Development and evaluation of ice-ocean reanalyses using the S(T) assimilation system

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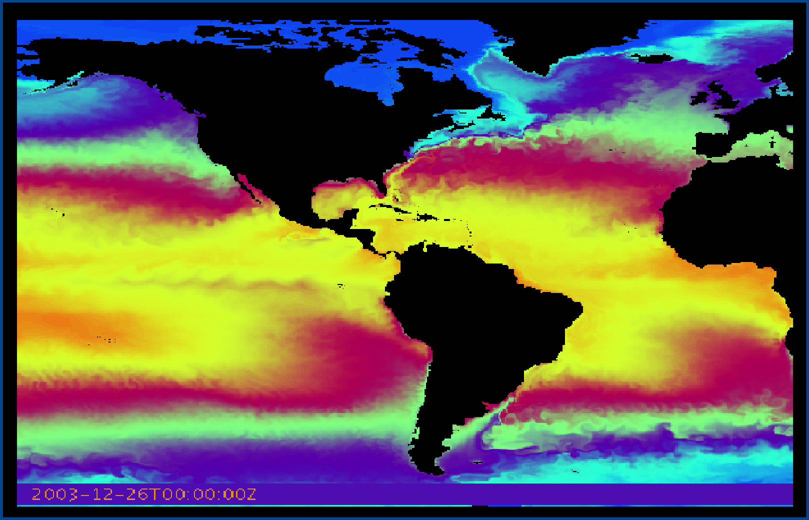
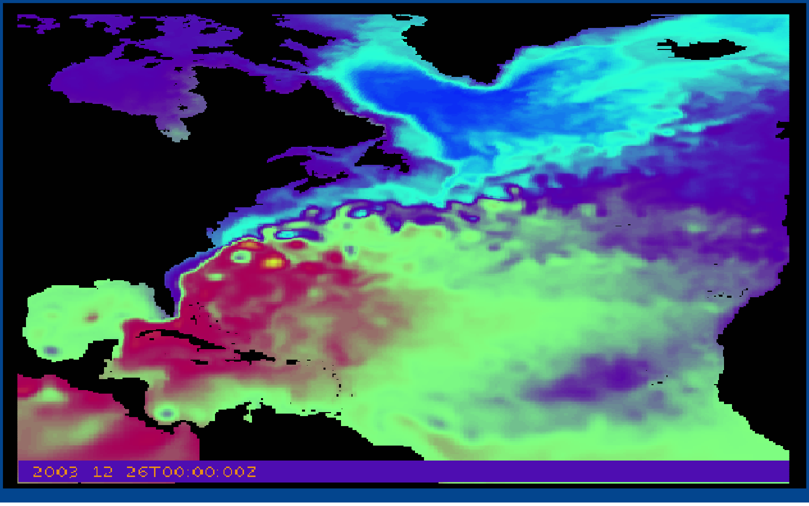
Now at: DFO/EC





Collaborators:

- ESSC: K. Haines, A. Gemmell, R. Mugford J. Blower, D. Bretherton
- ECMWF: M. Balmaseda, K. Mogensen
- CERFACS: A. Weaver
- UK Metoffice: M. Martin, D. Lea
- DRAKKAR: B. Barnier, T. Penduff, J.M. Molines, G. Madec, A.M. Treguier, A. Biastoch, C. Boning

Dalhousie, February 24th, 2009

NATURAL ENVIRONMENT RESEARCH COUNCIL
ENVIRONMENTAL SYSTEMS SCIENCE CENTRE

The University of Reading

Overview

- Ocean Reanalysis
  - Uses of reanalysis
  - Challenges of historical datasets
- Assimilation on isotherms
  - Depth versus temperature level assimilation
  - Impact of Argo assimilation
- New global ice-ocean reanalyses
  - Mean biases
  - Water mass properties
  - Transports

Uses of ocean reanalysis

- Initialization of seasonal forecasts:
  - Seasonal: ECMWF (Vidard et al. MWR, 2007)
  - Decadal : UK Metoffice DePreSys (Smith et al., Science, 2007)

- Climate signals:
  - Sea level rise:
    - Wunsch et al. (J. Clim., 2007)
  - Ocean heat content:
    - Carton and Santorelli (Submitted to J. Clim.)
    - Kohl and Stammer (JPO, 2007)
  - Meridional overturning circulation:
    - Wunsch and Heimbach (JPO, 2006)
    - Balmaseda et al. (GRL, 2007)

CLIVAR Global Synthesis and Observations Panel (GSOP) Intercomparison

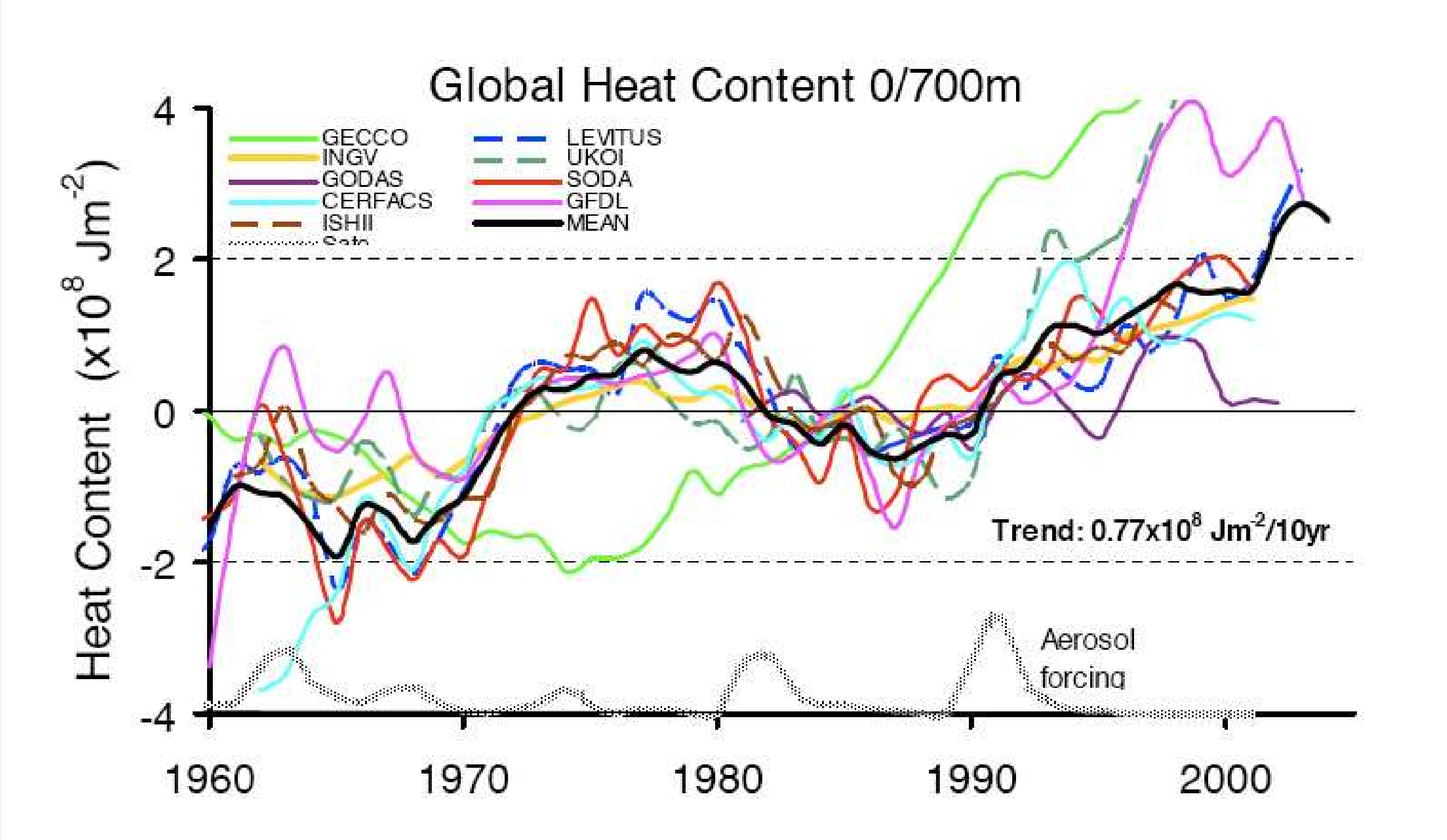
- Main goals:
  - Evaluate quality and skill of existing global synthesis products (reanalyses) for climate applications
  - Determine common strengths and weaknesses and their usefulness for various climate applications

- Reanalyses included:
  - ECCO-GODAE, ECCO-JPL, GECCO, ECMWF, SODA, CERFACS, MERCATOR, INGV, MOVE, GFDL, Reading, UKDP, UKOI
  - Includes model resolutions from 2 to ¼ degree
  - Range of assimilation methods (e.g. OI, KF, 4DVAR)
  - Some span last several decades, although most only cover recent period (1992 onwards)

www.clivar.org/organization/gsop/projects.php

Global ocean heat content variability

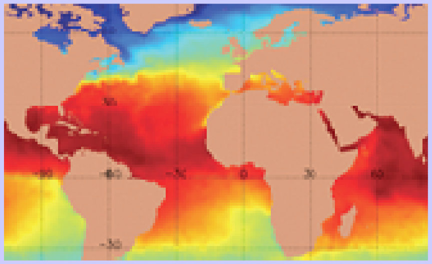
Carton and Santorelli, submitted to J. Clim.



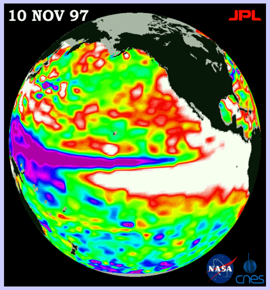
Challenges posed by historical ocean datasets

- Satellite:
  - SST, Sea level
- Buoy, tide gauge, drifters
- XBT
  - Bias problems with fall rate (Wijffels et al. 2008)
  - Only near-surface (top 300-500m)
  - Poor spatial distribution (localized to ship tracks)
- CTD casts and moorings
- Argo:
  - Autonomous profiling floats
  - Near-global coverage of T,S over upper 2000m
  - Radical improvement in subsurface ocean sampling beginning around 2002

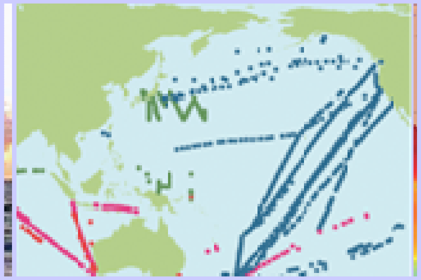
SST

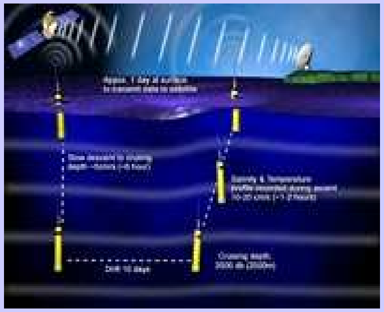


Altimetry

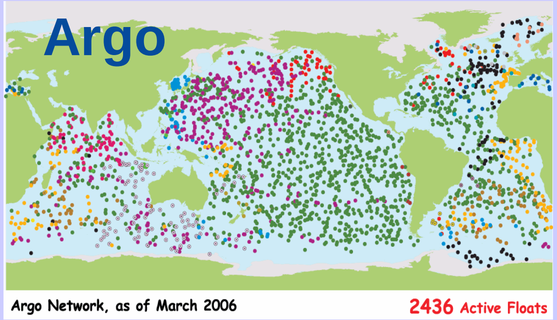


XBT



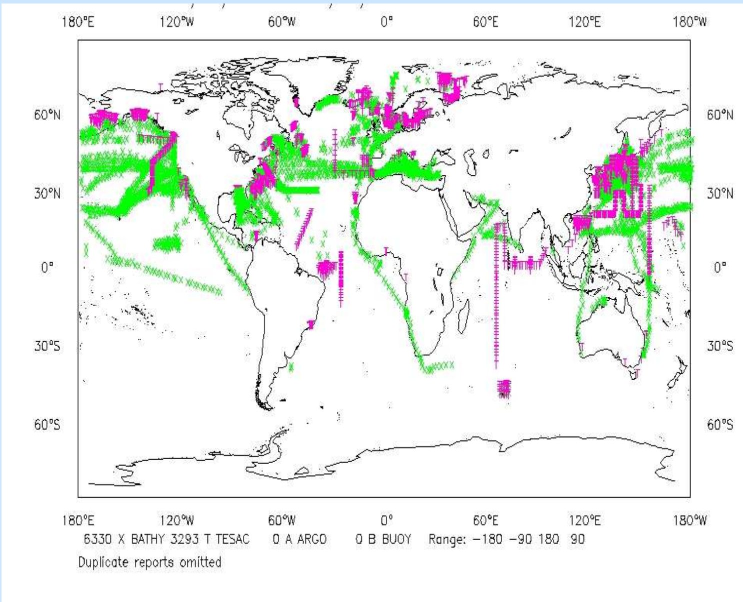


Argo

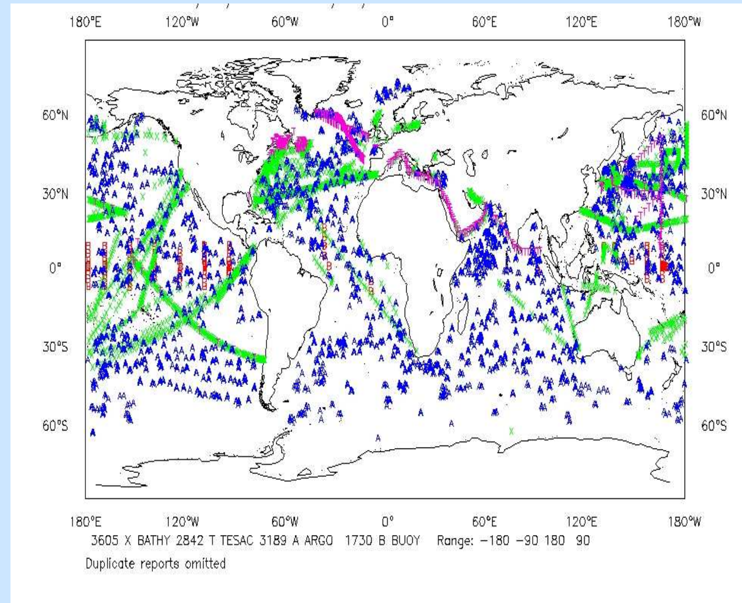


Challenges posed by historical ocean datasets

June, 1975



June, 2004



Argo
Buoy
CTD
XBT

Argo radically improves:
- spatial sampling
- salinity observations

Questions:

1. How can we best make use of observations prior to Argo?

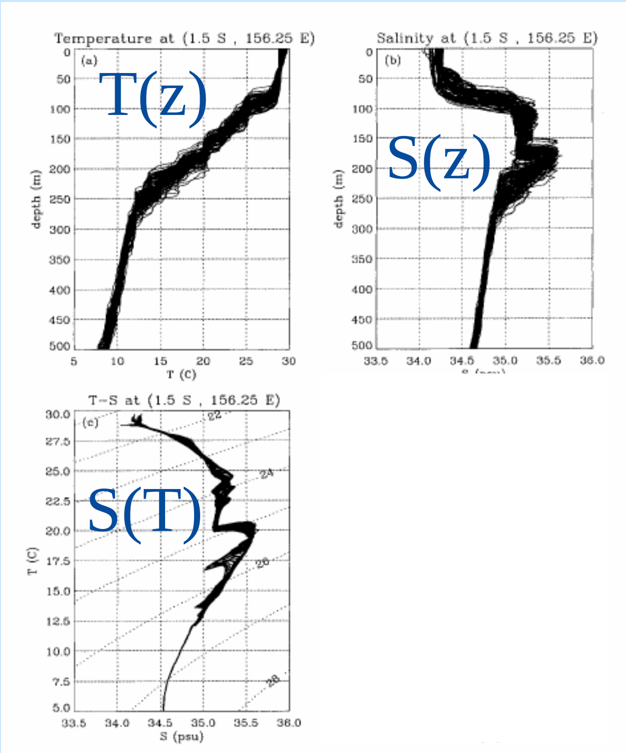
2. Can Argo help us with this?

How can we best make use of the available observations?

Two types of variability: dynamic and that due to water mass changes

Dynamic: high frequency
short correlation scales

Water mass: low frequency
long correlation scales



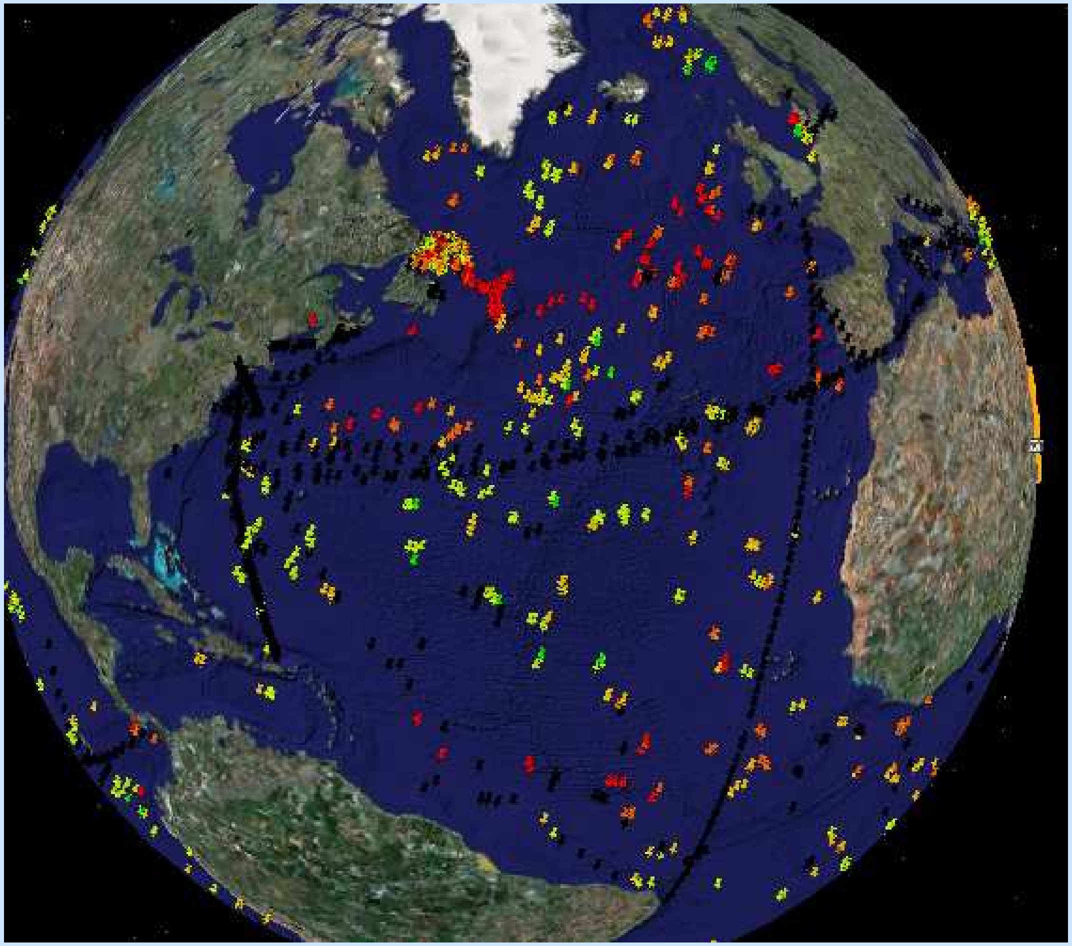
Implications for data assimilation:

- collocalization
- error covariances
  (i.e. length scales)

Collocalization RMS S(z)

- Screenshot of OceanDIVA output visualised in GoogleEarth
- Pins are coloured by RMS misfit of model – observed salinity
- Comparison is for January 2004 of 47yr 1 degree model control run

RMS > 0.4 psu
RMS < 0.1 psu



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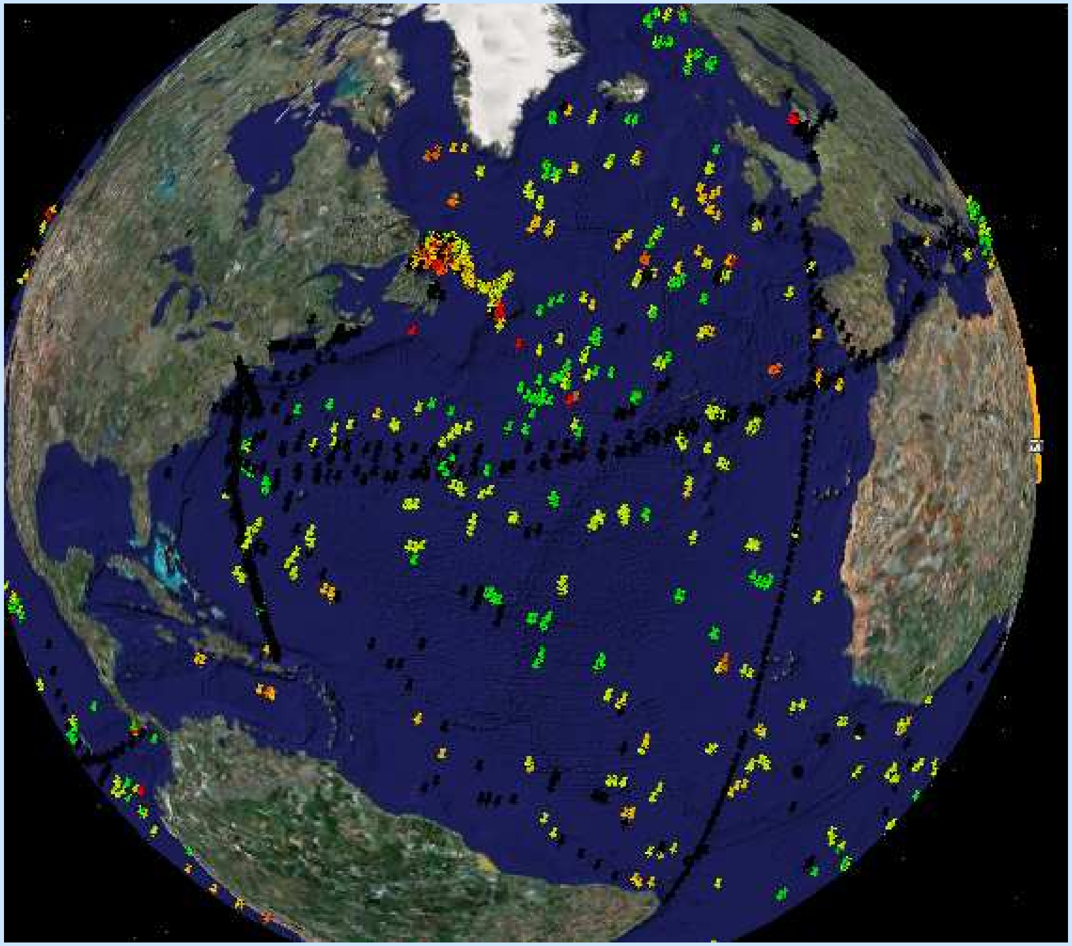
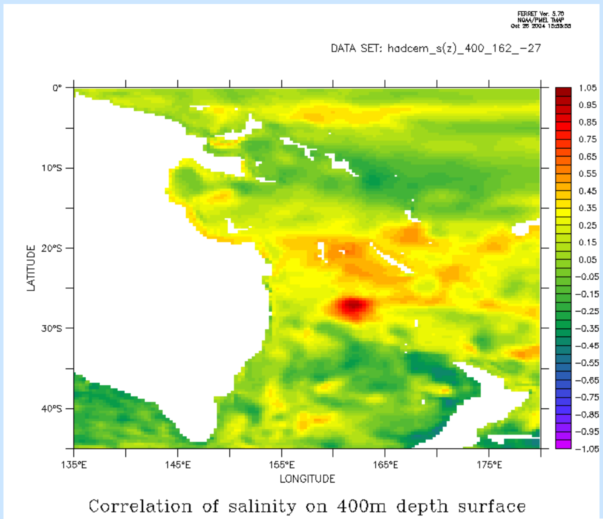


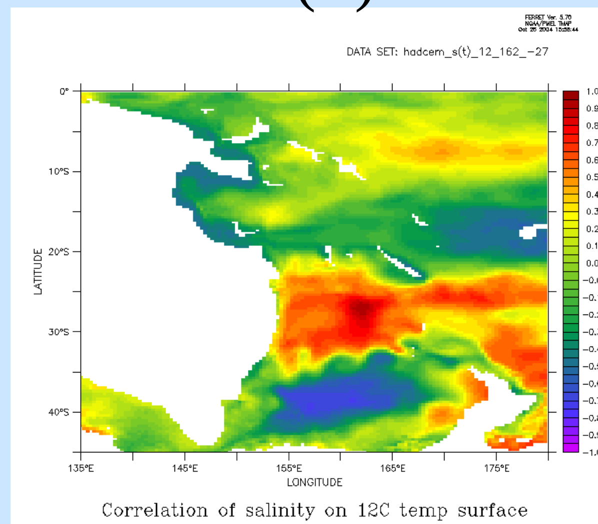
Longer covariance length scales along isotherms

One-point correlation maps in HadCEM

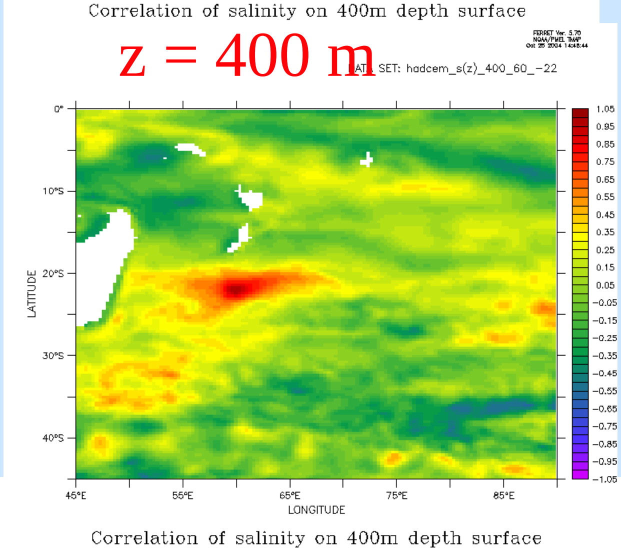
S(z)



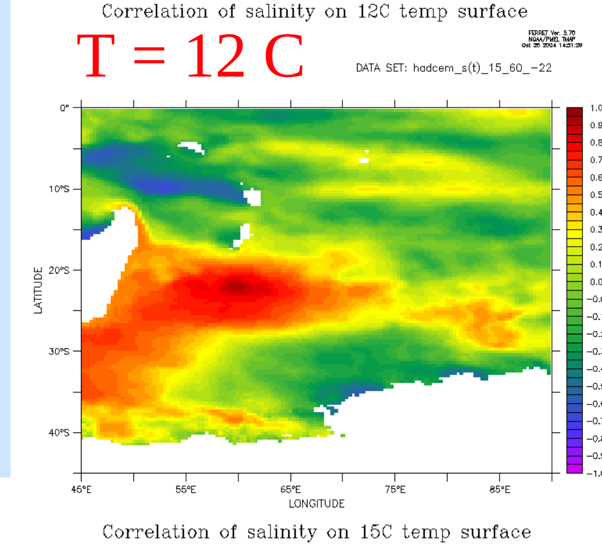
S(T)



z = 400 m



T = 12 C

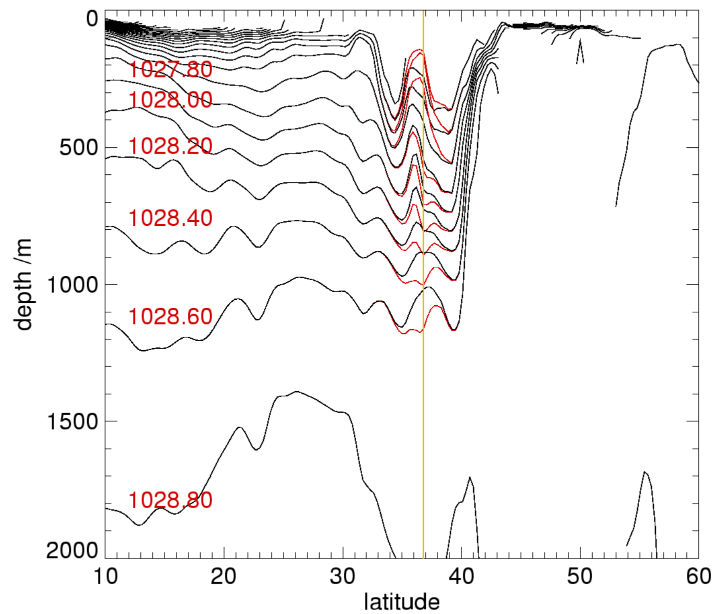


Haines et al. (MWR, 2006)

Assimilation of 1 observation (near Gulf Stream)

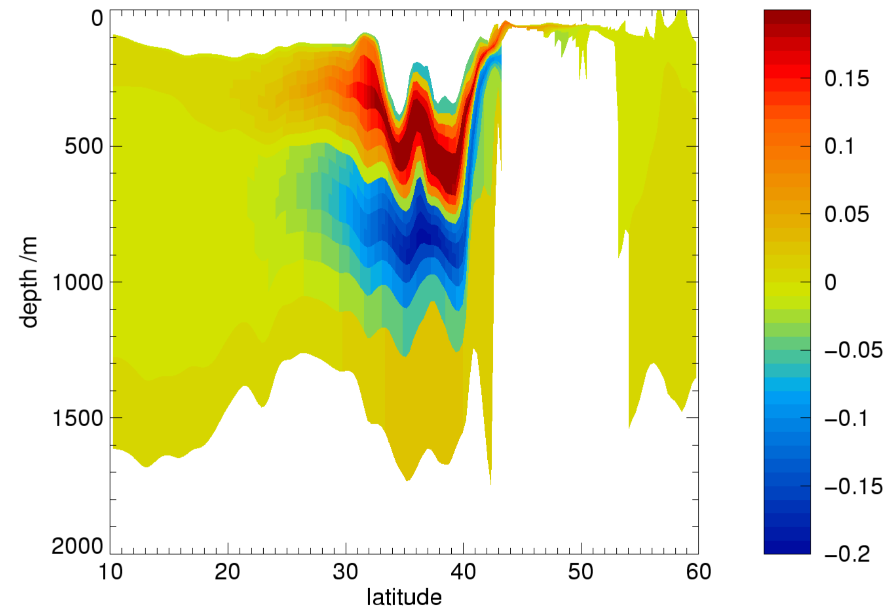
T(z), S(z) → z(ρ) , π (ρ) → Assimilate → T(z), S(z)

Density level depth z(ρ)
before and after assimilation



50 km length scale

Spiciness increment π (ρ)



300 km length scale

Data Assimilation

Kalman Filter Equation:

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{K} (\mathbf{y}_o - \mathbf{H}\mathbf{x}_b)$$

where $\mathbf{x}_a$ is the model analysis state vector

$\mathbf{x}_b$ is the model background state vector(first guess)

$\mathbf{y}_o$ is the observation vector

$\mathbf{K}$ is the gain matrix

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where $\mathbf{x}_a$ is the model analysis state vector

$\mathbf{x}_b$ is the model background state vector(first guess)

$\mathbf{y}_o$ is the observation vector

$\mathbf{K}$ is the gain matrix:

$$\mathbf{K} = \mathbf{B}\mathbf{H}^T\,(\,\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}\,)^{-1}$$

where $\mathbf{H}$ is the observation operator

(interpolation to observation space)

$\mathbf{R}$ is the observation error covariance

$\mathbf{B}$ is the background error covariance

How do we specify B?

Model background error covariance

- Commonly specified using:
  - Covariance length scales (e.g. SODA, Carton et al. 2000)
  - Model EOFs (Mercator (SEEK); Brasseur and Verron, 2006)
  - Model forecast error covariances (Bluelink; Oke et al. 2006)

- Our approach:
  - "Flow dependent" error covariance
    - Assimilation along isotherms or isopycnals

S(T) Assimilation method

<u>Standard method:</u>

$$T_a(z) = T_b(z) + K_z\,[T_o(z) - H\,T_b(z)]$$
$$S_a(z) = S_b(z) + K_z\,[S_o(z) - H\,S_b(z)]$$

<u>S(T) algorithm:</u>

$$T_a(z) = T_b(z) + K_z\,[T_o(z) - H\,T_b(z)]$$
$$S'_a(z) = S_b(z) + \Delta S_{bal},$$ such that

ΔS_{bal} ensures $S'_a(T_a) = S_b(T_a)$

} from a T obs

$$S_a(T_a) = S'_a(T_a) + K_T\,[S_o(T_a) - H\,S_b(T_a)]$$

} from an S obs

- K_T allows spreading over much greater distances than K_z due to increased covariance length scales on isotherms.
- Also, second salinity increment is independent of the 1st!

Model/forcing details

- NEMO (v2.3) modelling framework:
  - OPA9 ocean model
    - 46 z-levels, free surface, partial steps, energy-enstrophy conserving momentum advection, TKE vertical mixing
    - Namelist settings and keys as in DRAKKAR ‘G70’ series
    - No 3D relaxation to climatology (apart from small regions used in G70)
  - LIM2 ice model
  - Tripolar grid :
    - ORCA1: Global 1° resolution, 1/3° tropical enhanceme nt
    - ORCA025: Global 1/4° resolution

- Bulk forcing (DFS3) from :
  - T,Q,U,V: ERA40/ECMWF Operational Analyses
  - Qlw, Qsw, Precip, Snow : CORE (ISCCP), with reduction applied to precipitation at high latitudes.
  - 60 day / 10m SSS relaxation with 5X under-ice relaxation
  - Forcing details identical to G70

Assimilation scheme and forcing details

- Assimilate in situ temperature and salinity data only
- Observations from quality-controlled ENSEMBLES data set (Ingleby and Huddleston, 2007) from UK MetOffice (EN3_v1c)
  - includes WOD05 and Argo
- Uses NEMOVAR online observation operator (FGAT)
- Analysis Correction Method (Lorenc, 1991) for z and T levels implemented within NEMO code (<10% increase in computation cost)
- Spatially-varying length scales (Carton et al., 2000):
    - ZONAL: 450km tropical to 375km mid-latitudes
    - MERID: 250km tropical to 375km mid-latitudes
- T-level increments only used between 40N-40S, and below 100m depth. Outside this region *z*-level increments are used
- 5 day assimilation cycle with 1 day IAU.

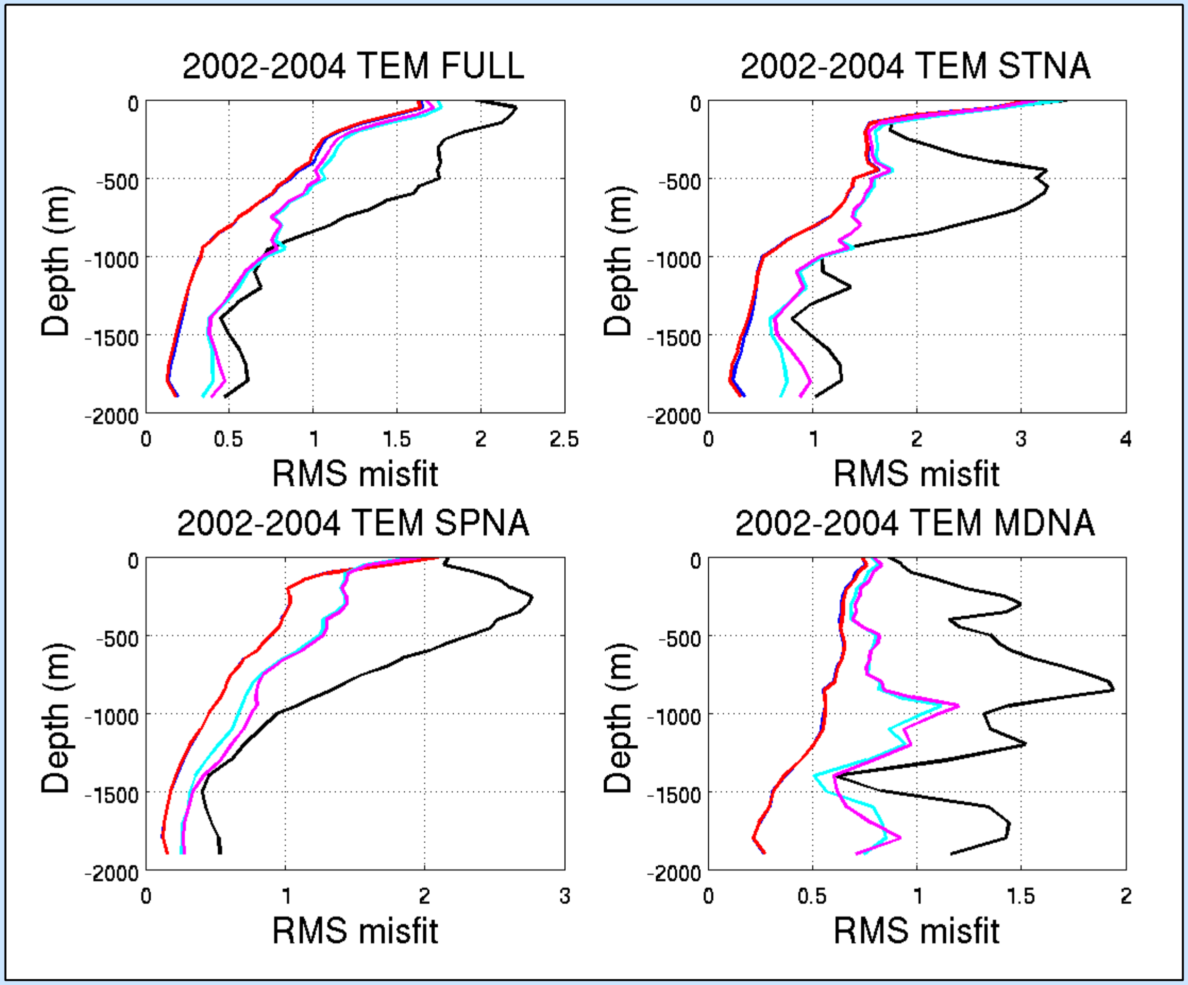
Ocean Reanalysis Experiments

- Illustrate:
  - Impact of Argo
  - Difference between assimilation on Z and T levels
- 1 degree model (ORCA1):
  - 3-year experiments (Jan. 1, 2002 – Dec. 31, 2004), initialized from a 44-year control run.
    - ALL: Assimilate all in situ observations from ENSEMBLES data (i.e. XBT, CTD, moorings and Argo)
    - NOARGO: Withold Argo data from above
  - ALL and NOARGO but using standard Z-level assimilation

Smith and Haines, QJRMS (in press)

RMS Temperature Misfits : 2002-2004

ORCA1 - Ctl
ORCA1 – Z level
ORCA1 – T level
ORCA1 – Z level, No Argo
ORCA1 – T level, No Argo



FULL – Global

STNA – Sub-trop. N. Atl.
20N-45N, 80W-8W

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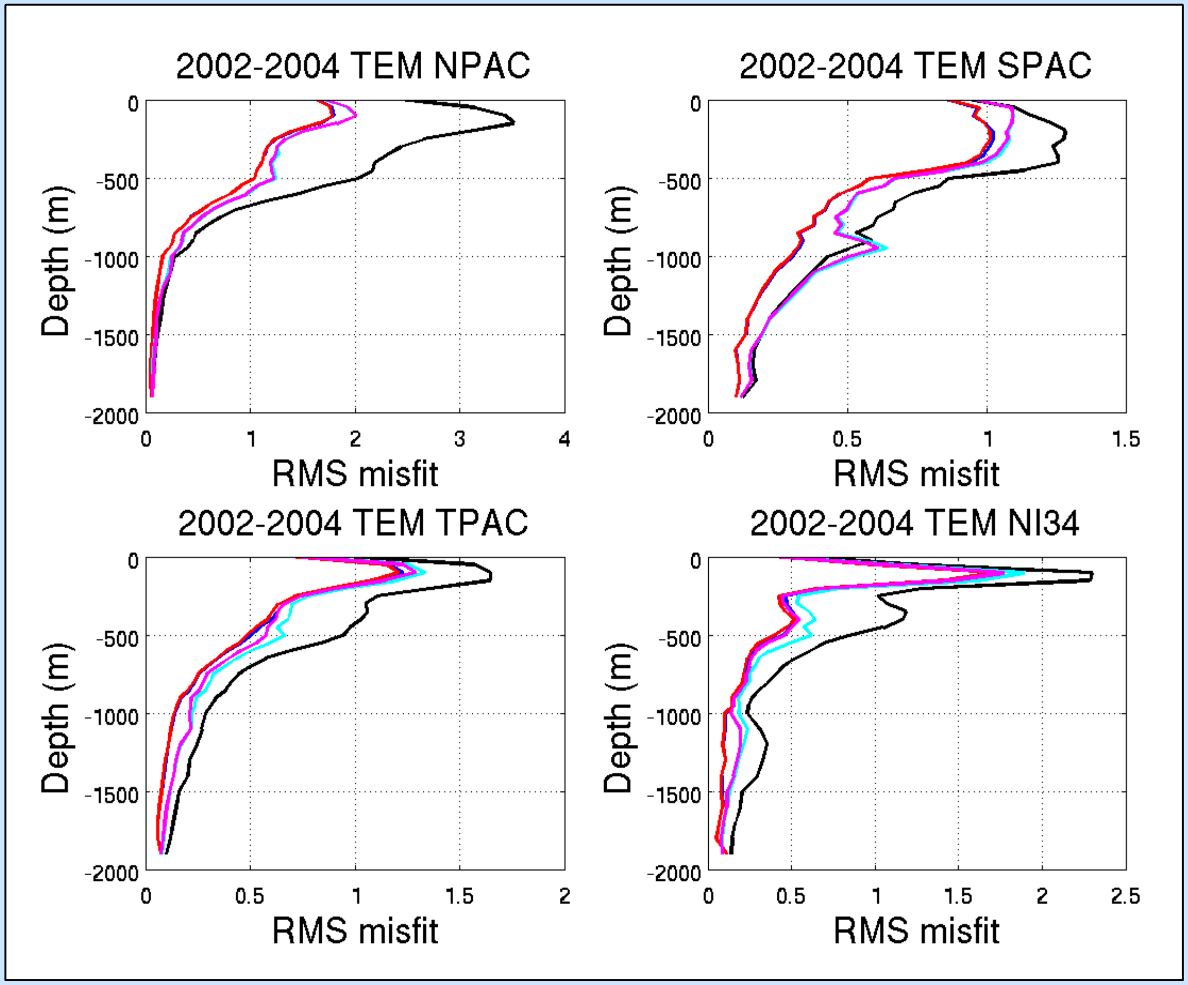
30S-30N

NI34 – Nino 3.4
5S-5N, 170W-120W



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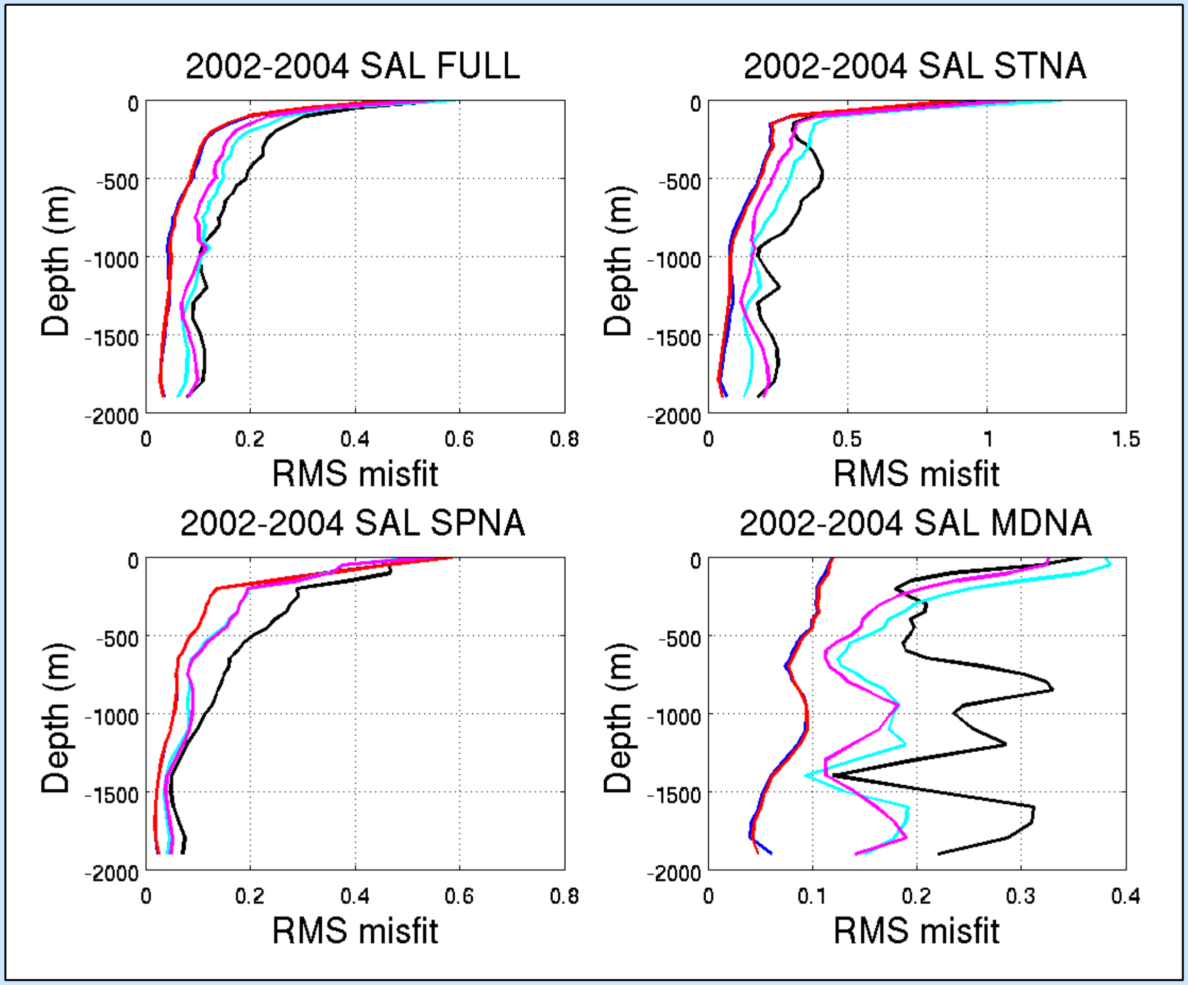

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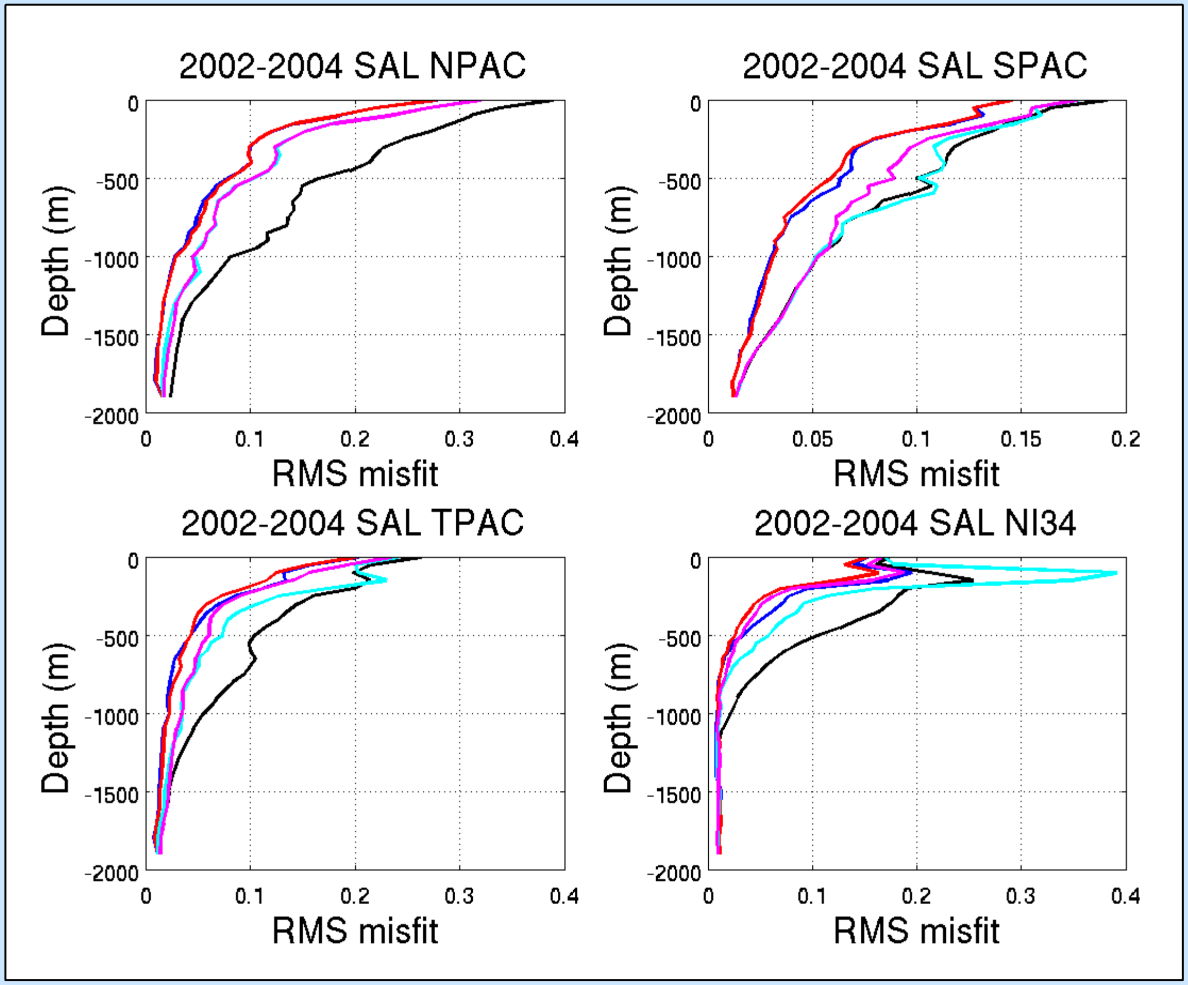

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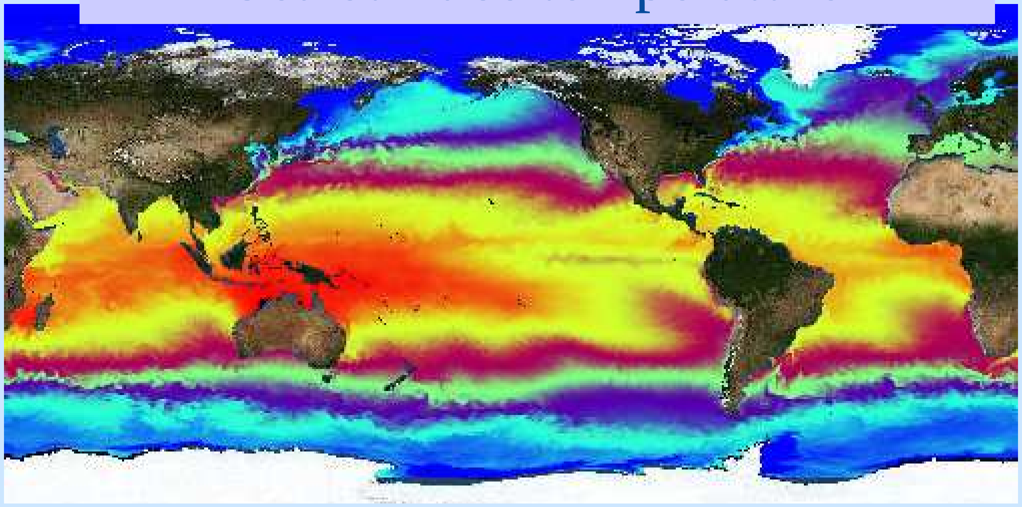
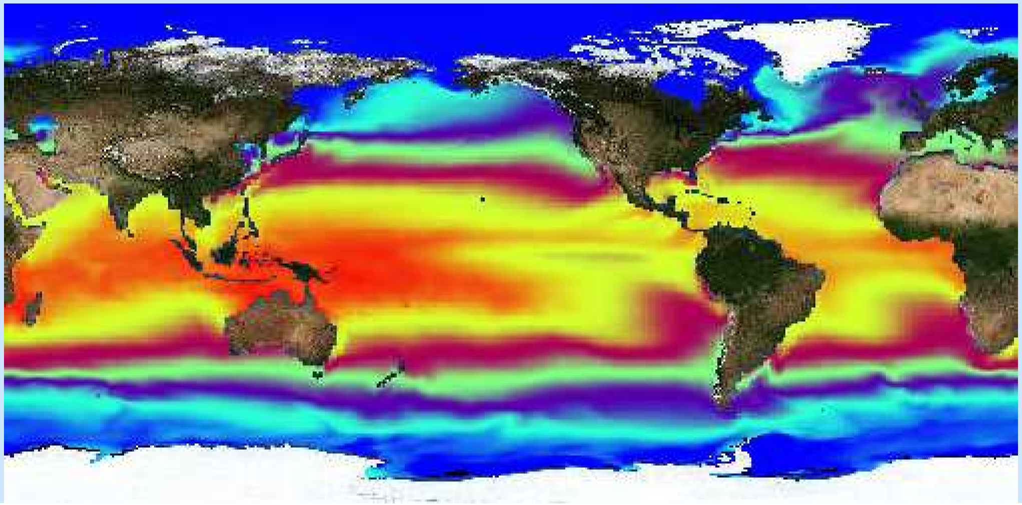
Global reanalysis using S(T) assimilation

Sea surface temperature



- ¼ degree reanalysis
  - Eddy-permitting
  - 1987-2007

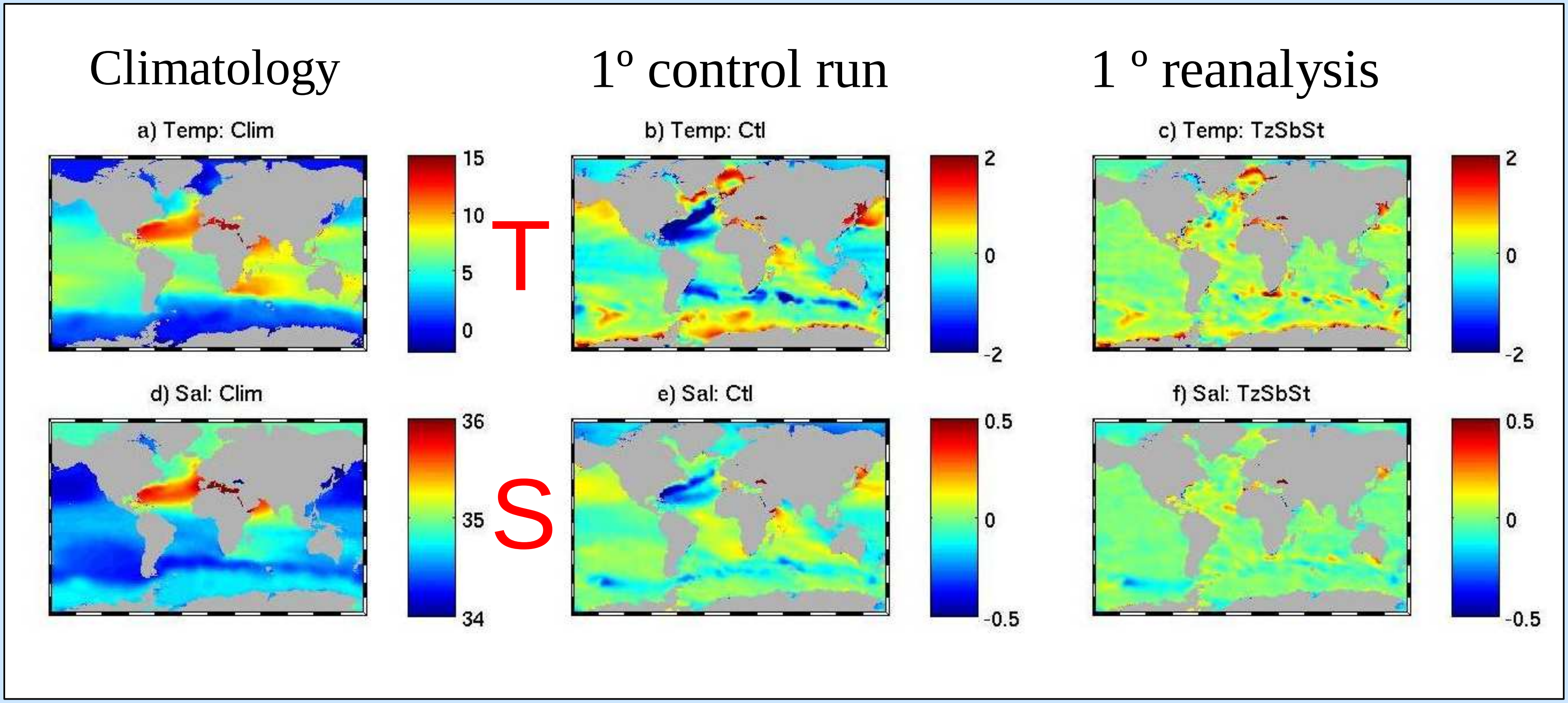


- 1 degree reanalysis
  - 1/3º Eq enhancement
  - 1958-2007

Both reanalyses available at:
BODC, Godiva2 and OceanDIVA

Differences with climatology

Average 300-1000m

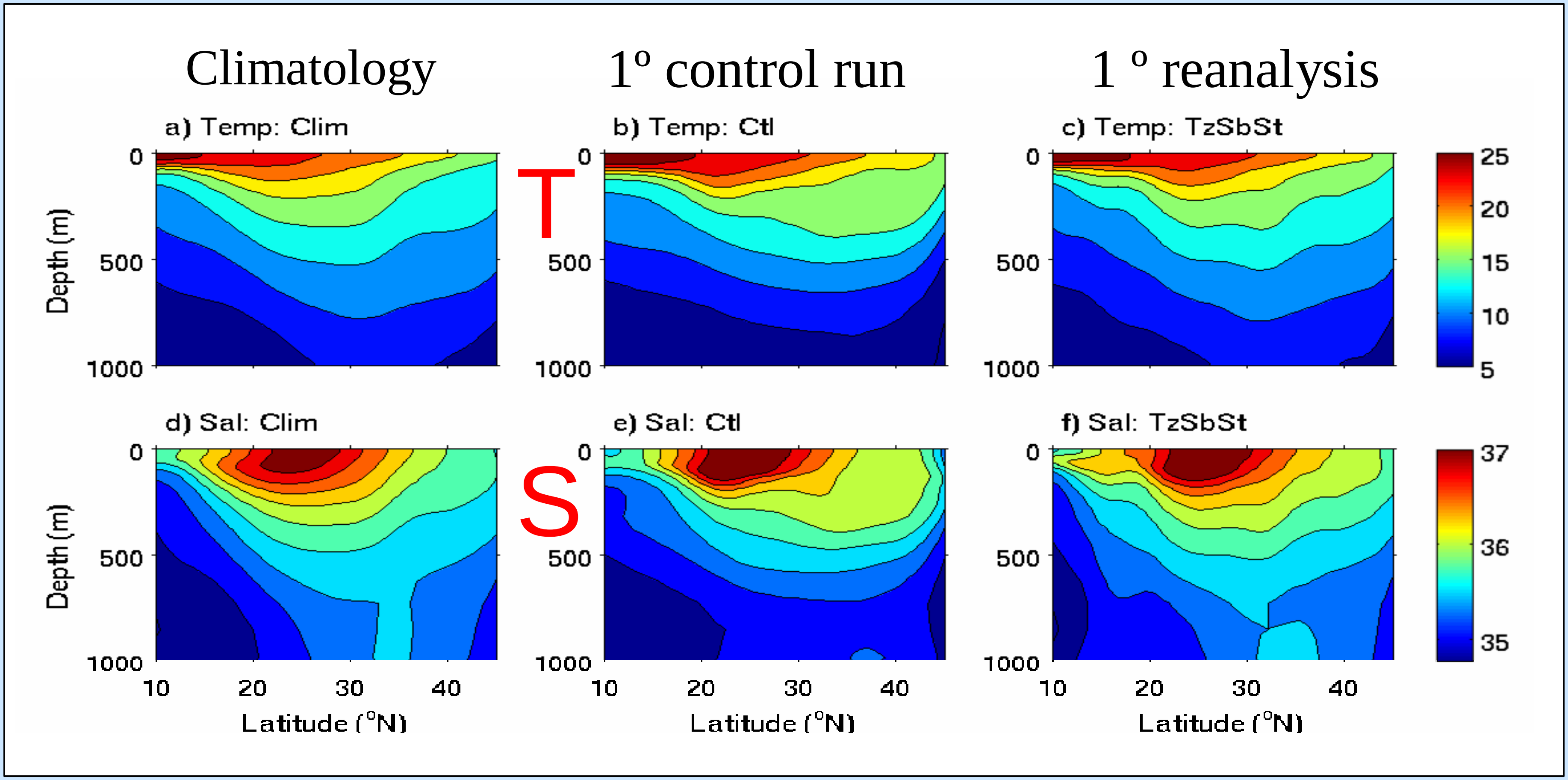


- Annual mean for 2004
- Large bias in Subtropical North Atlantic in control
- Biases corrected in reanalysis

Smith and Haines, QJRMS (in press)

Differences with climatology

Average 300-1000m



Smith and Haines, QJRMS (in press)

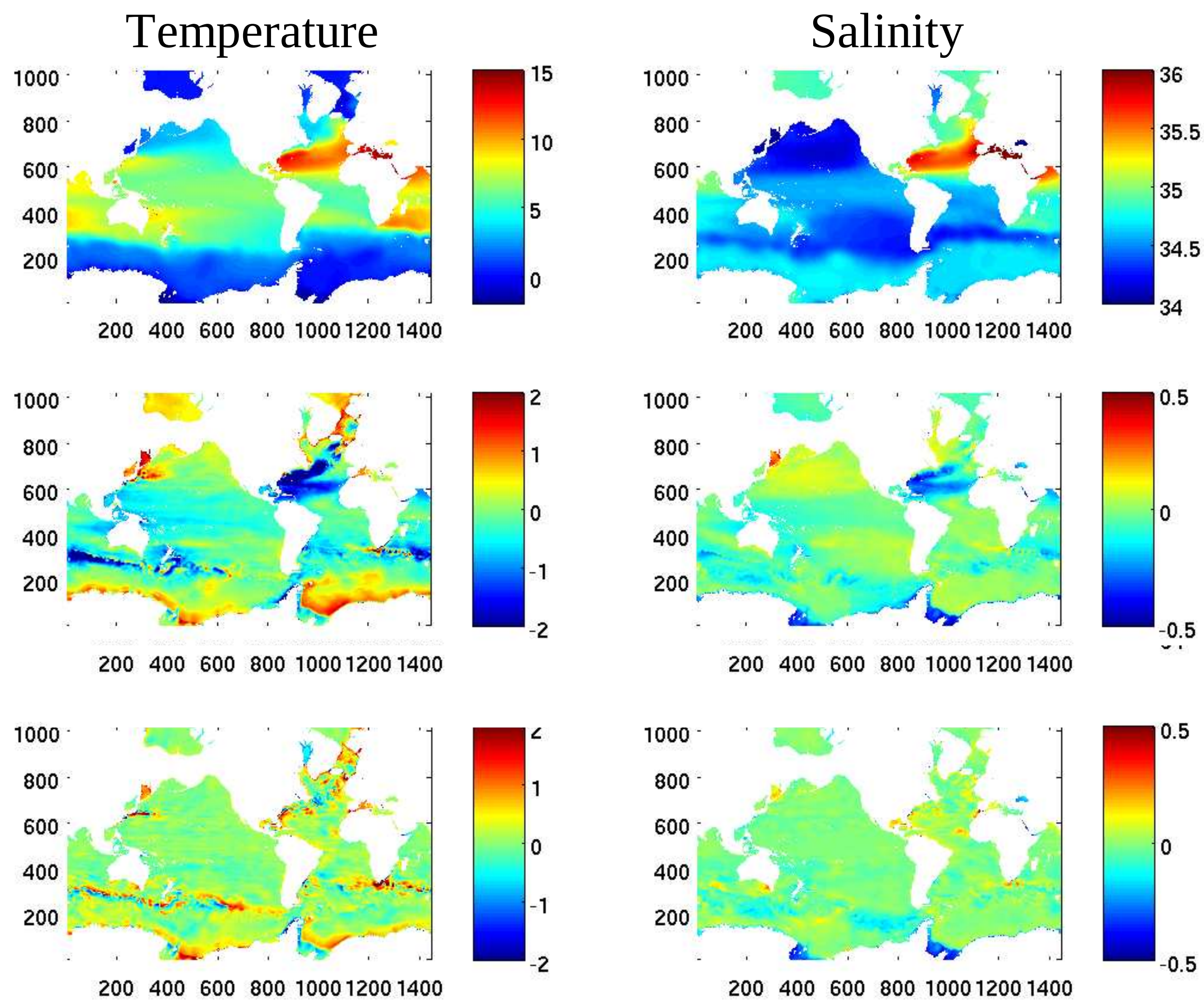
Biases in the mean state

Average 300-1000m

Climatology

¼ º control run

¼ º reanalysis



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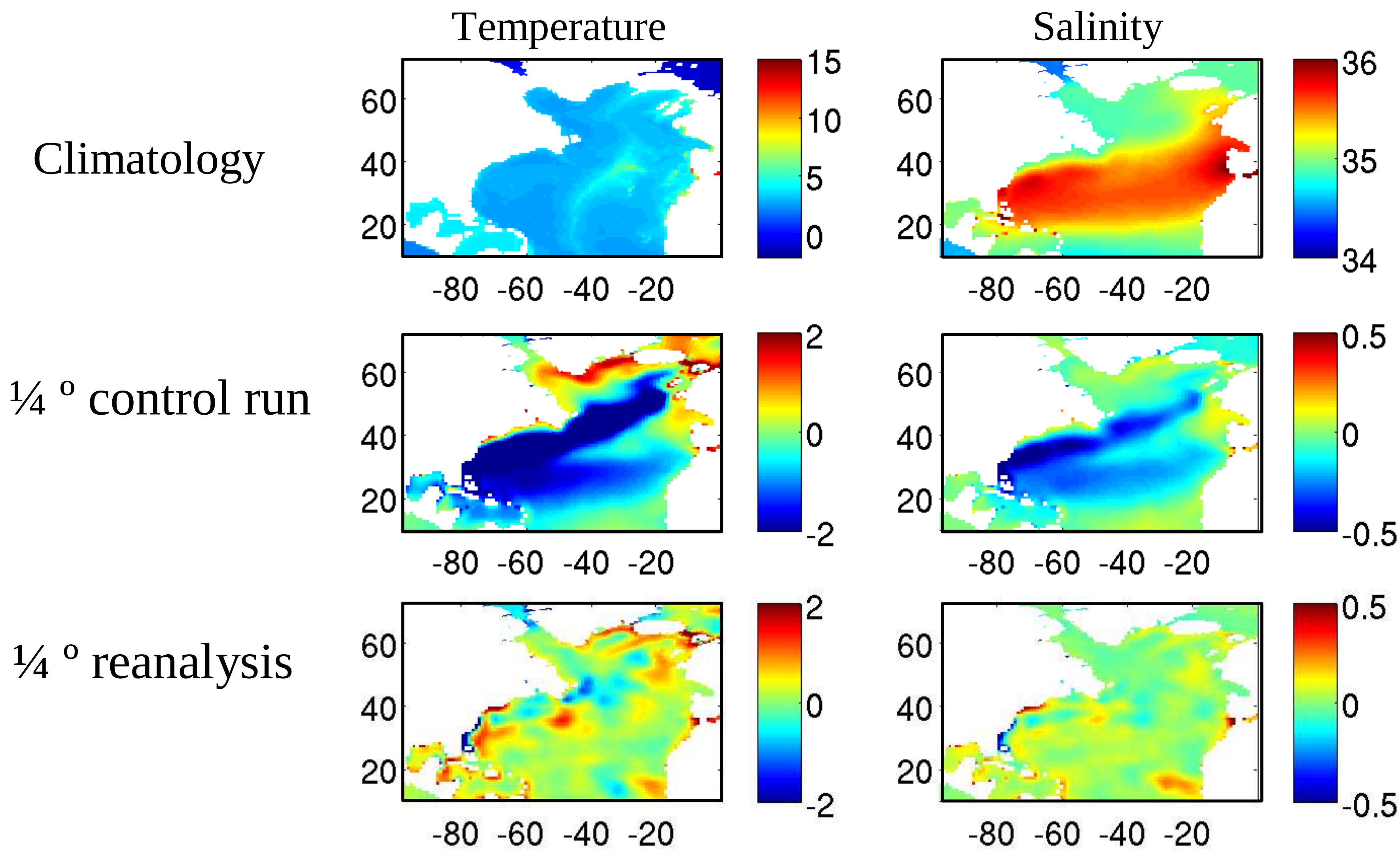

RMS Temperature Misfits : 1988-2004

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ORCA1-R07 (assim)
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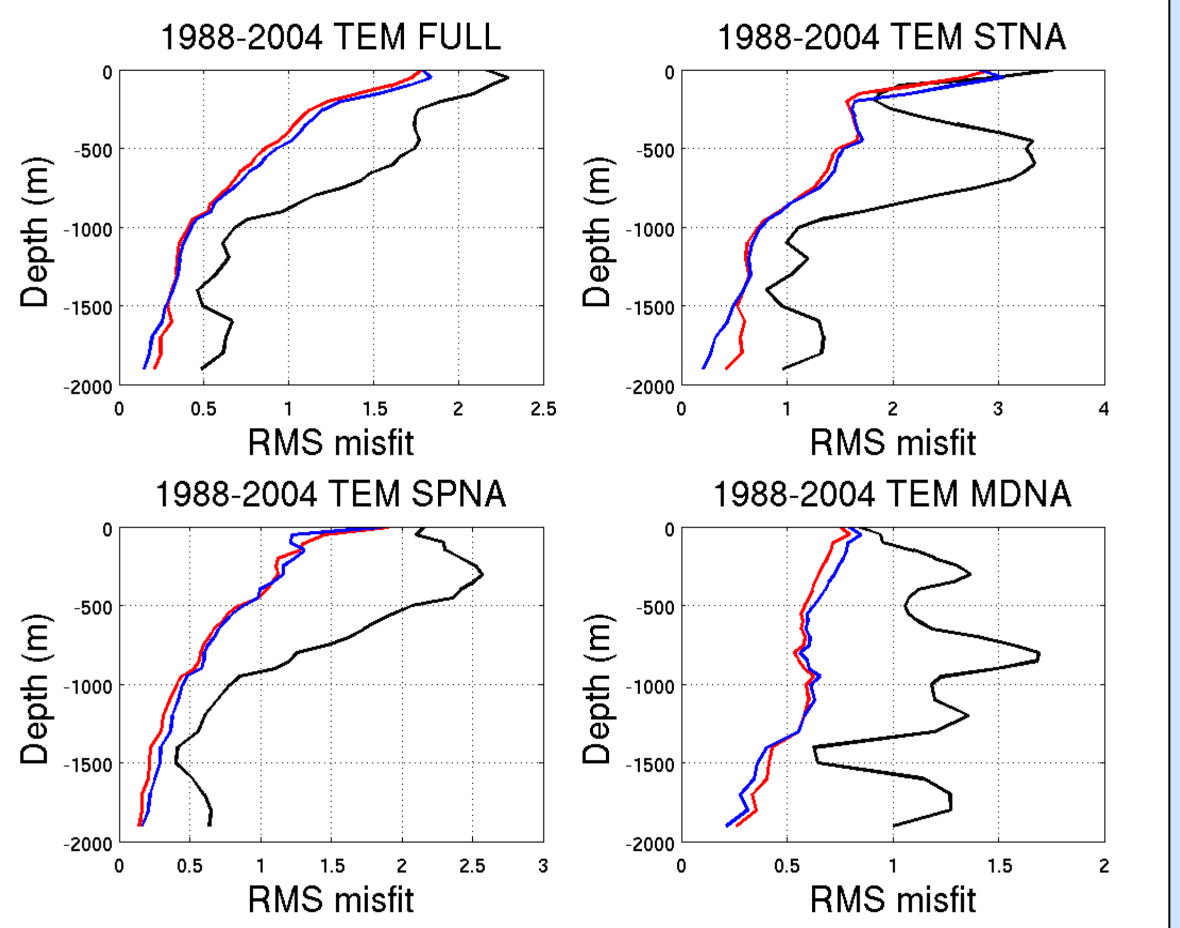

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RMS Salinity Misfits : 1988-2004

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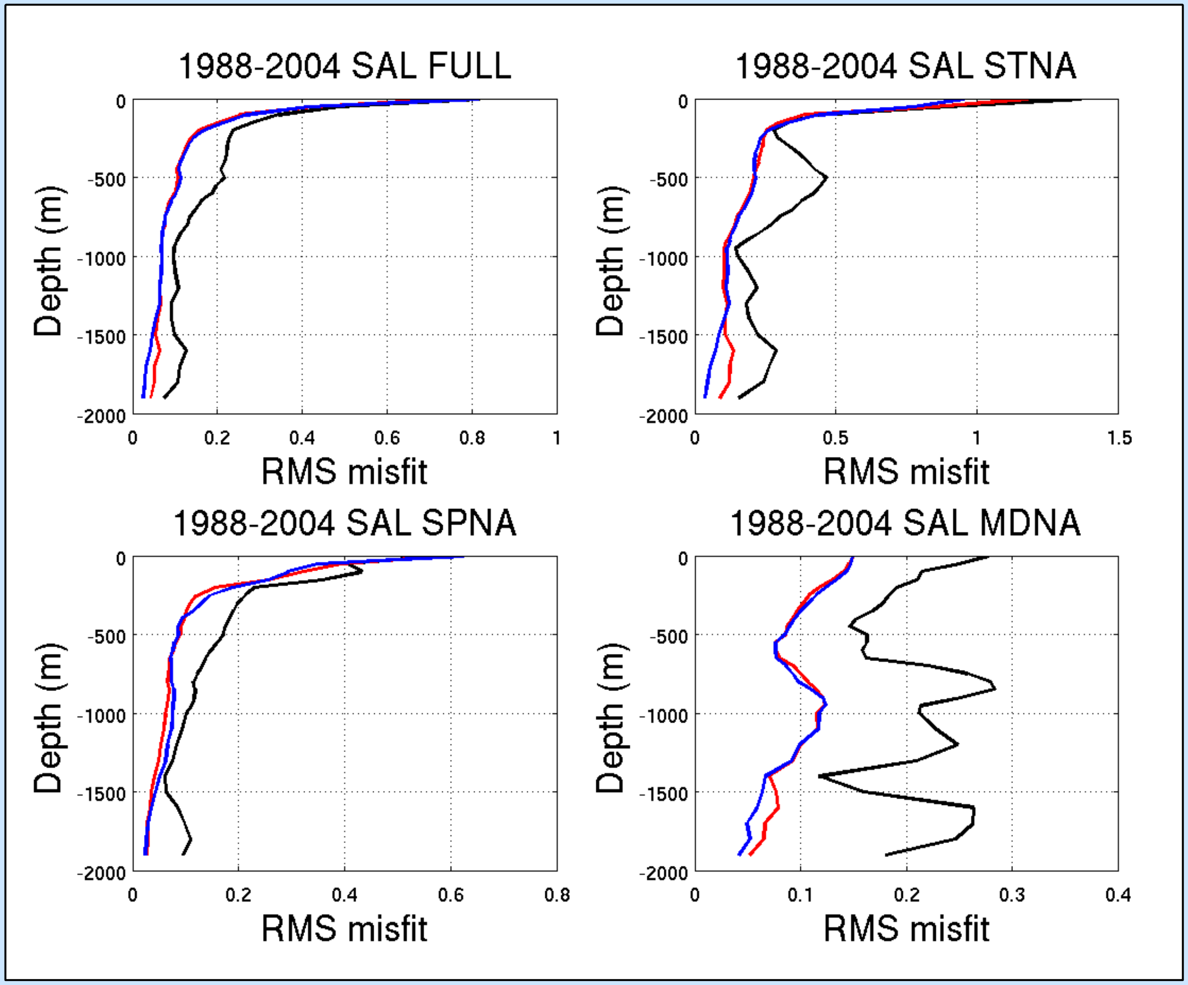

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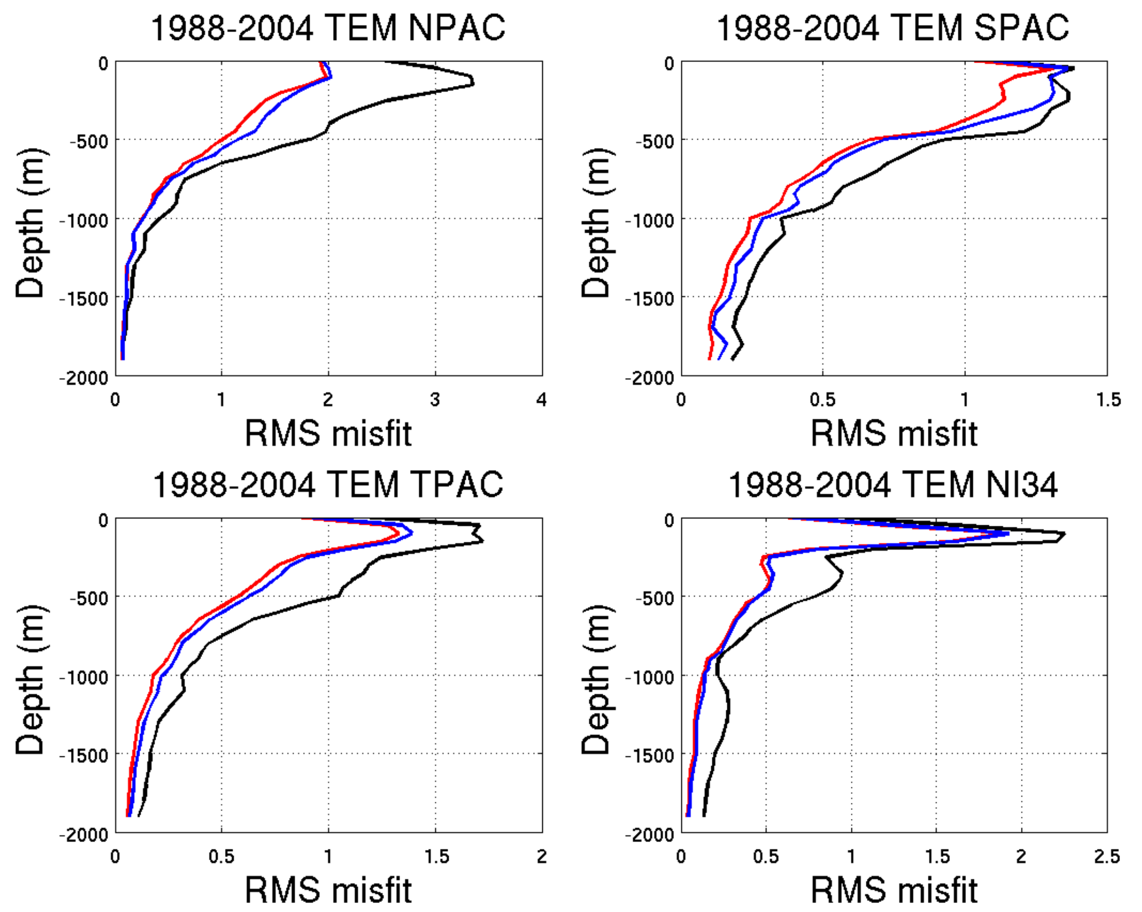

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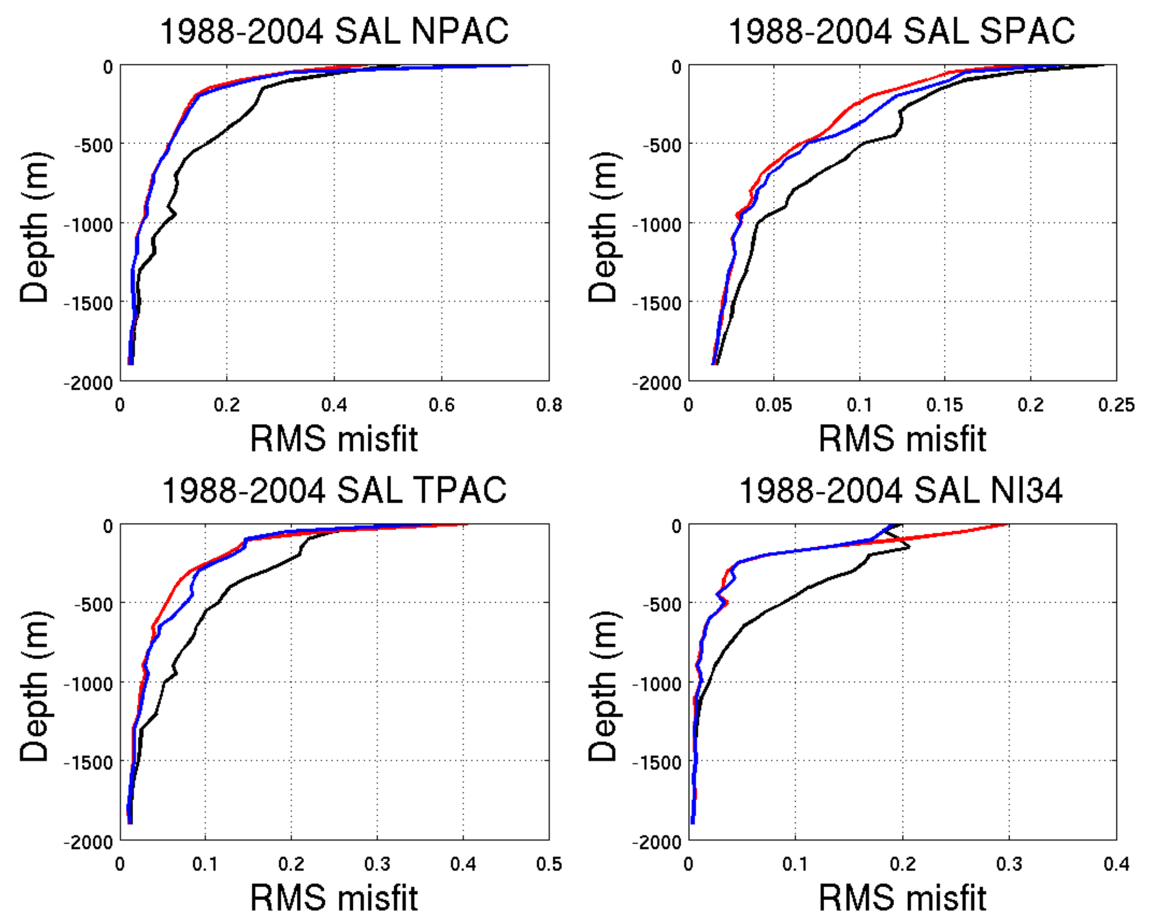

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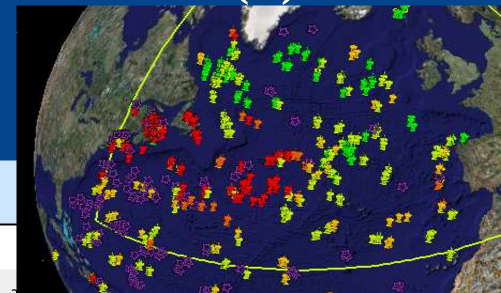
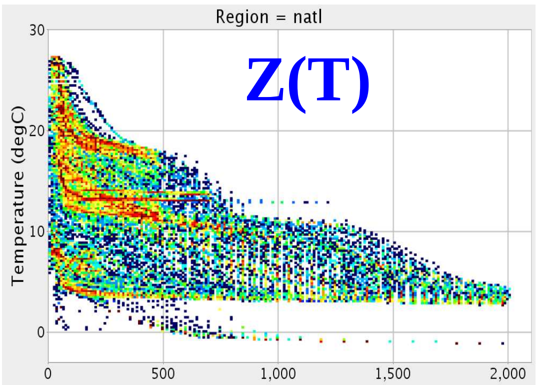
North Atlantic

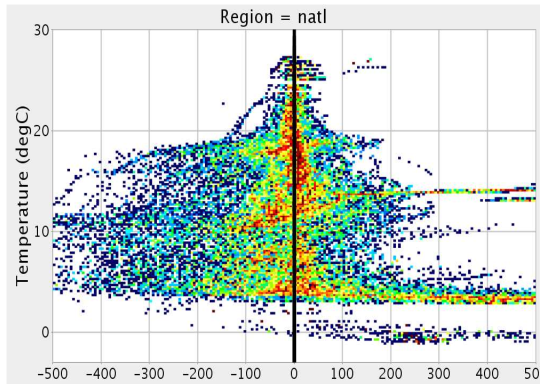
PDF of misfits for September 2004

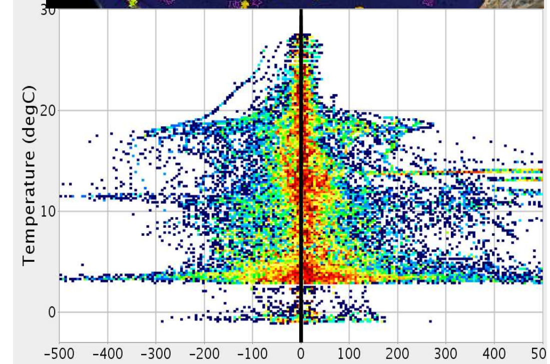
Rms S(T) misfit*



Temperature

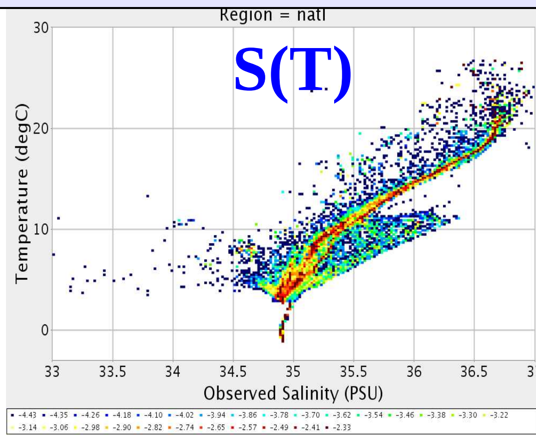


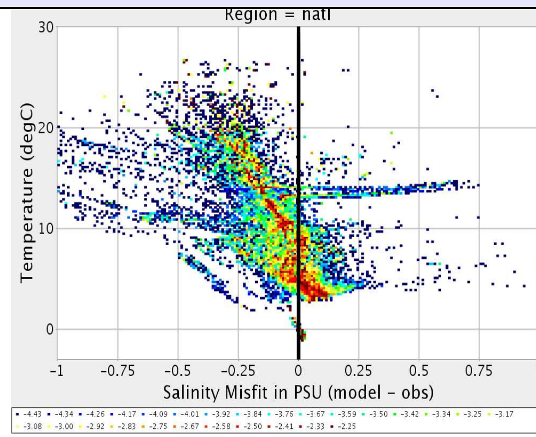


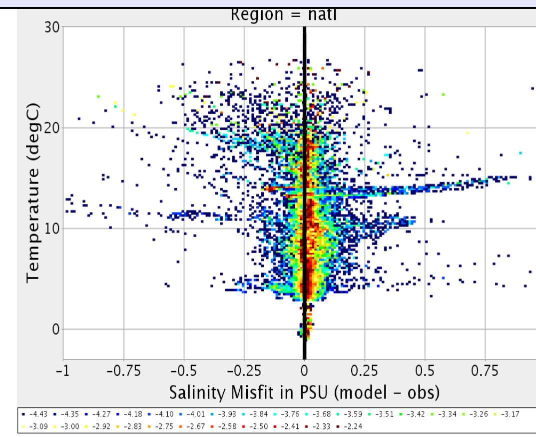


Observations | **¼ º control run** | **¼ º assim run**

Temperature

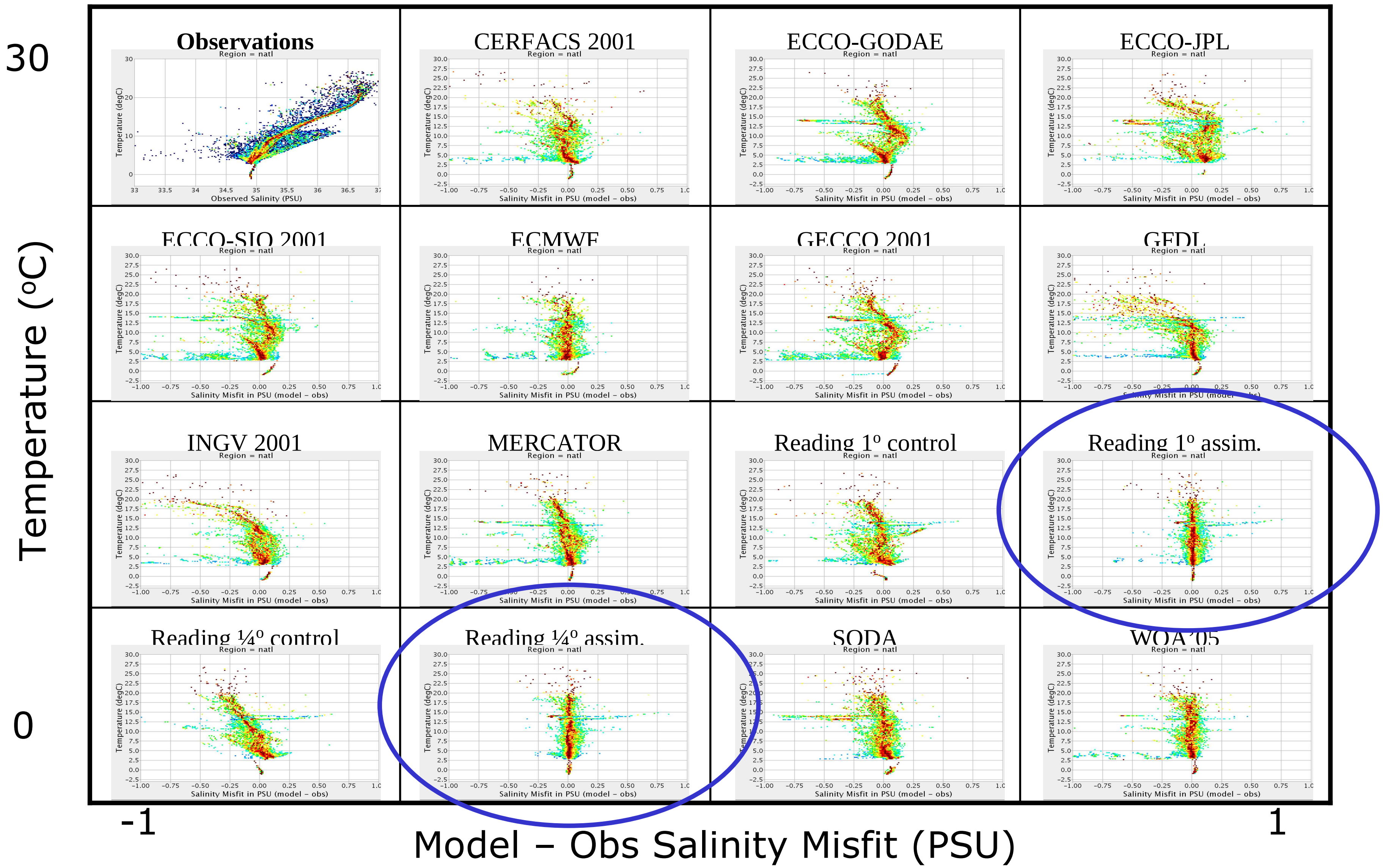






*Created using OceanDIVA: www.resc.reading.ac.uk

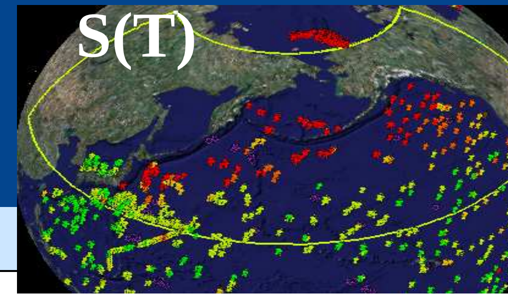
North Atlantic S(T) : CLIVAR GSOP water mass intercomparison

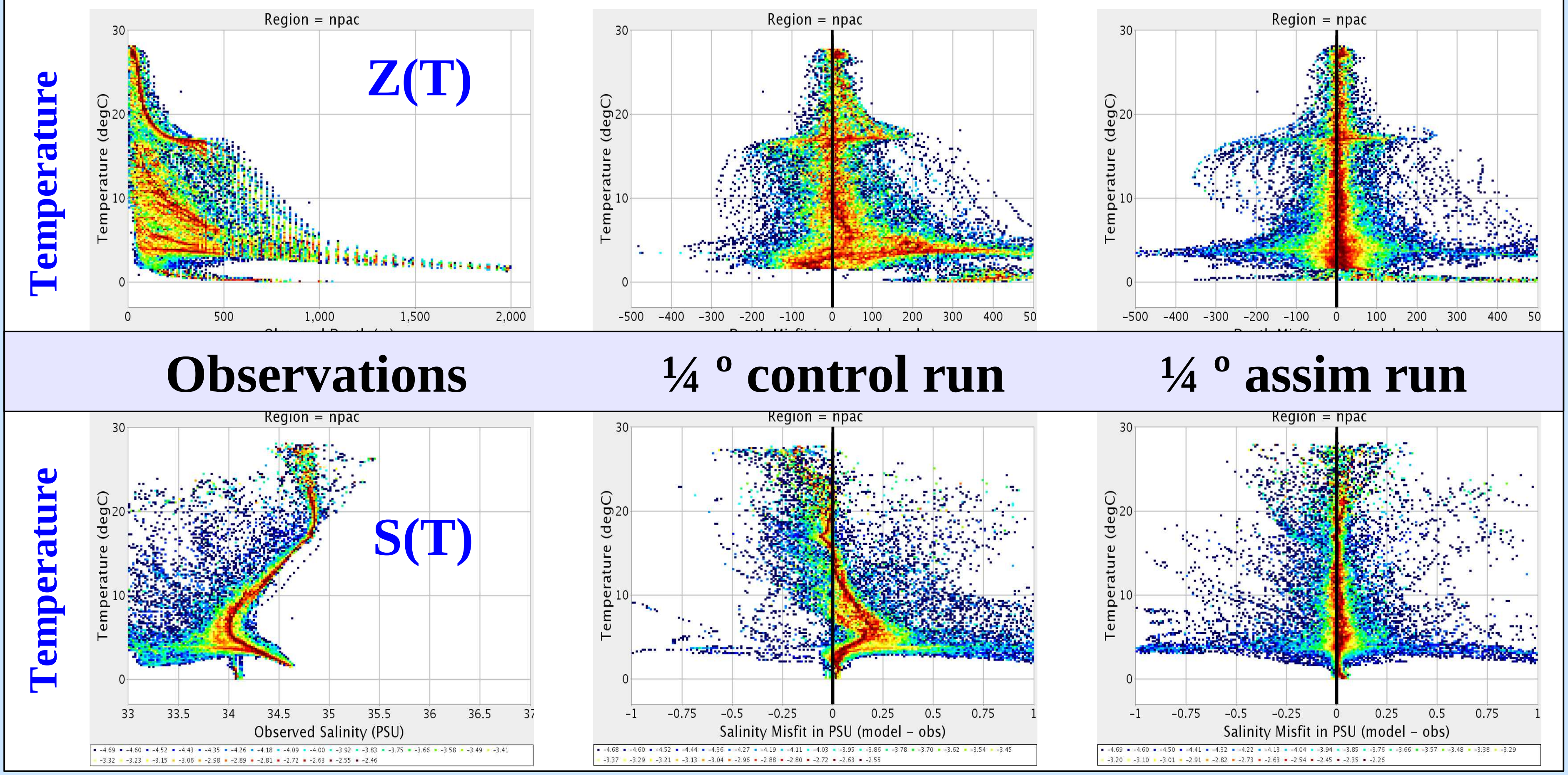


Gemmell et al. (2008)

North Pacific

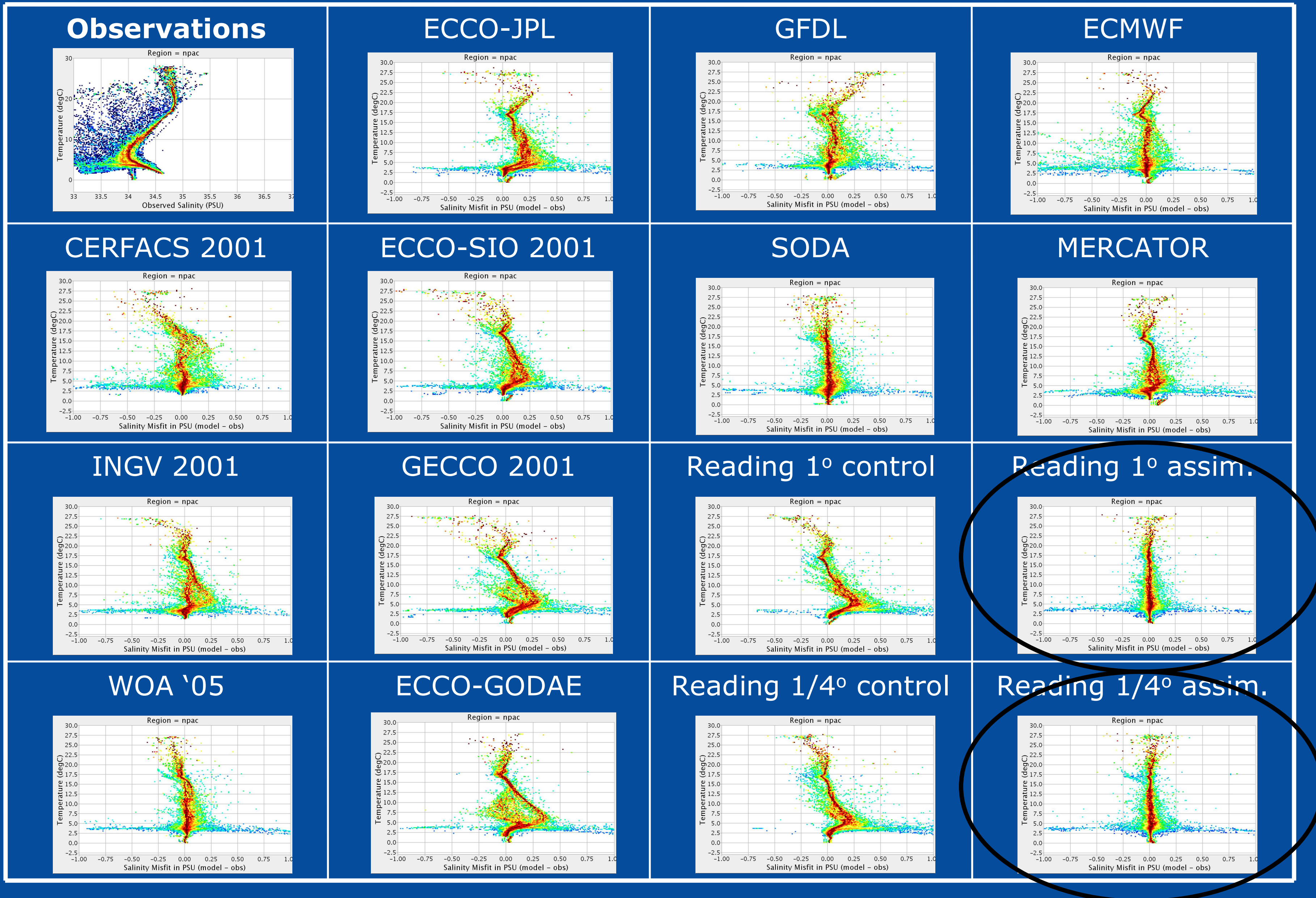
PDF of misfits for September 2004





- Reanalysis shows much tighter distribution than control run for all temperature classes.
- In particular, note the correction of the positive salinity bias (for T=2-10C) in the control
- Calculation made using OceanDIVA online web service

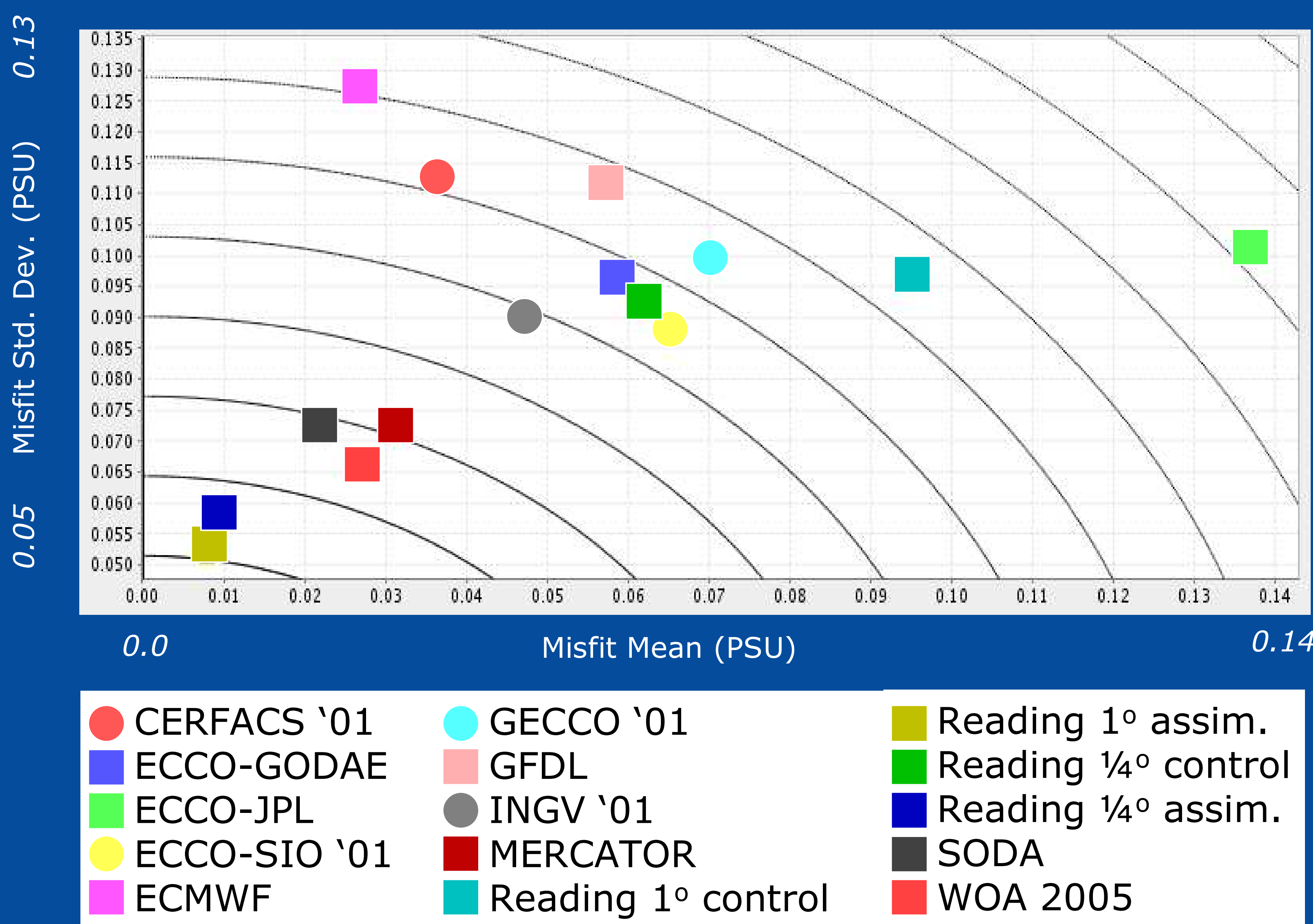
North Pacific S(T) across syntheses



Gemmell et al. (2008)

Bias v Standard Deviation

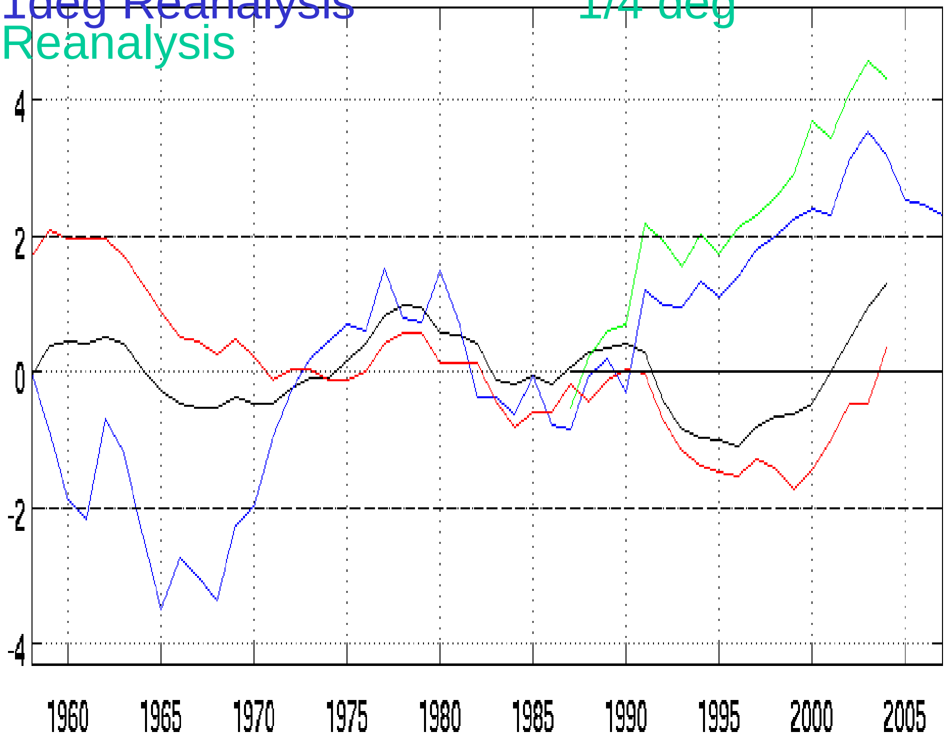
North Pacific – S(T) – over T range 5-17 ºC



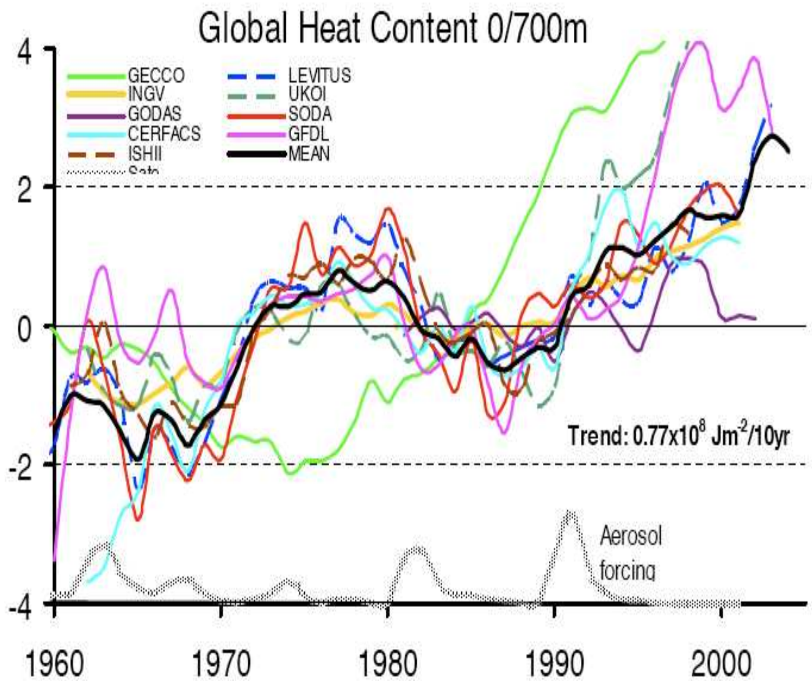
Global ocean heat content variability

1deg Control 1/4 deg Control

1deg Reanalysis 1/4 deg Reanalysis



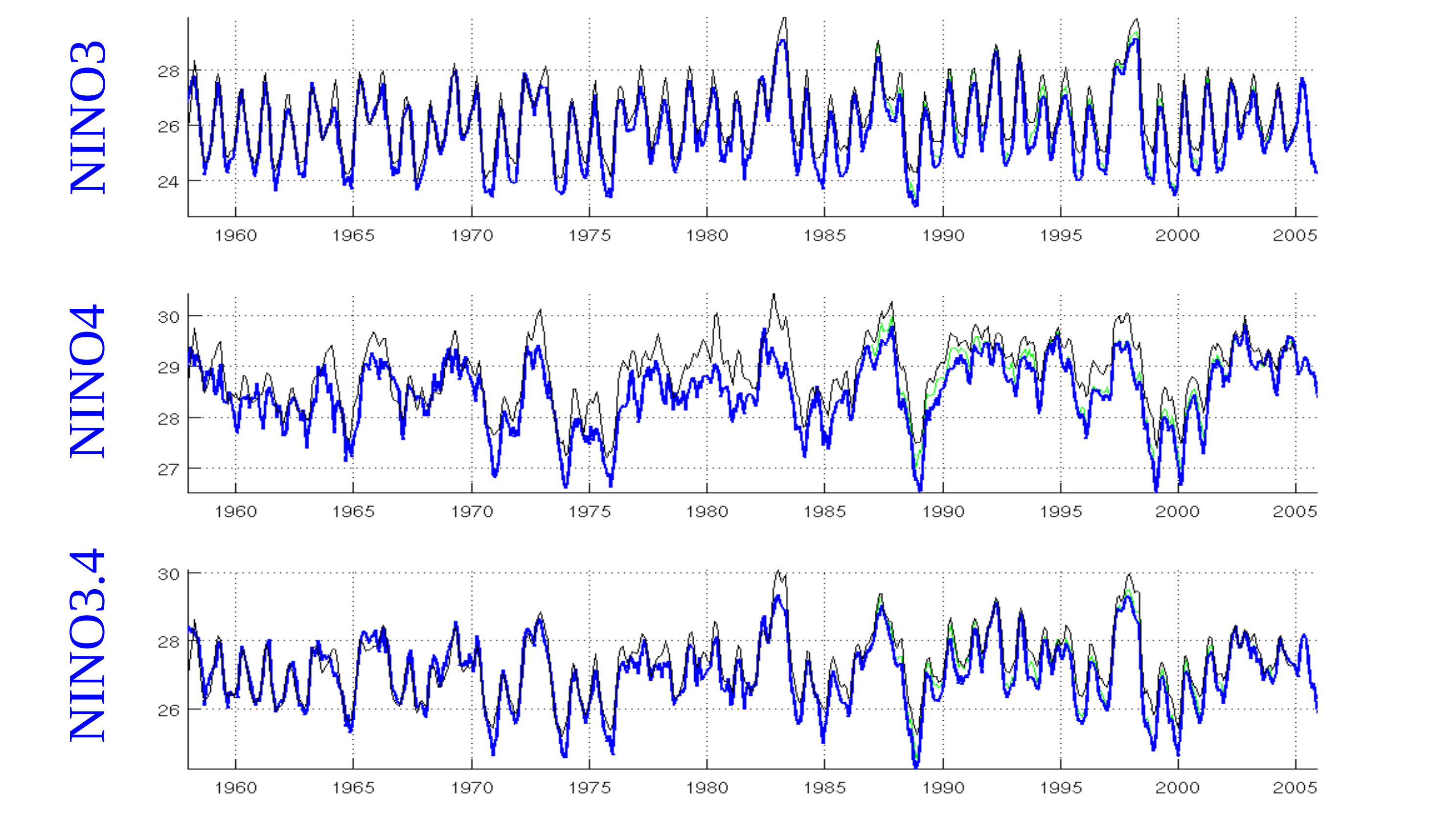
Carton and Santorelli, submitted to J. Clim.



- Reading reanalyses similar to other products
- Assimilation corrects drifts in control runs

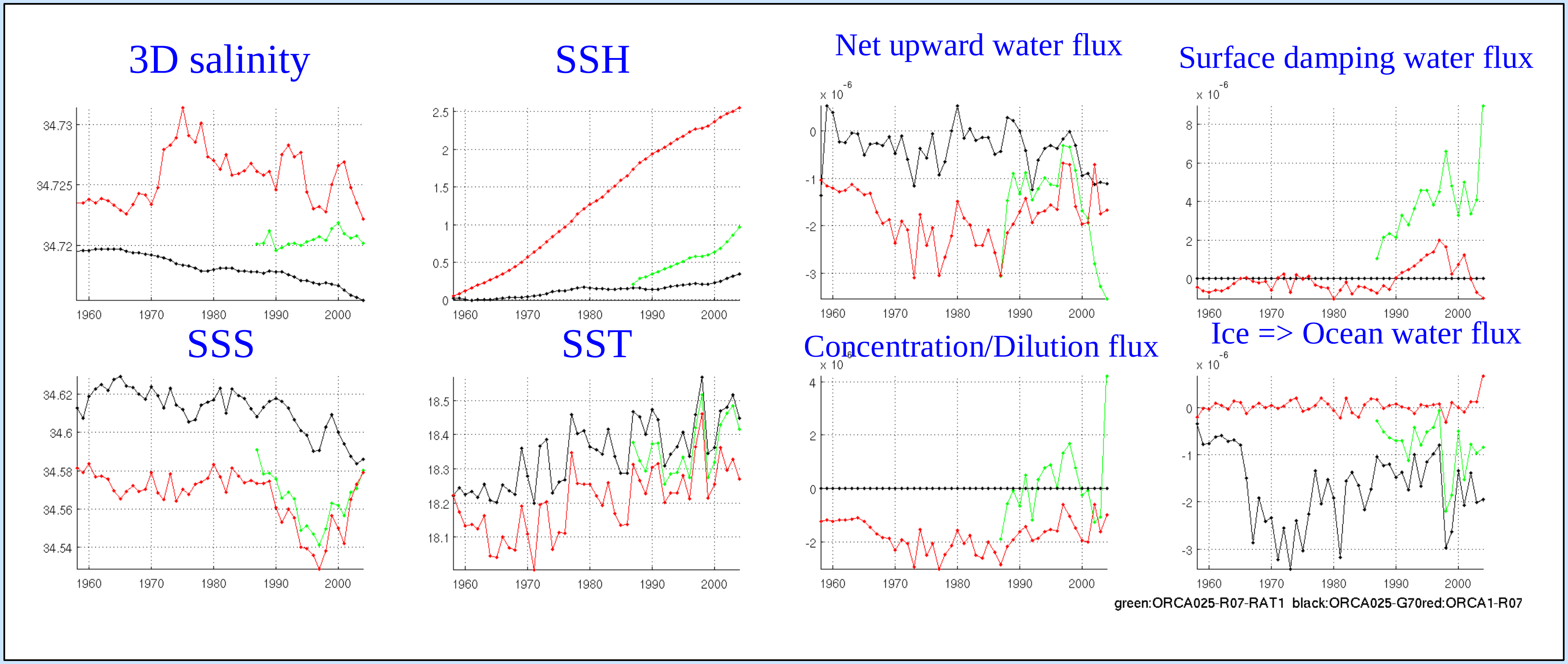
Tropical Pacific SST

¼ º control run ¼ º reanalysis Obs



Global mean quantities

ORCA025-G70 : 1/4° Control
ORCA025-R07 : 1/4° Reanalysis
ORCA1-R07 : 1° Reanalysis



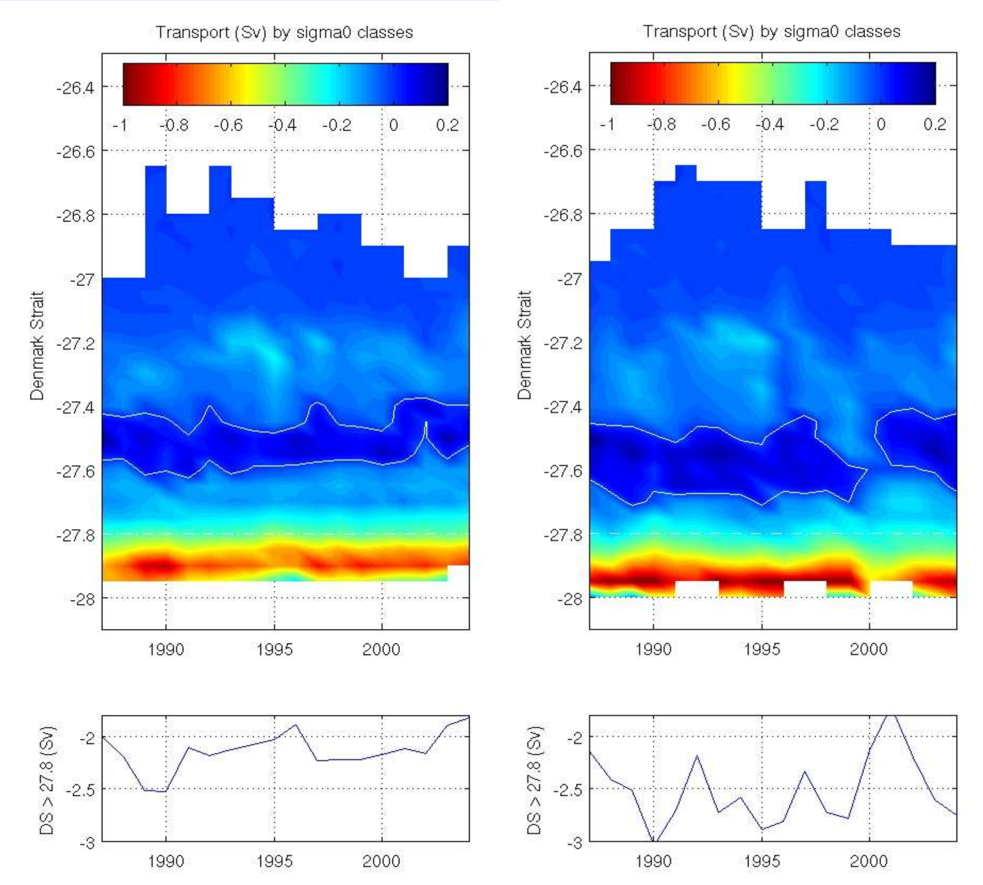
Transport through Denmark Strait

- Figure shows transport as a function of density class, with warm colours indicating southward flow

- Dense overflow in control weakens and freshens over time

- Reanalysis maintains strong southward dense flow and shows increased interannual variability

1/4° Control | 1/4° Reanalysis

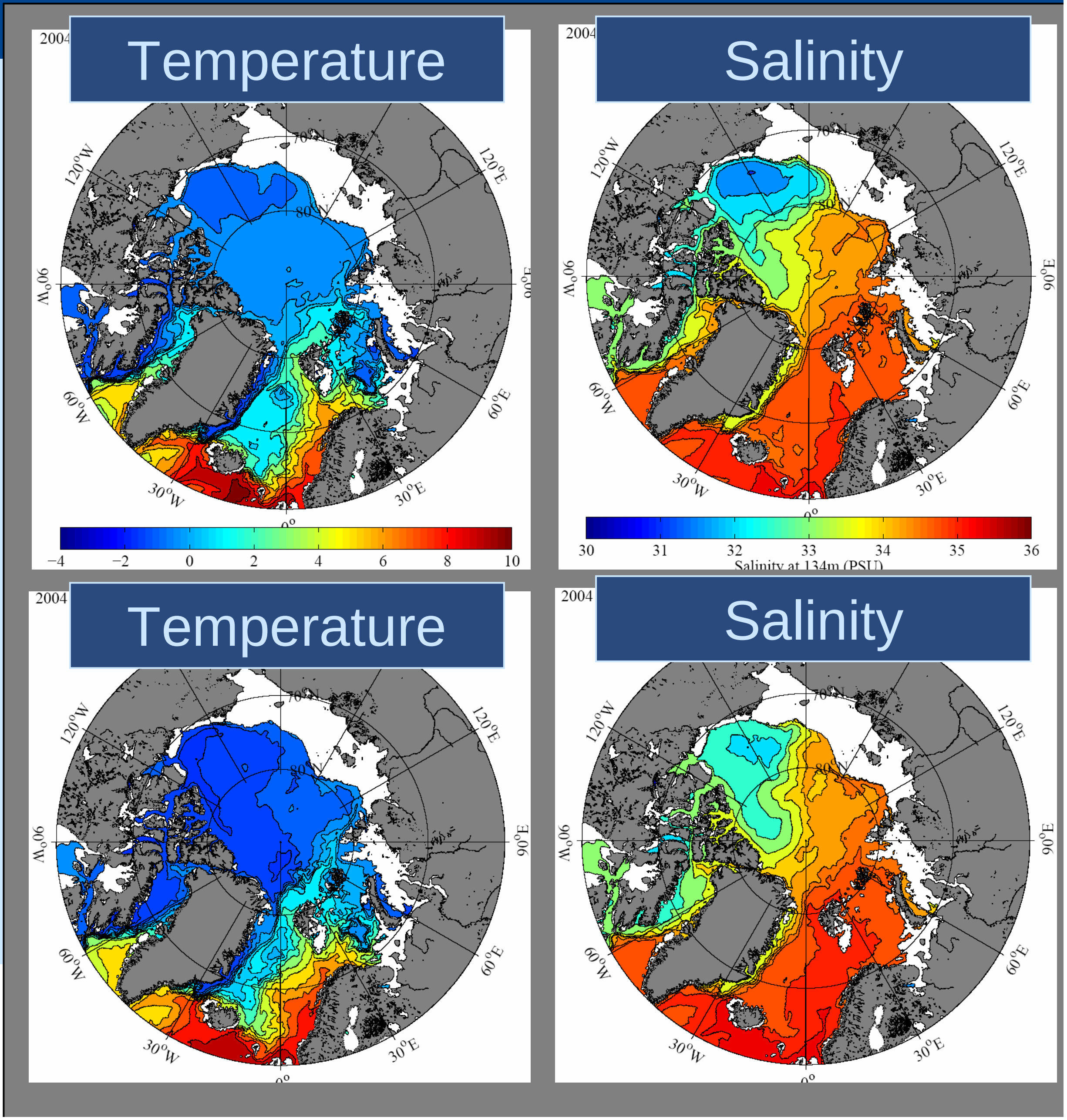


Improvements to the Arctic Ocean

1/4° Control Run
(no assimilation)

¼ °Reanalysis

Mugford et al. (in prep.)



Arctic Freshwater Fluxes

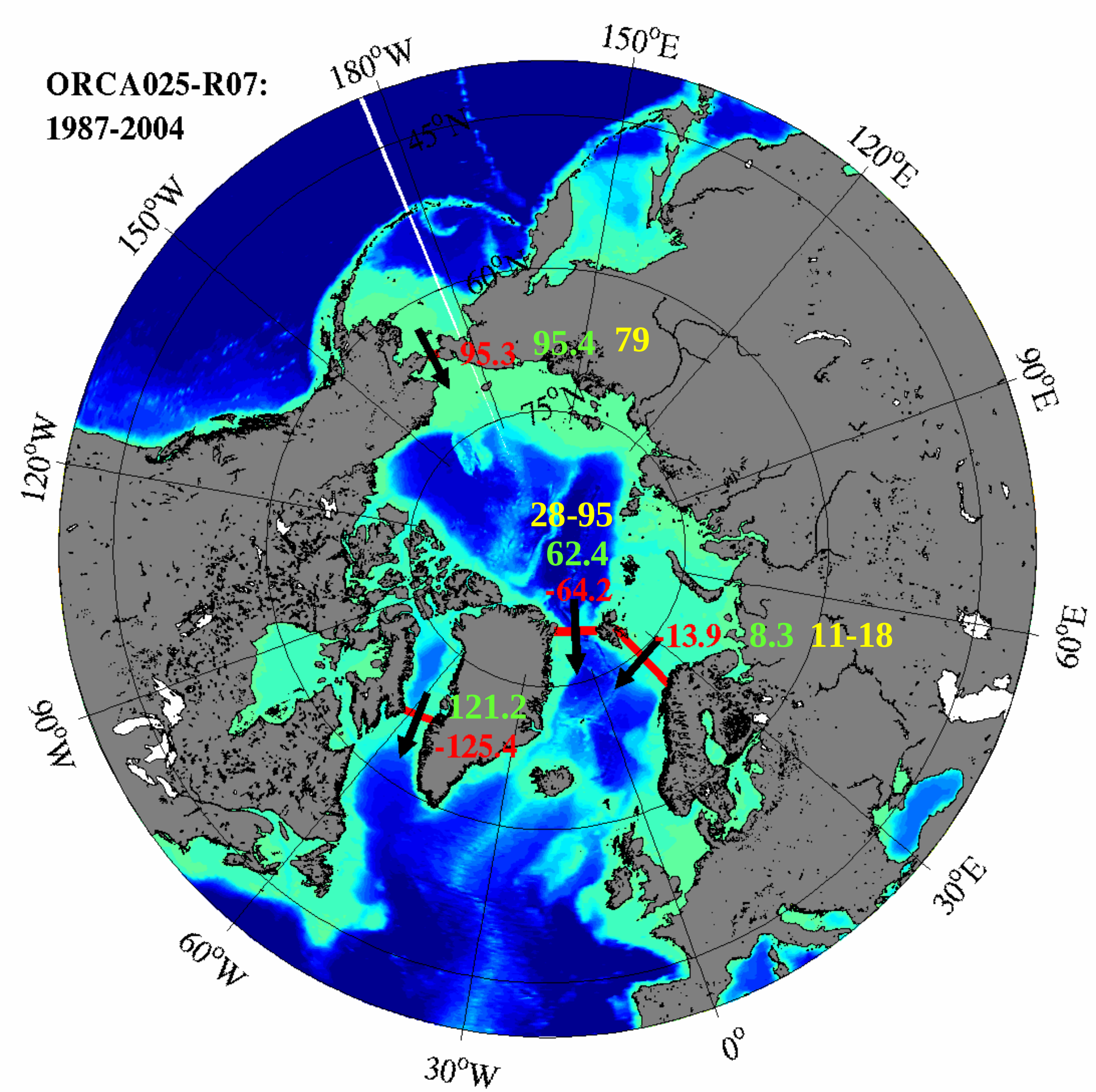
ORCA025-R07

1/4° Reanalysis

ORCA025-G70

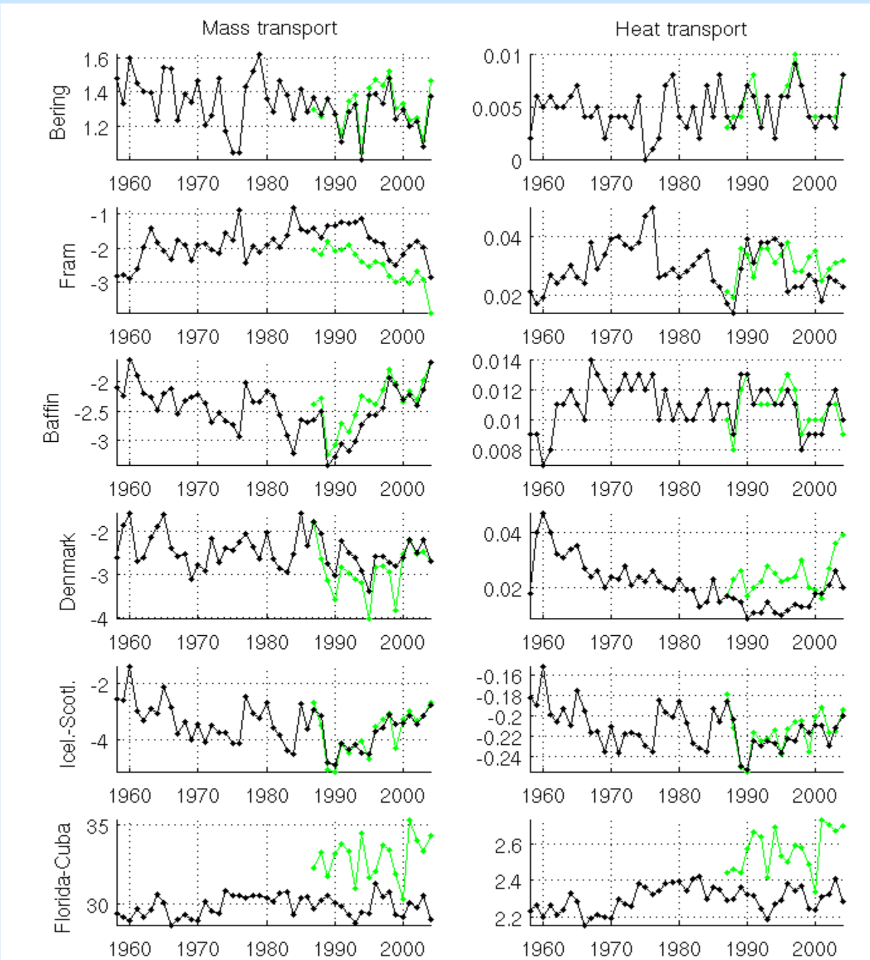
1/4°Control

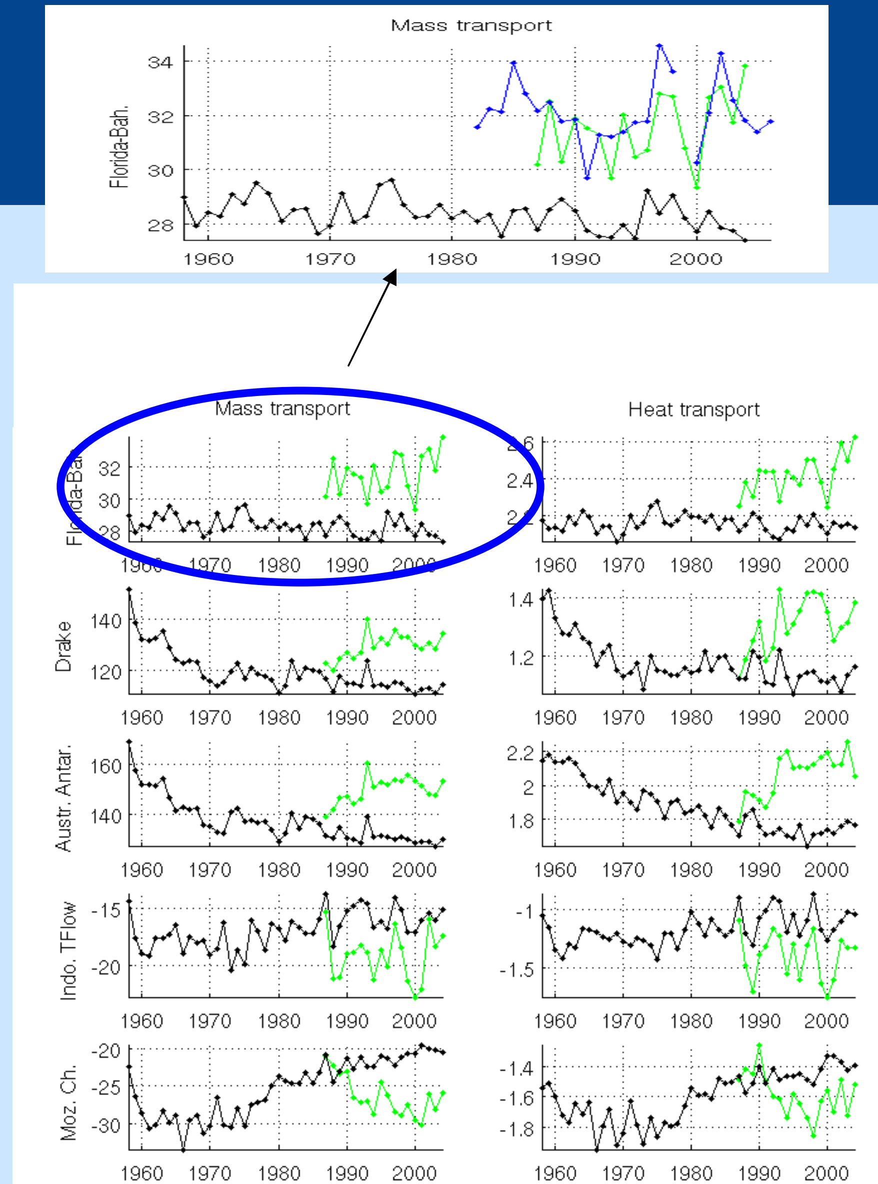
Observations



Mugford et al. (in prep.)

Transports

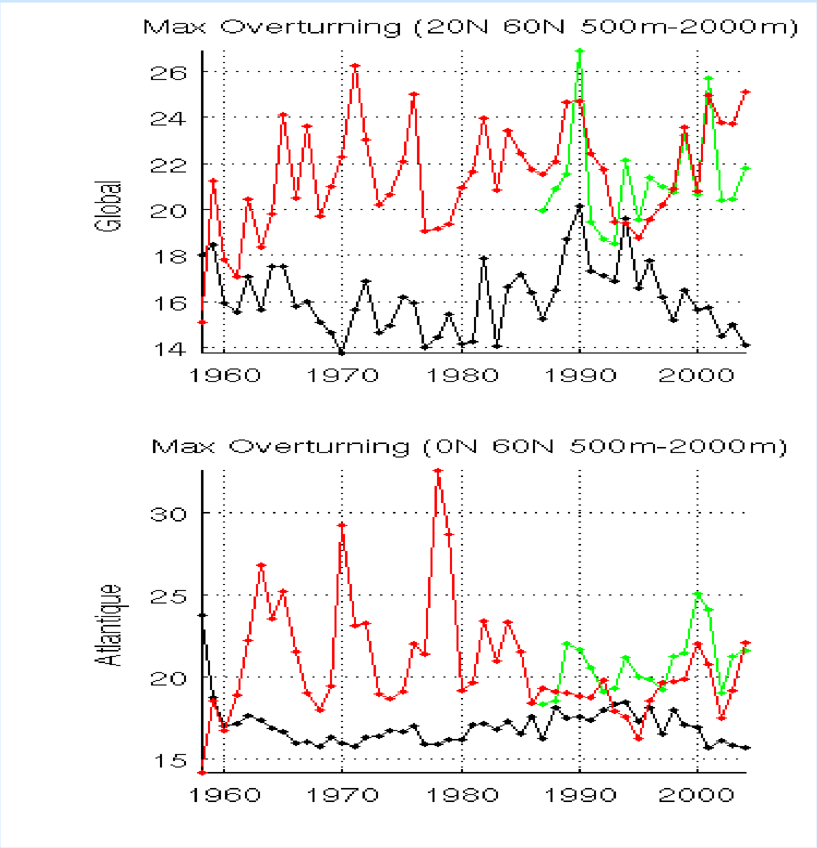


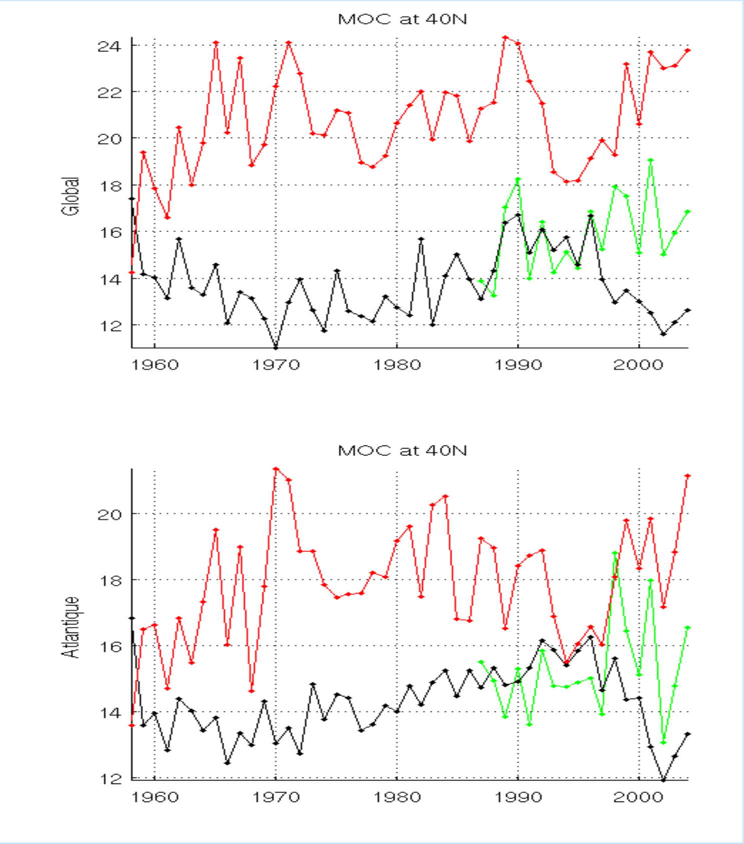


¼ º control run ¼ º reanalysis

Meridional overturning

ORCA025-G70 : 1/4° Control
ORCA025-R07 : 1/4° Reanalysis
ORCA1-R07 : 1° Reanalysis





Summary

- The S(T) algorithm has been implemented into the NEMO global ice-ocean model
- Two reanalyses have been made: a 50-year reanalysis at 1° resolution, and a 21-year reanalysis at 1/4° resolution.
- Overall, the assimilation is able to prevent drifts in many ocean metrics, and brings the model in better agreement with accepted values.
- An evaluation of water mass properties in various ocean syntheses performed as part of the CLIVAR-GSOP intercomparison, shows that the S(T) reanalyses provide excellent agreement with in situ observations.
- Results suggest that assimilation of salinity data along isotherms should provide better recovery of historical water mass properties than using depth level method
- Studies underway to use reanalysis for:
  - Heat and salt content variability
  - Arctic freshwater budget
  - Impact of assimilation on ecosystem models
  - Force a global coastal ocean modelling system (GCOM)
- Future Work:
  - Still need to determine most appropriate S(T) lengthscales (requires front detection)
  - Density/spice assimilation
  - Investigate sensitivity to DFS4 and ERA-Interim forcing
  - Implement altimetry assimilation