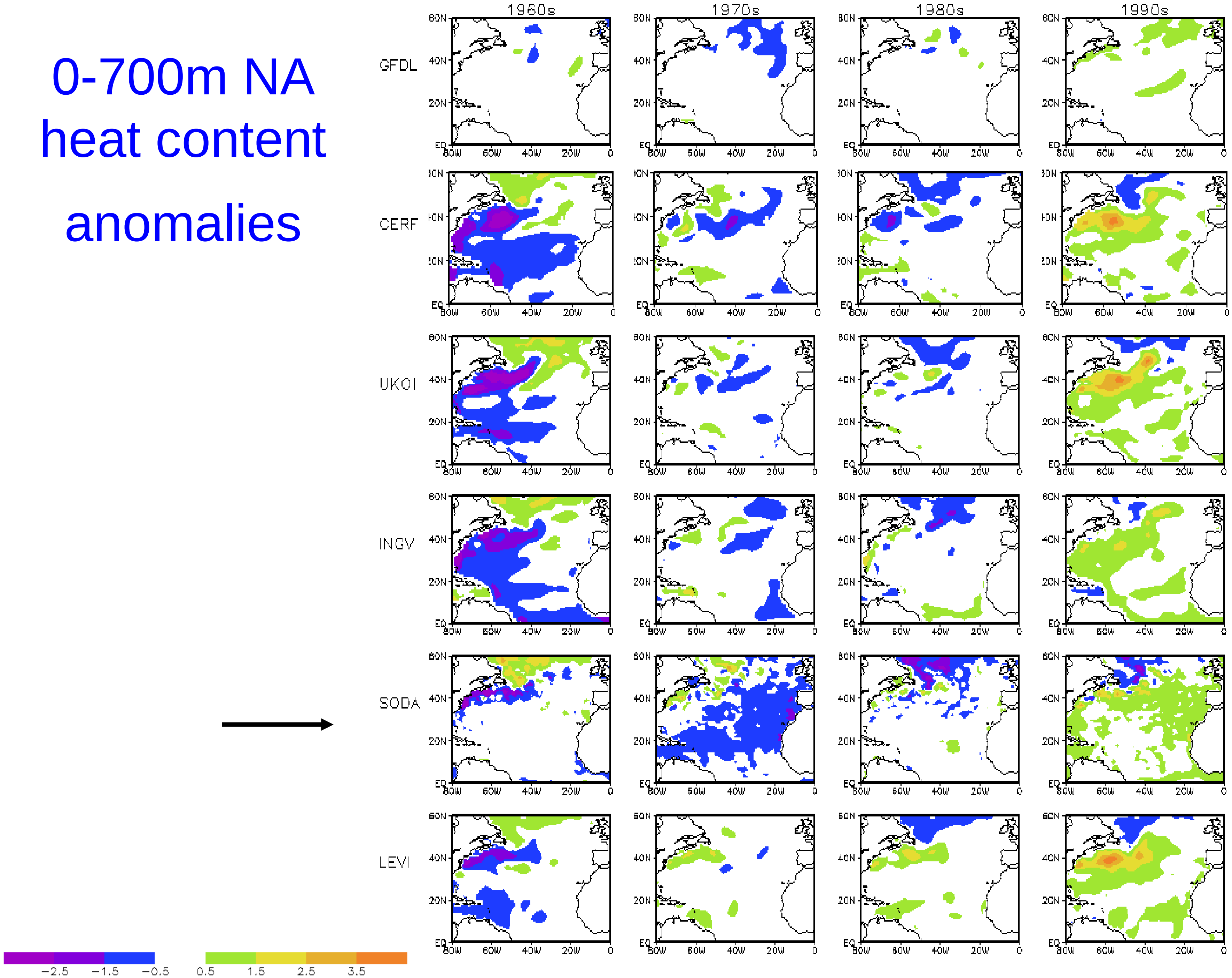
Analysis	**In situ data**	**Satellite and altimetry data**	**Model forcing**	**Analysis procedure**
SODA 1.4.2 (1962-2001) [*Carton and Giese*, 2006]	WOD 2001 temperature and salinity profiles, real-time temperature observations from NODC/NOAA archive, TAO/Triton mooring array and ARGO drifter observations	NOAA/NASA AVHRR SST data and ERS 1/2, TOPEX/POSEIDON, JASON altimeter data	ERA 40 winds	10-day assimilation cycle with Incremental Analysis Update
Willis (1993-2005) [*Willis et al.*, 2004]	WOD 2001, GTSPP, WOCE and ARGO in situ profiles	TOPEX/POSEIDON, Jason1 and ERS 1/2 altimetric data	N/A	A “difference estimate”
Levitus (1955-2003) [*Levitus et al.*, 2005]	WOD 2001 plus real-time and delayed-mode temperature profiles from GTSPP	N/A	N/A	Objective analysis
INGV (1962-2001) [*Davey*, 2006]	WOD 2001 supplemented with WOCE, Australian XBT data, PMEL CTD reports and GTSPP	GEOSAT,TOPEX/POSEIDON, ERS 1/2, Jason-1 and ENVISAT altimetric data	Levitus climatology, ERA 40 climatological fluxes	SOFA
CERFACS (1962-2001) [*Davey*, 2006]	WOD 2001 supplemented with WOCE, Australian XBT data, PMEL CTD reports and GTSPP	GEOSAT,TOPEX/POSEIDON, ERS 1/2, Jason-1 and ENVISAT	Levitus climatology, ERA 40 climatological fluxes	3DVar
UKOI (1962-1998) [*Davey*, 2006]	WOD 2001 supplemented with WOCE, Australian XBT data, PMEL CTD reports and GTSPP	GEOSAT,TOPEX/POSEIDON, ERS 1/2, Jason-1 and ENVISAT	Levitus climatology, ERA 40 climatological fluxes	OI
GFDL CM2.0 and CM2.1 models [*Delworth et al.*, 2006]	N/A	N/A	1860 values for solar, land cover, greenhouse gases	Coupled Model

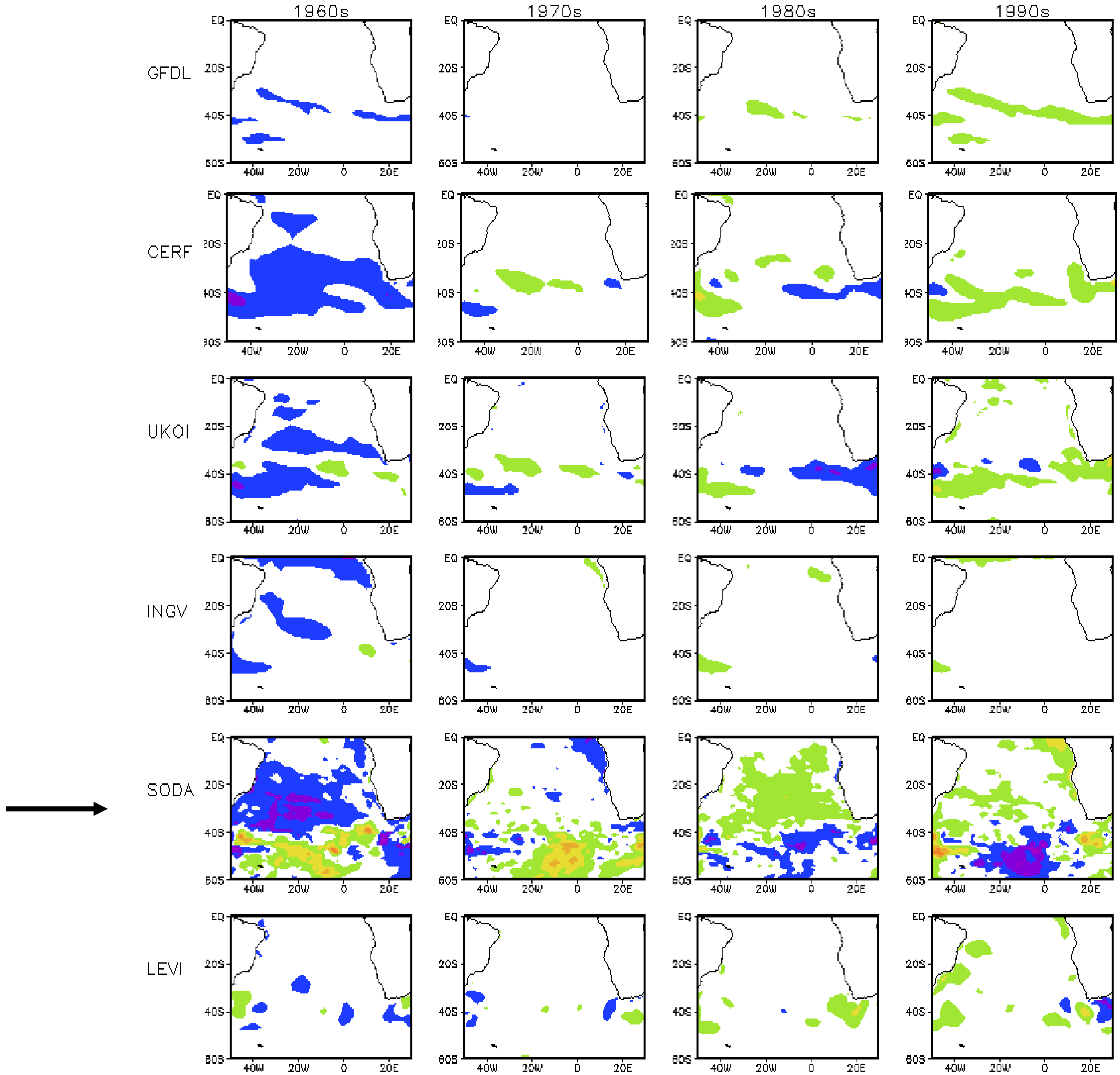
Estimates of global heat storage



A. Santerelli, unpublished, 2007

0-700m NA heat content anomalies



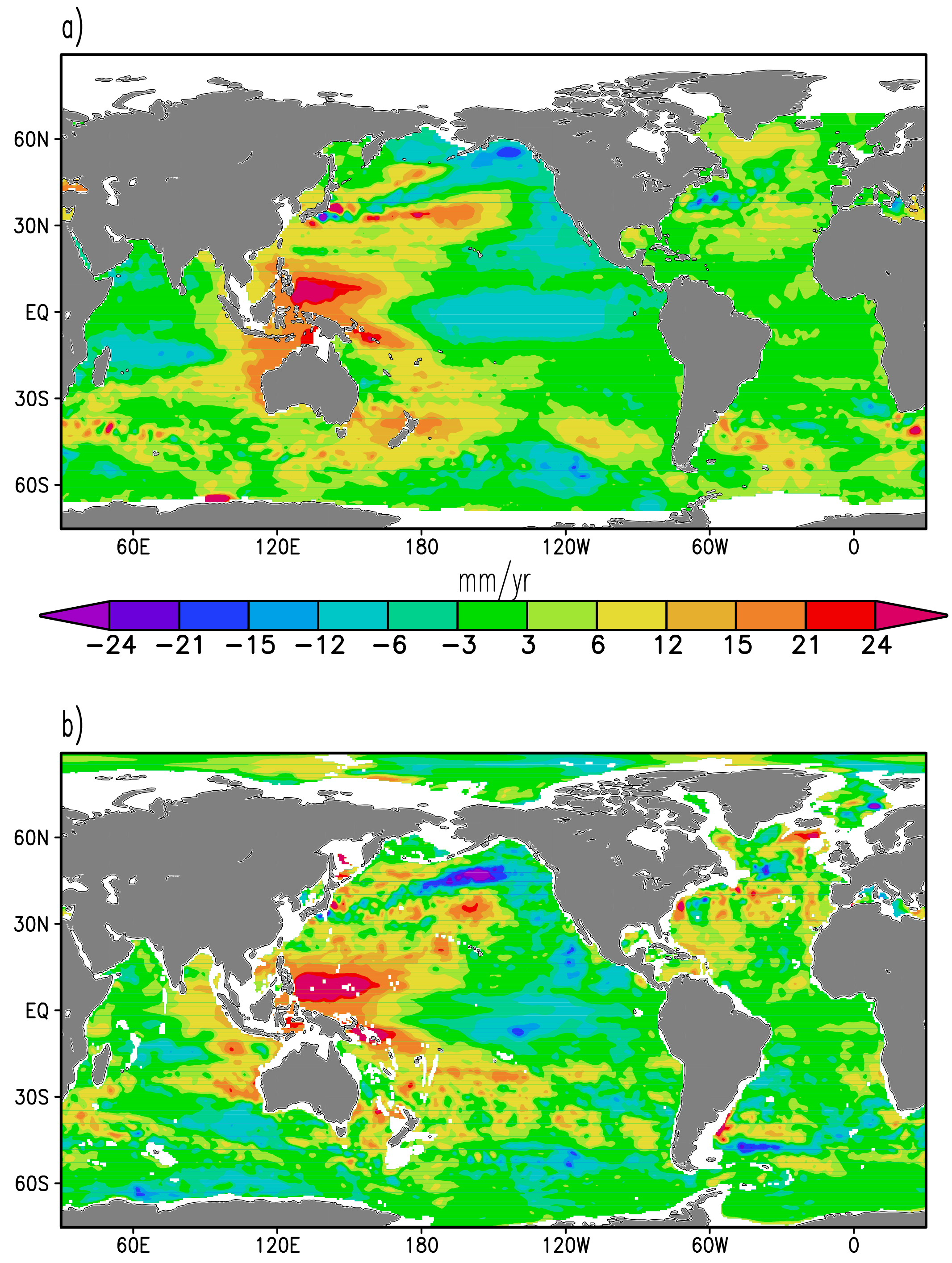

1960s
1970s
1980s
1990s
GFDL
CERF
UKOI
INGV
SODA
LEVI
EQ
20S
40S
60S
40W
20W
0
20E

Sea level trend 1993-2001

Topex/Poseidon sea level

SODA1.2*

***Altimetry not included**



Prospects for a 100yr ocean reanalysis

Centennial ocean reanalysis relies fundamentally on a corresponding atmospheric reanalysis

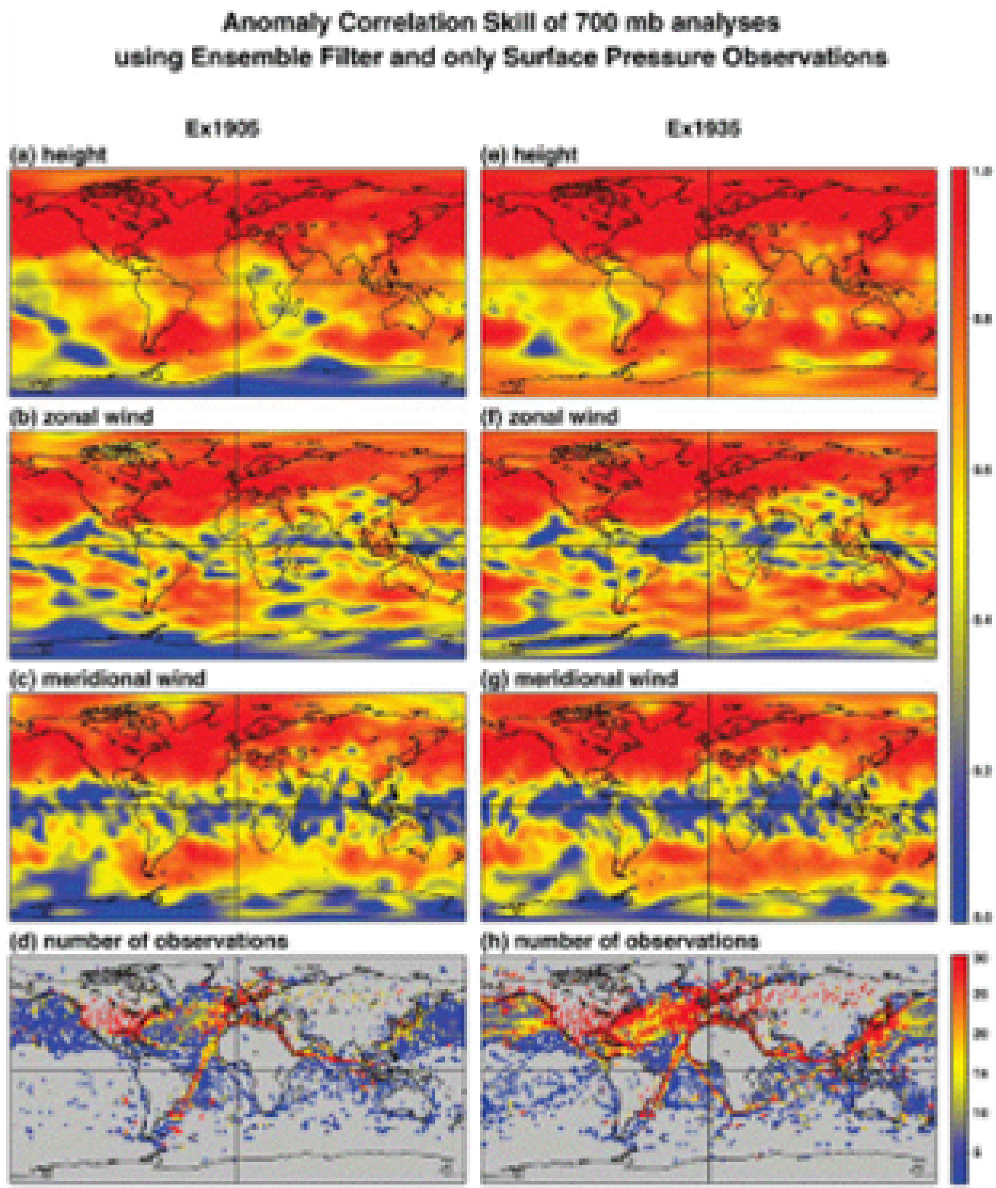
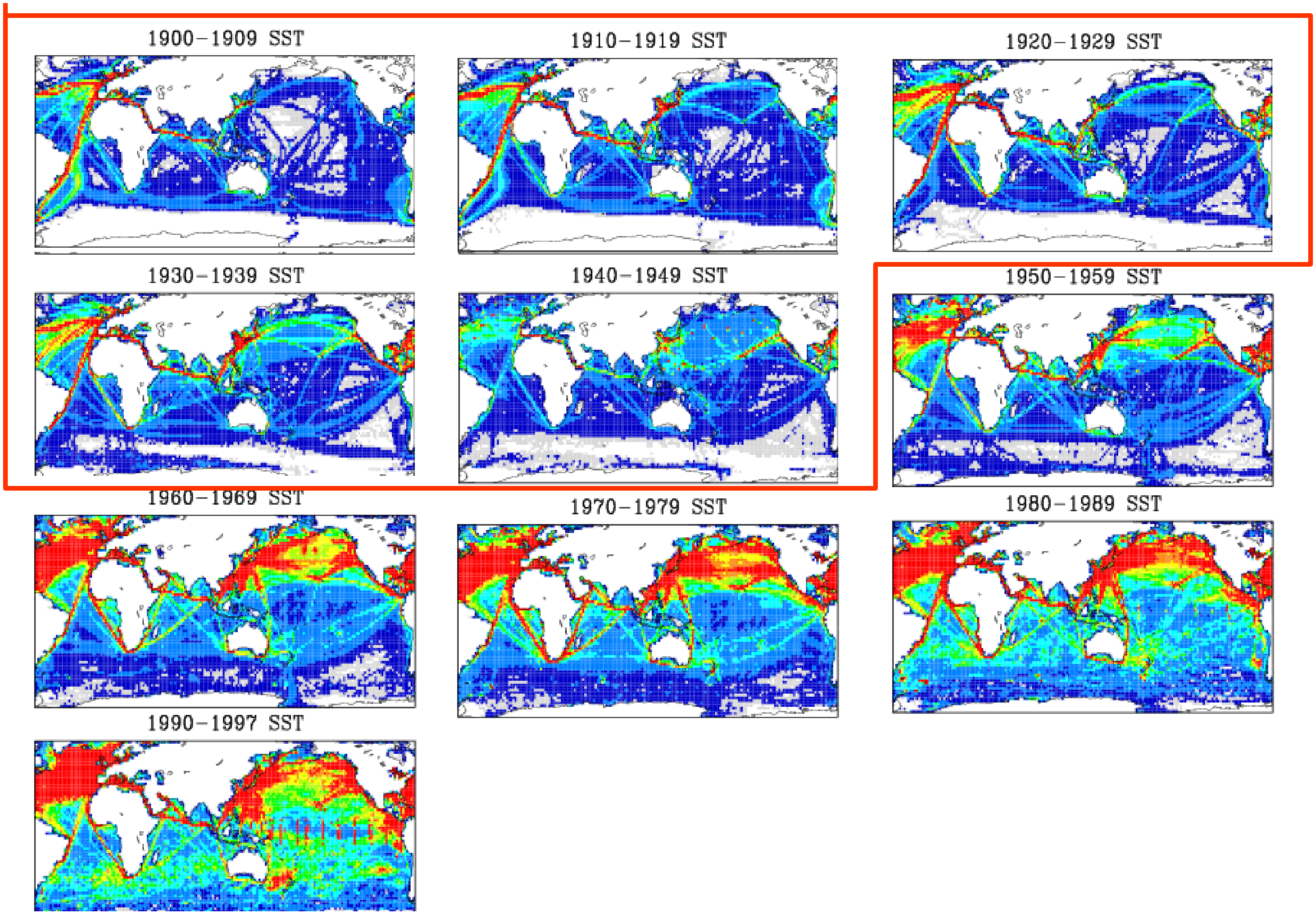


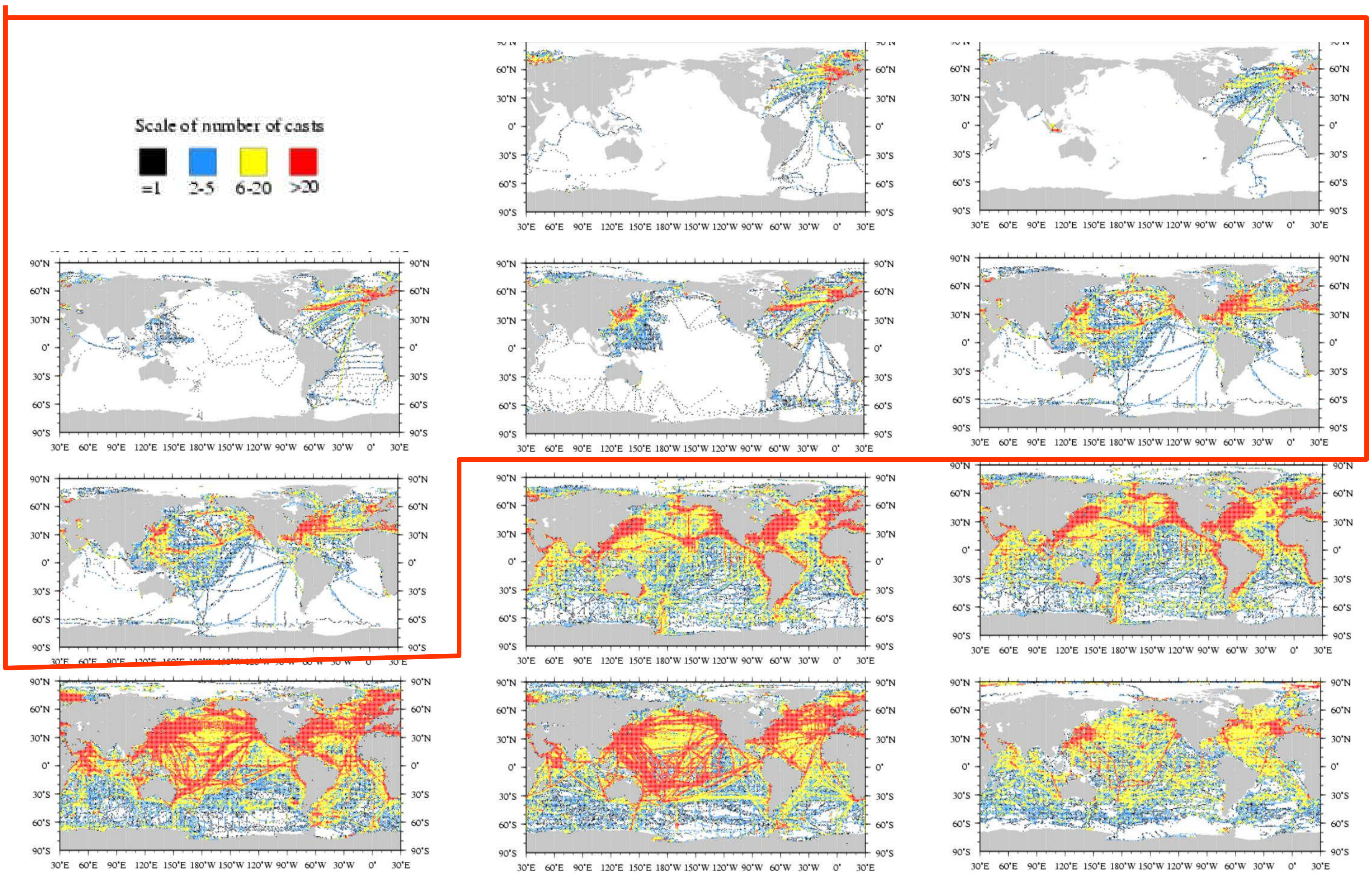
FIG. 6. Local anomaly correlation of Dec 2001 4-times-daily analyses from the full NCEP–NCAR reanalysis and (left) 1905 and (right) 1935 assimilation experiments using the ensemble filter. Correlations are shown for (a), (e) 700-mb geopotential height; (b), (f) 700-mb zonal wind; and (c), (g) 700-mb meridional wind. Colors in the bottom panels indicate the number of surface pressure observations used in each 2.5° × 2.5° grid box.

Campo et al., 2006

In situ SST Observations



Expansion of the profile network



Some References

- Carton, J.A., G.A. Chepurin, X. Cao, and B.S. Giese, 2000a: A Simple Ocean Data Assimilation analysis of the global upper ocean 1950-1995, Part 1: methodology, *J. Phys. Oceanogr*., **30,** 294-309.
- Carton, J.A., G.A. Chepurin, and X. Cao, 2000b: A Simple Ocean Data Assimilation analysis of the global upper ocean 1950-1995 Part 2: results, *J. Phys. Oceanogr*., **30,** 311-326.
- Carton, J.A., B.S. Giese, and S. A. Grodsky, 2005: Sea level rise and the warming of the oceans in the SODA ocean reanalysis, *J. Geophys. Res.*, **110**, art# 10.1029/2004JC002817.
- Carton, J.A., and B.S. Giese, 2007: A reanalysis of ocean climate using SODA, Mon. Wea. Rev., accepted.
- http://www.clivar.org/organization/gsop/synthesis/synthesis.php