

- 1. Summary of Presentation on Ocean Observing System Experiments (by Yosuke Fujii)**
- 2. A few bullets from the Presentation on Forecasting Systems Needs.**

# Evaluation of the Tropical Pacific Observing System from the Ocean Data Assimilation Perspective

## Contributors

**Yosuke Fujii (MRI/JMA, Japan)**

James Cummings (NRL, USA)

Yan Xue (NOAA/NCEP, USA)

Andreas Schiller (CSIRO, Australia)

Tong Lee (NASA/JPL, USA)

Magdalena Balmaseda (ECMWF)

Elisabeth Remy (Mercator, France)

Suhei Masuda (JAMSTEC, Japan)

Oscar Alves (CAWCR/BoM, Australia)

Gary Brassington (BoM, Australia)

Bruce Comuelle (SIO, USA)

Mathew Martin (UKMO, UK)

Peter Oke (CSIRO, Australia)

Gregory Smith (Environment Canada)

Xiaosong Yang (NOAA/GFDL, USA)

# ★ Purpose/way of this presentation

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- ✓ **Discuss requirements of Tropical Pacific Observing System from the ocean Data Assimilation (DA) perspective**
- ✓ Mainly discuss on observations of physical parameters for ocean interior states (including those at the sea surface)
- ✓ Discussion on observations of atmospheric and biochemical parameters are left to other white papers.
- ✓ Evaluate results of Observing System Evaluation (OSEval) activities mainly in order to answer the following questions.
  - To what extent are these requirements being delivered by existing networks?
  - What role is being played by TAO/TRITON in meeting this requirement?
- ✓ **Classify the purpose of Ocean DA systems into**
  - 1. Seasonal-to-Interannual (SI) forecasting**
  - 2. Short-medium range ocean forecasting**
  - 3. Ocean state estimation for climate research**
- ✓ Discuss on ocean DA systems associated with each purpose, separately.
- ✓ **Requests of the endorsements for supporting activities**

# 1. Requirements for Ocean DA systems for SI forecasting

## ★ What are main drivers?

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- ✓ Ocean DA systems are **an essential component of general S-I forecasting systems** in operational centers as well as Coupled ocean-atmosphere General Circulation Models (CGCMs)
- ✓ The estimation of the tropical Pacific Ocean state through ocean DA is vital for S-I forecasting system because **most predictability for S-I forecasts comes from ENSO**.
- ✓ Ocean DA systems are also employed in operational centers **for monitoring the equatorial wave activity, variability of the thermocline along the equator**, and other ocean phenomena associated with ENSO.

### Typical specification of current operational ocean DA systems for S-I forecasts

- ✓ Resolution: 0.5-1° in horizontal (no eddy model), 10 m in vertical
  - It is desirable to be used in ensemble forecasts as a part of CGCMs.
    - ➡ It needs to be light for computing.
  - But UKMO started to use a 1/4° resolution ocean model, recently.
- ✓ Assimilation scheme: 3DVAR (NCEP, JMA, ECMWF), EnOI (ABoM)
- ✓ NCEP uses a **“weakly coupled”** data assimilation scheme.

# ★ Variable requirements (1)

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## ◆ (Subsurface) Ocean Temperature

- ✓ Essential because the thermocline variation plays important roles in ENSO.
- ✓ Baroclinic Kelvin wave activities along the equator frequently affect occurrences of El Ninos and La Ninas.

### ✓ Baseline requirement of the resolution (for detecting ENSO variability).

Zonal:	500-1000km	Meridional:	200km
Vertical:	5-10m	Temporal:	1-5-daily

- Higher resolution is favorable for detecting TIW, equatorial upwelling, etc.

### ✓ TAO-TRITON array

- The horizontal resolution is suitable for detecting the ENSO variability
- The vertical resolution is insufficient to detect the thermocline accurately.
- Often time-averaged before assimilated. (The hourly data is not fully used.)
- TAO buoys in the eastern Pacific seem to be particularly needed to constrain model biases and uncertainties in air-sea fluxes.

### ✓ Argo floats

- The vertical resolution is well sufficient.
- The meridional resolution is a bit coarser and few floats stay in the vicinity of the equator.
- They are complementary to the TAO-TRITON array.

# ★ Variable requirements (2)

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## ◆ Sea Surface Temperature (SST)

- ✓ Essential because
  - anomalous SST distribution is the most remarkable feature of El Niños and La Niñas
  - it directly affects the atmospheric global circulation and climate.
- ✓ 1° and 1 day resolution SST data is typically used currently.
- ✓ Effectively observed from Satellites and calibrated using in-situ observations.
- ✓ Basically sufficient for reconstructing the variability associated with ENSO and for the current ocean DA systems with typically 0.5-1° resolutions.
  - 0.25 ° resolution will be required for next generation systems.

## ◆ Sea Surface Height (SSH)

- ✓ Variability of the thermocline depth can be also detected by SSH observation.
- ✓ The resolution of SSH observed from satellites (100-300km across the paths; 10-40 days) are sufficient for the ENSO.
- ✓ However, the impacts of assimilating SSH is generally minor
  - because the information duplicates with the subsurface temperature data
  - because of the complicated vertical structure in the equatorial region (SSH has a vertically integrated information alone.)
- ✓ Assimilation of SSH needs support from sub-surface TS profiles.

# ★ Variable requirements (3)

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## ◆ Salinity

- ✓ It affects SST through
  - the stability of stratification (e.g., the barrier layer)
  - the advection of warm water (e.g. fresh water jet)
  - These features are particularly important around the equatorial salinity front.
- ✓ TAO/TRITON array
  - Most ATLAS buoys observe SSS alone.
  - TRITON buoys observe SSS and subsurface salinity.
  - The meridional and vertical resolution is not sufficient.
- ✓ Argo Floats
  - The horizontal resolution is not enough but much higher than the moorings.
  - The vertically high-sampling profiles have substantial impacts on the reproduction of the salinity field.
- ✓ Salinity variability can be detected in SSH data when the temperature profile is well observed by other measurements and salinity has large variability.
- ✓ SSS observations from satellites may support the detection of the SSS variability associated with ENSO, and migration of the SSS fronts.

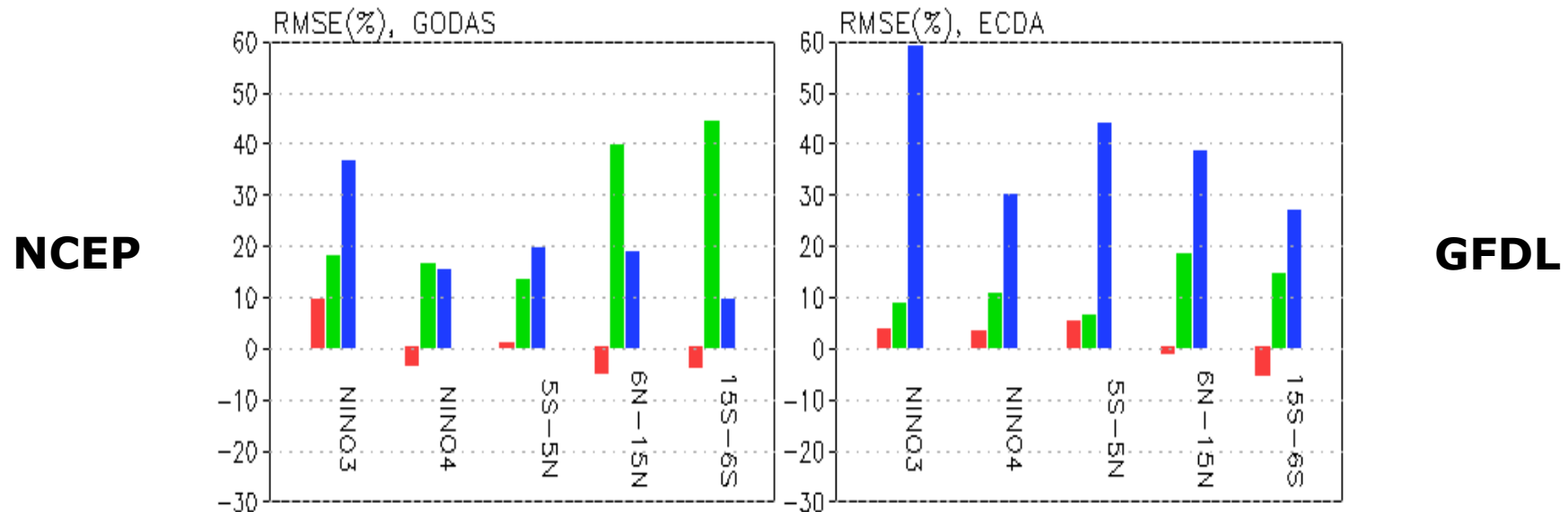


# ★ OSE for TPOS using SI forecast systems in NOAA

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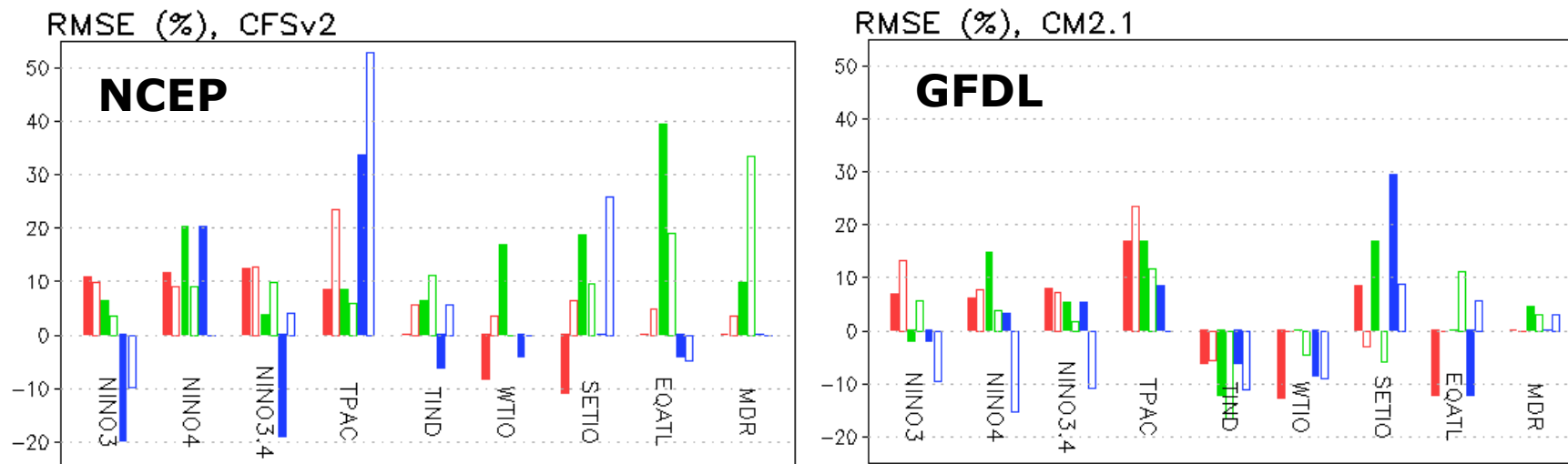
- Collaborative Effort between NOAA/NCEP and NOAA/GFDL assessing the value of the TAO data in the presence of the Argo using Observing System Experiments (OSEs)
- Coordinated OSEs and hindcast experiments using the NCEP and GFDL ocean data assimilation and seasonal forecast systems for the Argo period **2004-2011**
- Four OSE runs are made that include
  - **no ocean observations (CTL)**
  - **all ocean observations (ALL)**
  - **all except the moorings (noMoor)**
  - **all except the Argo (noArgo)**
- Hindcast experiments are initialized with from OSEs around January 1, April 1, July 1 and October 1 during 2004-2011.

# ★ Impact on the sea surface height analysis



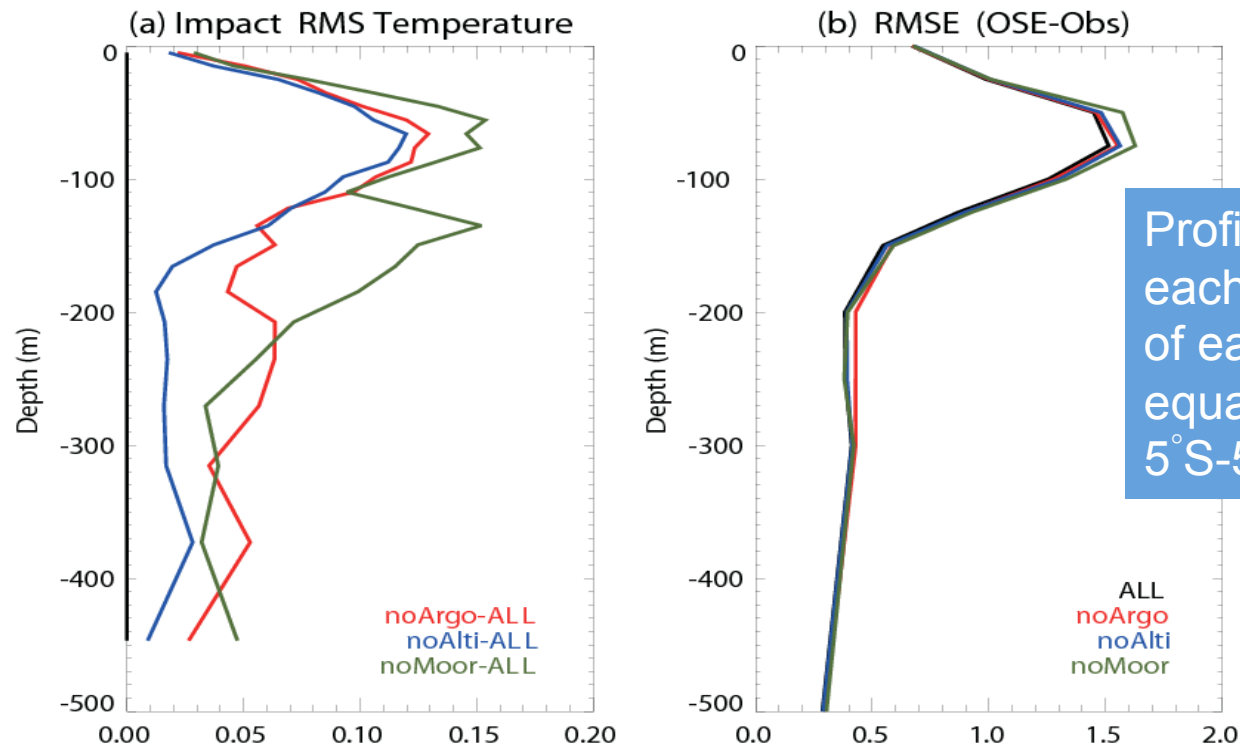
- Validated against independent satellite SSH on interannual variability (monthly anomaly in 2004-2011)
- RMSE difference normalized by RMSE of ALL:
  - noMoor - ALL (red) --> impacts of moorings
  - noArgo - ALL (green) ---> impacts of Argo
  - CTL - ALL (blue) --> impacts of all in-situ profiles
- Inclusion of TAO improved RMSE by 5-10%
- Inclusion of Argo improved RMSE by 10-18% near Eq.
- Inclusion of TAO, Argo, XBT together improved RMSE by 8-50%

# ★ Impact on Seasonal Forecast Skill



- RMSE skill for various SST indices at 0-5 month lead (filled bar) and 5-9 month lead (unfilled bar)
- RMSE difference normalized by RMSE of ALL:
  - noMoor – ALL (red bar) --→ impacts of moorings
  - noArgo – ALL (green bar) ---> impacts of Argo
  - CTL – ALL (blue bar) --→ impacts of all in-situ profiles
- TAO (red bar) improved RMSE by **10-20 % for ENSO**
- Argo (green bar) improved RMSE by **5-20% for ENSO**
- TAO, Argo, XBT together improved RMSE for ENSO, but not for short lead for NCEP and not for long lead for GFDL, indicating **model systematic biases and model initialization shocks are obstacles to realize possible benefits** of ocean observing systems --- needs to improve initializations.

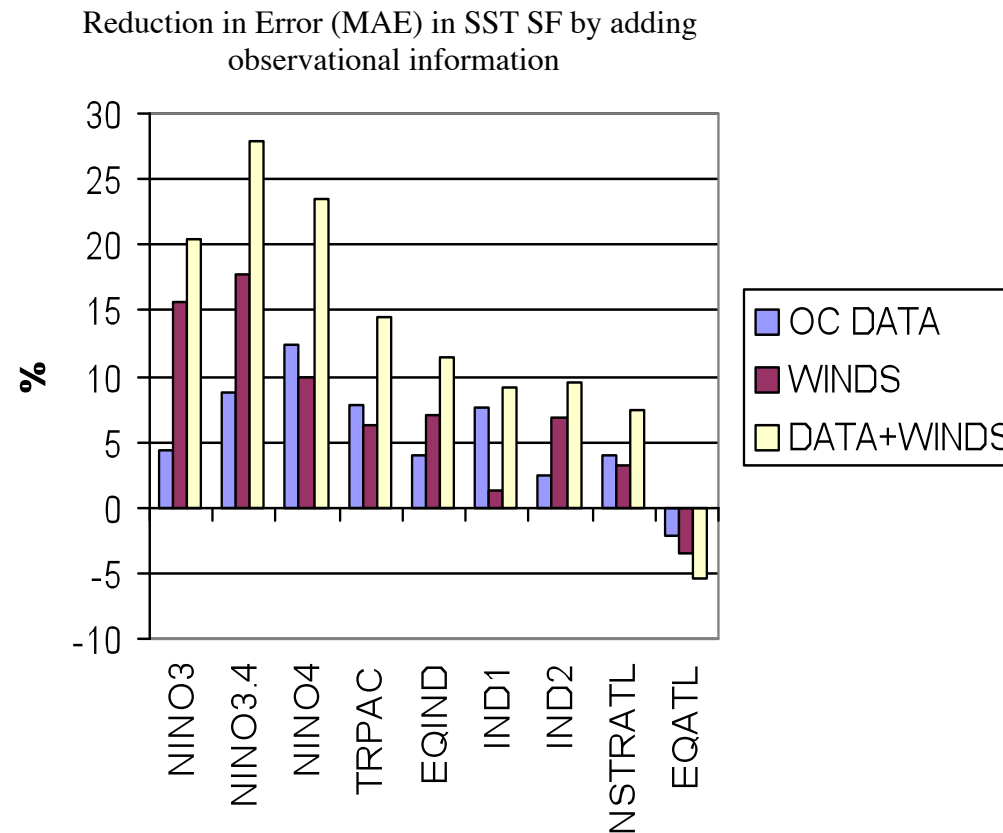
# ★ Complementarity from ECMWF OSE results



Profiles of the (a) RMSD between each OSE and ALL, and (b) RMSE of each OSE for T in the eastern equatorial Pacific (90-130°W, 5°S-5°N).

- ◆ The left panel shows the data impact on the analysis; the right panel shows the data impact on the error.
- ◆ Whenever any data type is withheld, the fit to in situ temperature profiles degrades.
  - all data types contribute some unique information to the data assimilating system, that is, **they are complementary to each other.**
- ✓ Impacts of the bias correction scheme is not counted here.

## Impact of winds and subsurface obs on seasonal forecast skill (S3)



Winds and subsurface observation contribute to the forecast skill, especially in Eq. Pacific

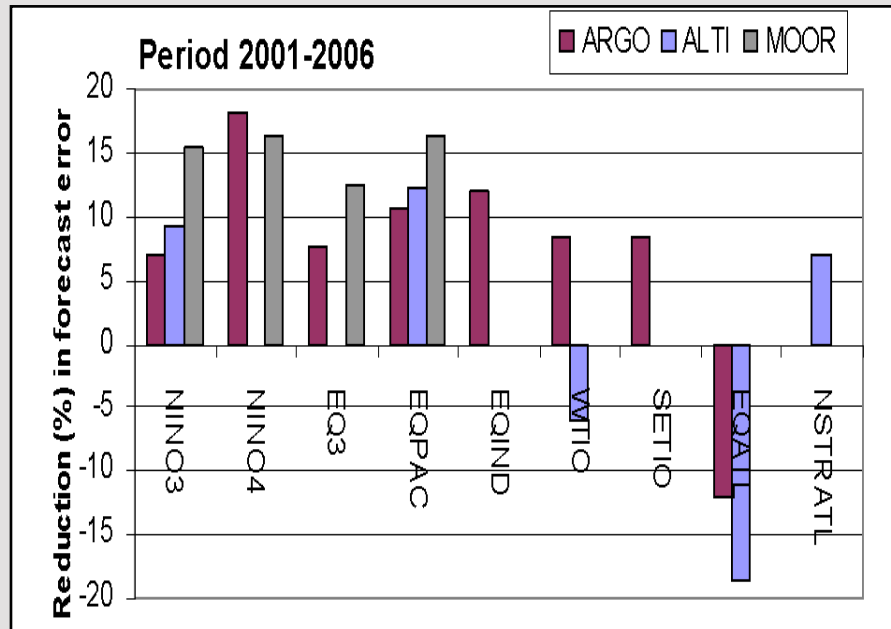
Additional experiments suggested that no observing system was redundant.

The negative impact in the Equatorial Atlantic attributed to model error.

More OSEs with different systems presented in WP5

# Assessing the Ocean Observing System

(S3)



From Balmaseda and Anderson 2009

See also Fujii et al 2008

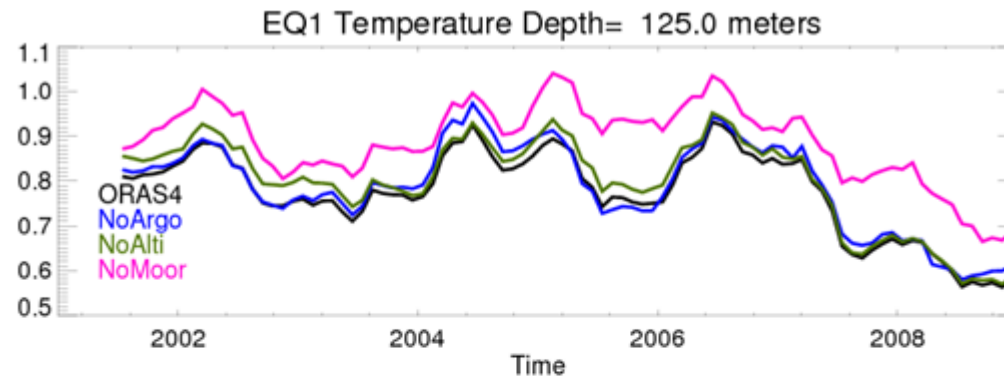
1. No observation system is redundant  
Not even in the Pacific, where Argo, moorings and altimeter still complement. Lessons for other basins?
2. There were obvious problems in the Eq Atlantic: model error, assimilation, and possibly insufficient observing system

## Important to bear in mind

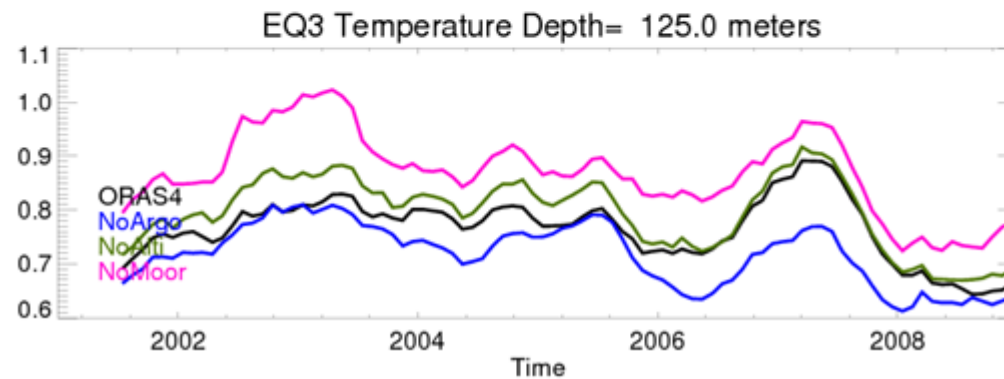
1. The assessment depends on the quality of the coupled model
2. Need records long enough for results to be significant => any observing system needs to stay in place for a long time before any assessment is possible.

# Recent ECMWF OSEs (ORAS4)

Impact on Ocean Analysis: Fit (RSME) to moorings



Eastern Pacific: Argo does not improve the fit to moorings



Western Pacific: Argo degrades the fit to moorings ?

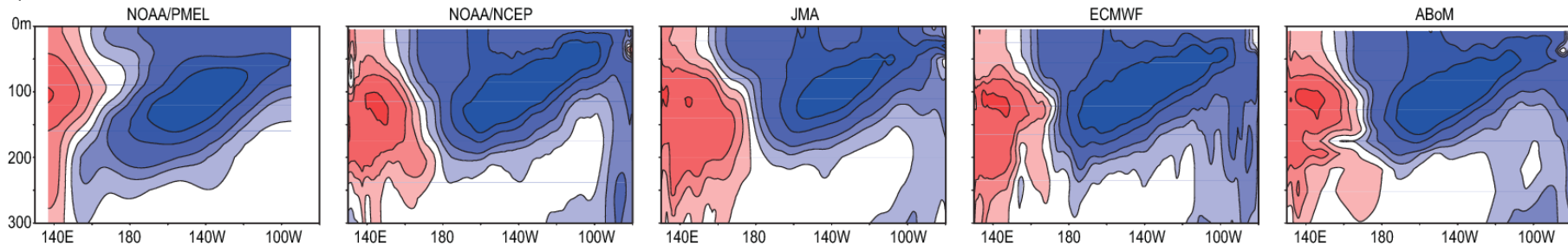
No significant impact found in seasonal forecasts:

Model error? Others (over-dispersive model, bias correction...)?

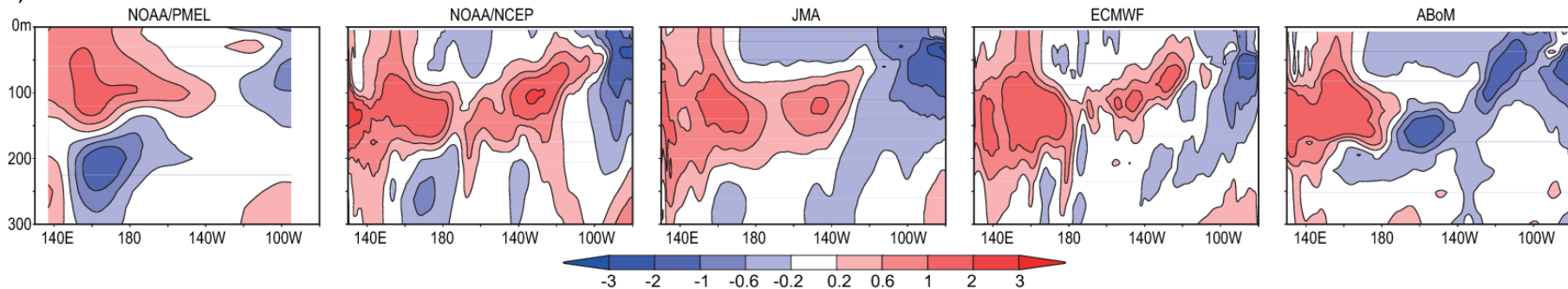
# ★ Gaps emerging after the recent TAO crisis

Comparison of the T anomaly in the equatorial Pacific ( $2^{\circ}\text{S}$ - $2^{\circ}\text{N}$ ) vertical (0-300m) section

a) JAS 2010



b) JAS 2013

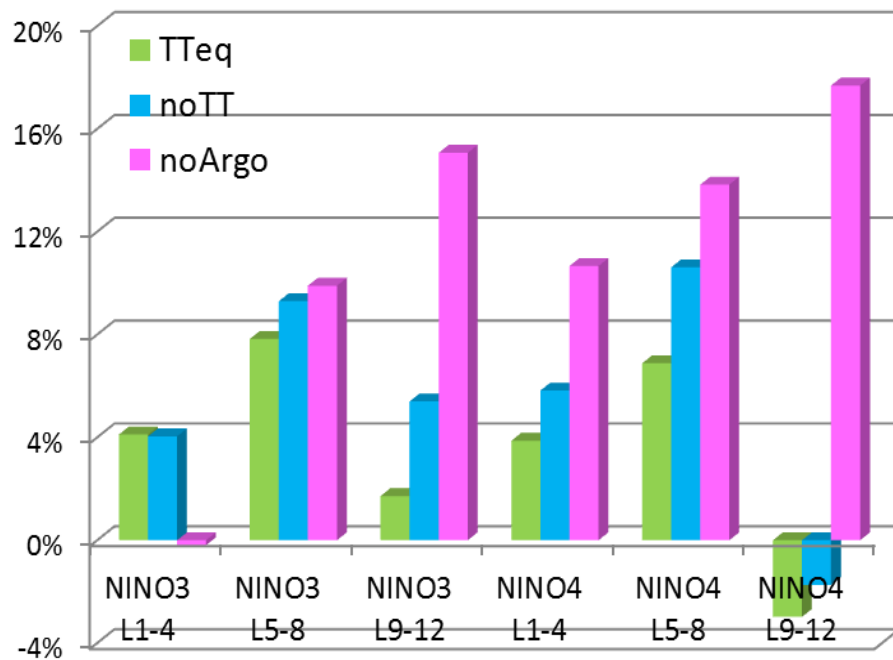


- ✓ The T analysis fields seem to be **more diverse in 2013** than in 2010.
- ✓ **The analysis by PMEL**, which people thought observed features were reflected in most, **is not reliable anymore in 2013** due to the lack of the TAO data.
- ✓ NOAA, JMA and ECMWF plan to start the real-time comparison of the equatorial Pacific temperature fields. It is **desirable that the activity is endorsed by TPOS2020**.



# ★ Can they be filled with adjusting existing network?

One possibility is to maintain the buoys in 2°S-2°N alone, but ...



Normalized Increase of the RMSE of the NINO3 and NINO4 SST indices in the hindcasts using each OSE runs from those using the reference runs for 1-4, 5-8, and 9-12 month lead-time forecasts in the JMA OSE experiments.

	TAO/TRITON	Argo
TTeq	2°S-2°N alone	ALL
noTT	None	ALL
noArgo	ALL	None

- ✓ The forecasting skill will be reduced from the reference run in most cases.
- ✓ The reduction is similar to the case where all TAO/TRITON data is withheld for the relatively short lead time forecasts of the NINO3 index.
- ✓ Thus, deliberate evaluations are required for the adjusting.

## 2. Requirements for Ocean DA systems for ocean forecasting

## ★ What are main drivers?

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- ✓ Ocean forecasting systems **serve as backbone for a variety of applications** of ocean security, search and rescue, monitoring of marine eco-systems, sonar operations, etc.
- ✓ The implementation of **GODAE (1998-2008)** and its follow-on program, **GODAE Ocean View (2009-current)**, underpin the developments of the ocean forecasting systems in the last 15 years.

### Typical specification of current operational ocean DA systems for ocean forecasts

- ✓ Resolution:  $1/12$ - $1/4^\circ$  in horizontal (eddy-permitting/resolving model)
- ✓ A variety of assimilation schemes (OI, 3DVAR, EnOI, EnKF, etc.) are used in those systems.
- ✓ Typically forecasts of 5-days to 1-month are performed routinely with those systems.

## ★ Variable requirements

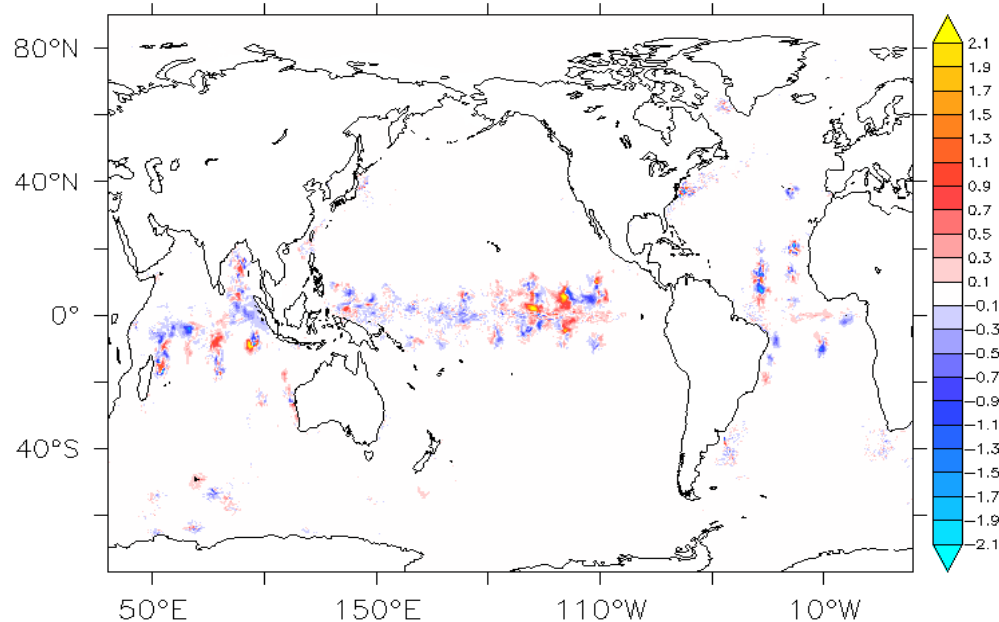
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- ✓ The systems generally assimilate in-situ temperature and salinity data including those observed by TAO/TRITON array and ARGO floats, and SST and SSH from satellites.
- ✓ The systems require TAO/TRITON data, as well as ARGO profiles, for constraining the ocean heat content, stratification and circulation in the tropics.
- ✓ However, **observations with a higher resolution** than that of current in-situ observing system **seem to be favorable** for those systems **because**
  - they are generally designed to reproduce the variability associated with **meso-scale eddies**
  - the eddy activities (e.g., TIW, the Mindanao eddy, etc.) are very vigorous in the northern Tropical Pacific.
- ✓ This requirement is partly satisfied by satellite observations of SSH and SST, but they are still not sufficient.
- ✓ Most systems do not use sub-daily high frequency measurements of the TAO/TRITON array but assimilate daily mean fields of the temperature and salinity measurements.
- ✓ However, high frequency measurements can be beneficial for some short-time forecasting systems (e.g., US-Navy NCODA system.)

# ★ Near-Real-Time (NRT) OSE

- ✓ GODAE Ocean View Observing System Evaluation (OSEval) Task Team has advocated for the development and application of tools and techniques that quantify the impact of ocean observations.
- ✓ The team also intends to issue observation impact statements that provide feedback and requirements to observation agencies through evidence of the impacts of the observations, mainly on operational systems.

T differences at 100m depth on the last day of the month between OSE experiments with and without TAO/TRITON data.

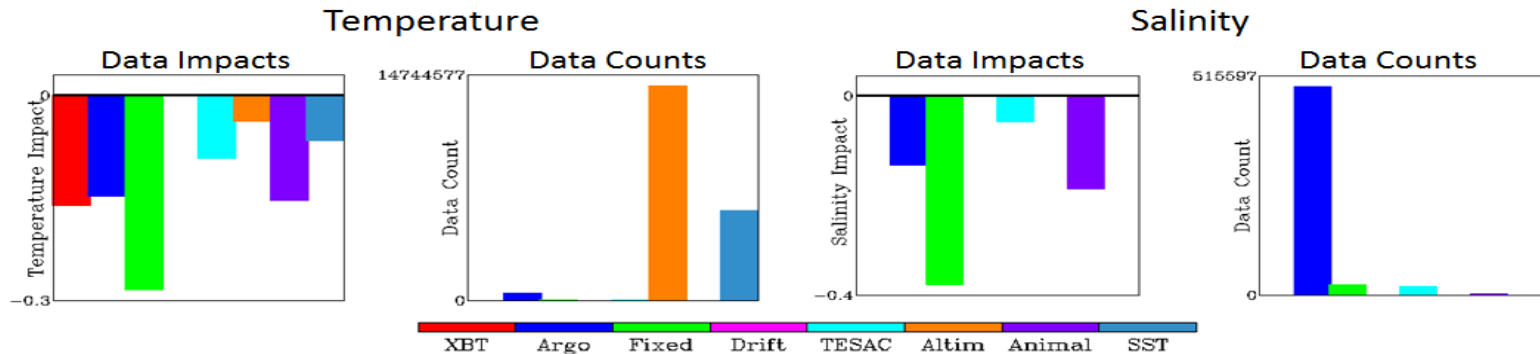


- ✓ The team plans to set up NRT OSEs in order to achieve routine monitoring of current observing systems.
- ✓ Mercator have conducted a NRT OSE for March 2013 following this initiative.
- ✓ Important differences are visible at and around the moorings and can reach 2°C.
- ✓ This is consistent with the results from another NRT OSEs in UKMO.

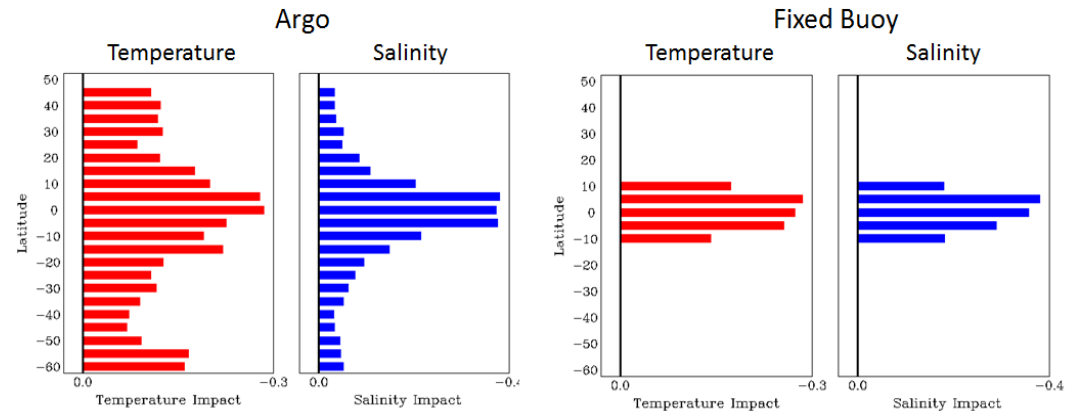
Lea et al QJRMS, 2014

# ★ Evaluation of the forecast sensitivities

Per observation Impacts of T and S on reducing HYCOM 48-hour forecast error using adjoint method (Pacific Ocean, 16 Sep - 30 Nov 2012)



Per observation impacts of Argo and fixed buoy arrays for T and S partitioned by 5° latitude bands.



- ✓ Impacts of temperature and salinity from all observing systems are beneficial.
- ✓ **Most effective data type** on a per observation basis are the tropical fixed moorings (TAO/TRITON array).
- ✓ The impact of Argo is comparable to the impact of the moorings in the tropics.

## ★ Gaps emerging after the recent TAO crisis

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- ✓ In my knowledge, they has not been examined yet.
- ✓ I hope the gaps in the ocean forecasting systems will be examined by members of the [GODAE Ocean View OSEval task team](#), as well as the optimal method how to adjust existing networks.
- ✓ For example, Mercator may implement an OSE experiment for the period before 2011 in the same configuration as their near-real-time OSE in 2013. Comparison of the results between these two will reveal the gaps.

### 3. Requirements for Ocean state estimation for climate researches



## ★ What are main drivers?

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- ✓ To make a historical records of the ocean state variation, which is physically well balanced, for climate researches.
- ✓ Possible targets are sea level variability, water-mass pathways, the subtropical cells in the Pacific, mixed-layer heat balance, estimating surface fluxes and river runoff, and interannual and decadal variability of the ocean heat content.
- ✓ Some of the estimated ocean fields are used for decadal predictions.

### Typical specification of current ocean DA systems for ocean estimation

- ✓ The majority is relatively low-resolution (no-eddy) model, but some systems apply eddy-permitting/resolving models.
- ✓ Most of ocean DA systems for S-I forecasting are also used for this purpose.
- ✓ However, the 4DVAR systems, that estimate a dynamically consistent ocean state, over a long-term (several months to several decades) in a single optimization (e.g., ECCO 4DVAR, JAMSTEC-K7 4DVAR), mainly targets for this purpose.
- ✓ Toward coupled data assimilation
  - Weakly coupled data assimilation by NCEP
  - Fully coupled data assimilation by the JAMSTEC K7 group (4DVAR) and by GFDL (EnKF).

## ★ Variable requirements

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- ✓ Most systems used for ocean estimation assimilate in-situ temperature and salinity profile data and sea level anomalies derived from satellite altimetry.
- ✓ TAO/TRITON mooring data provide an important constraint to these systems.
- ✓ **Observing systems stably sustained for a long period** (or permanently if possible !!) are desirable for a long-term ocean estimation.
  - Changes in observing systems induce temporal data gaps in the estimated ocean fields.
- ✓ The ocean and surface meteorology measurements from the tropical mooring array will become more and more important toward coupled data assimilation
- ✓ Masuda et al. try to evaluate the optimal repeating cycle for fixed-line ship observations using adjoint technique (Fig. 13 in the white paper).

## ★ Evaluation of existing networks and gaps

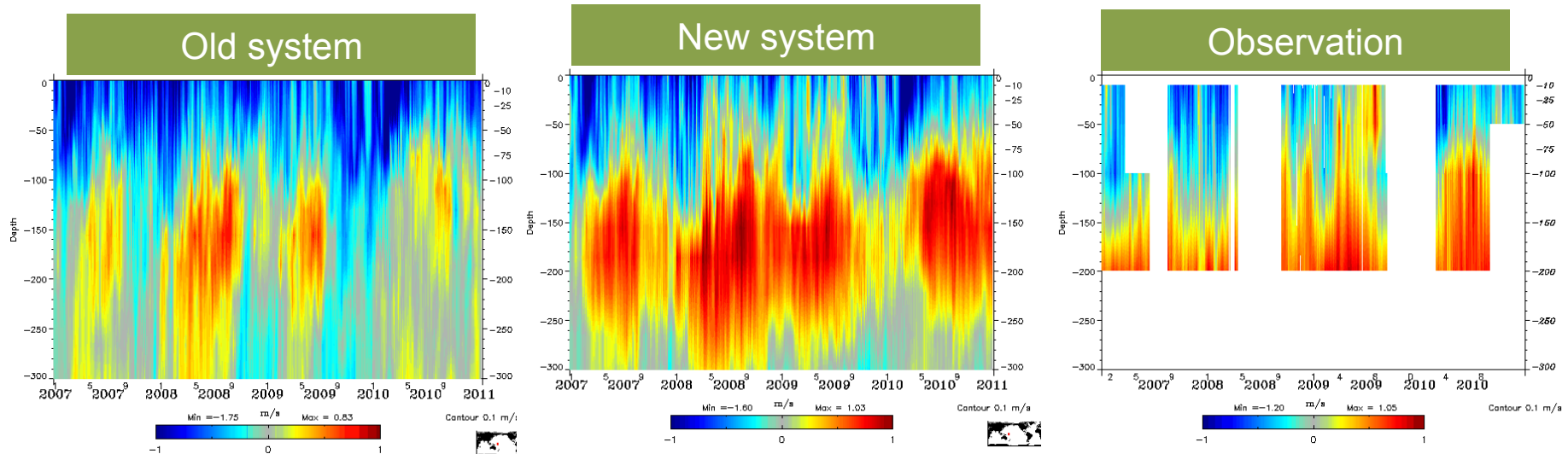
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- ✓ In my knowledge, the adequateness of existing network for the ocean state estimation have not been enough evaluated so far as well as the gaps due to the recent TAO crisis.
- ✓ The intercomparison among ocean reanalyses currently implemented under GSOP may provide us some hints on the adequateness.
- ✓ A regional assimilation effort at Scripps Institution of Oceanography has a plan to quantify the impact of moored observations of temperature, salinity, and velocity under the influence of meso-scale eddies using ECCO adjoint (4DVAR) assimilation system (resolution  $1/3$  to  $1/6^\circ$ ).

## 4. Common Issues

# ★ Requirements for validations

Validation of the zonal currents at  $165^{\circ}\text{E}-0^{\circ}\text{N}$  (t-z section) of the old and new GLORYS reanalysis against the TAO observations in Mercator



- ✓ The long time series provided by TAO moorings are extremely valuable to validate long-term simulations.
- ✓ Current measurements by moorings are also important as independent data.
- ✓ The multiple-parameter measurements of oceanic and atmospheric variables by moorings are important in the evaluation of the ocean state estimation systems and the corresponding heat budget analysis.
- ✓ Snapshots of the vertical section from the ship observation are useful to grab the image of the structures of TS fields and validate the DA results.

# ★ Potential trade-off and integration b/w networks

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- ✓ **Data assimilation essentially performs the integration between observing networks.**
- ✓ Updating to a higher-resolution model may enable it to use current observation data more adequately. (e.g., it leads a better use of the data detecting TIW, meridional current shear, etc. for S-I forecasting systems.)
  - But this is likely to require observation data with a higher resolution.
- ✓ Improvements of model physics, parameterization, etc. (e.g., to reduce model bias) may also enhance the data impacts.
- ✓ Introducing more sophisticated data assimilation scheme is another option to improve assimilated data efficiency.
  - For example, 4DVAR scheme have a potential to use high-frequency sampling data (e.g., TAO-TRITON data) more effectively.
- ✓ Assimilating current-measurement data may improve the systems.
- ✓ Introducing **the coupled data assimilation scheme** may enable it to use observation **data of the air-sea interface more effectively.**
  - Simultaneous observation of the boundary layers of both atmosphere and ocean may become important for constraining the coupled process.

# ★ Data and information Delivery

- ✓ Observation data are typically acquired through GTS in operational centers.
- ✓ TAO/TRITON profiles are transmitted in fragments (as partitioned data?) on GTS.
  - Due to the slow communication with the Argos satellite system.
  - Difficult to recover a full profile from partitioned data
  - Difficult to QC profile fragments (e.g., profile shape test not possible)
- ✓ Even if profiles received in a certain period (e.g., 1 day) are pooled, some levels are still unreported.
  - Due to the stop of transmittance by .data drift or error?
  - The data may be rejected by QC in some systems
- ✓ Difficult to perform data assimilation with a cycling period shorter than daily.
- ✓ **Need discussion on improving Real-Time Communication of TAO/TRITON.**
- ✓ More information in Neville's presentation.

## ★ Cautions on OSEval studies

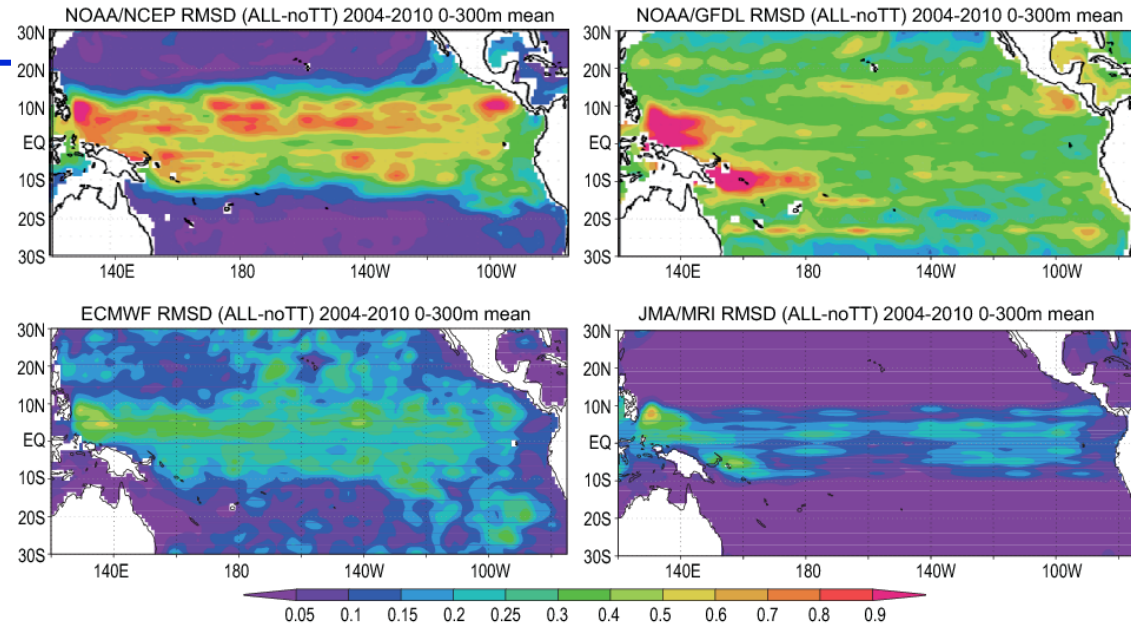
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- Results of OSEs severely depend on the quality and characteristic of ocean DA systems and the forecasting models.
  - ✓ Coupled model still have large mode errors and biases.
    - model biases can destroy the observation impacts.
  - ✓ A sophisticated model or data assimilation scheme may reduce the impacts of observations.
    - It may be able to subtracts information enough from small data.
- OSE and other observing system evaluation studies can evaluate only the impacts of data that are assimilated in the DA system.
  - Although atmospheric data observed by TAO/TRITON can also affects ocean DA systems, the impacts are not evaluated in the all studies.
- It should be also noted that historical observation data are often used for the calculation of statistical parameters and bias correction schemes in DA systems.
  - The impacts of those data is likely to be underestimated.



# ★ Multi-System OSE

0-300m averaged RMSD of temperature ( $^{\circ}\text{C}$ ) between ALL and noTT in 2004-2011 (2004-2010) for NCEP and GFDL (ECMWF and JMA/MRI).



- ✓ NOAA, JMA and ECMWF start **collaboration on the multi-system OSE** recently in order to examine the consistency among the results of OSEs in different centers.
- ✓ Impacts of TAO moorings are strongest (weakest) on NCEP (JMA) analysis, indicating **large sensitivities to TAO data input on the assimilation system**.
- ✓ For example, the figure indicated that the averaged RMSD of temperature between ALL and noMoor/noTT in 0-300m is relatively large in the far western equatorial Pacific, and around 8°S-160°E.
  - **Regions where the model accuracy is relatively low?**
- ✓ The RMSDs are also large in the zonal band along 5°N probably due to the energetic eddy activities.
- ✓ It is desirable that **TPOS2020 recommends this kind of collaboration studies**.

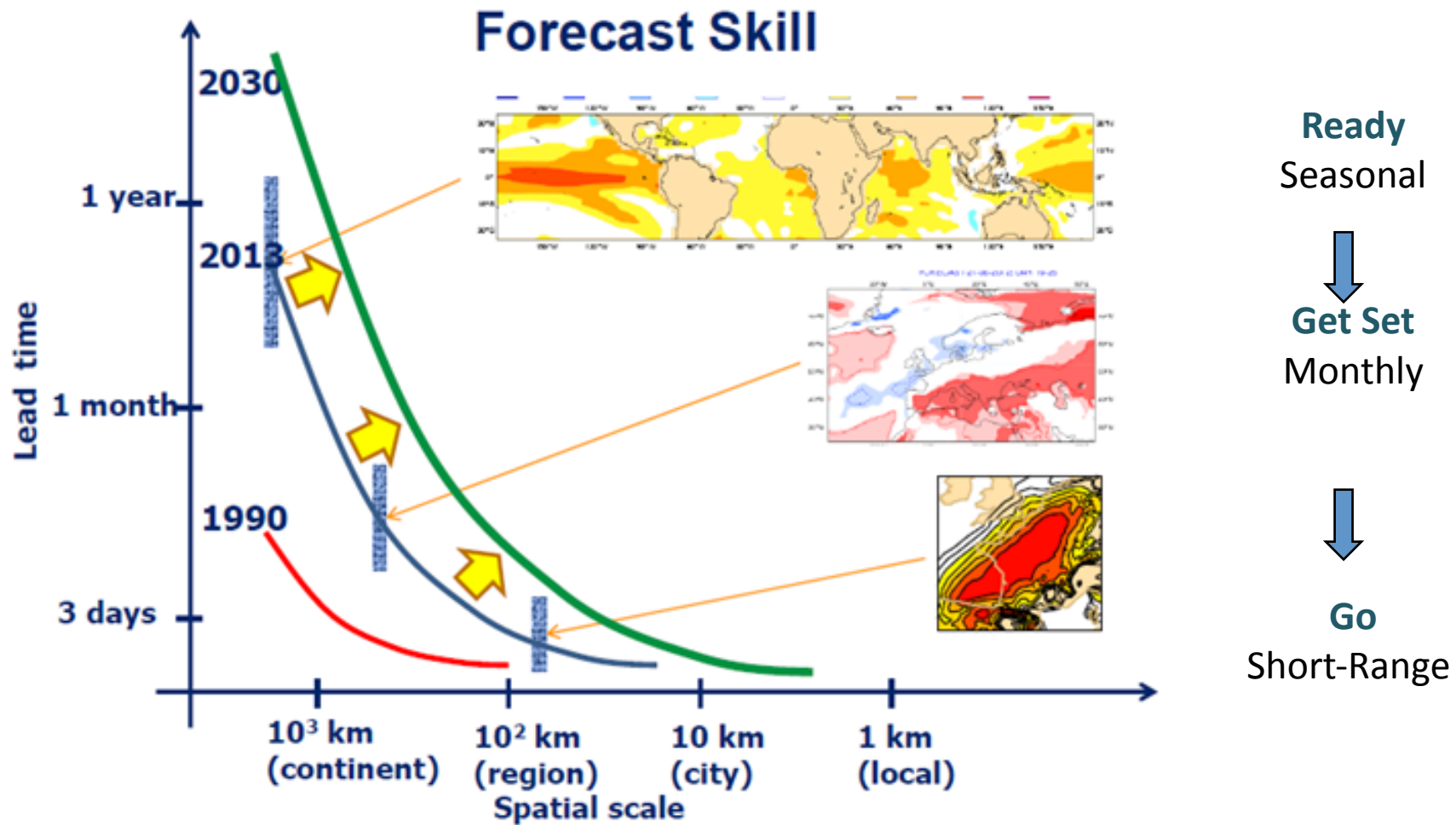
## 5. Summary and requests

# ★ Summary and Requests

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- The impacts of TAO/TRITON are generally in the same level with, and sometimes larger than those of Argo in the equatorial Pacific.
- We assume that **a further loss of TAO/TRITON data will lead to a degradation** of the forecast skill and will have a detrimental impact on many applications based on ocean DA systems.
- We are assured that continued deployment and maintenance of the tropical mooring arrays in all ocean basins is highly desirable.
- However, given funding constraints, a re-design of the mooring array might be appropriate and timely, taking into account the complementarity of other observing systems such as Argo.
  - **This effort should be aided by an internationally coordinated multi-model effort** in (tropical) observing system evaluation and design.
- The recent crisis of the TAO array provides the rationale for commencing new studies in evaluating the tropical Pacific observing system.
  - Follow-up of these studies will be carried out by the **GODAE Ocean View OSEval task team**
- **2 Requests for endorsements.**
  - Collaboration on the intercomparison of the equatorial Pacific T fields.
  - Collaboration on the multi-system OSE.

# Need for reliable forecasts of meteorology at different time scales



# Different lives of one observation

1. Initialization of Today's forecast (NWP, monthly, Seasonal)
2. Verification of yesterday, last month, last season forecast
3. Monitoring of climate conditions
4. Calibration of forecasts in 5 years time and beyond
5. Improved forecasting systems used in next decade

*Tangible impact of the observations on all these aspects is not easy to quantify objectively*

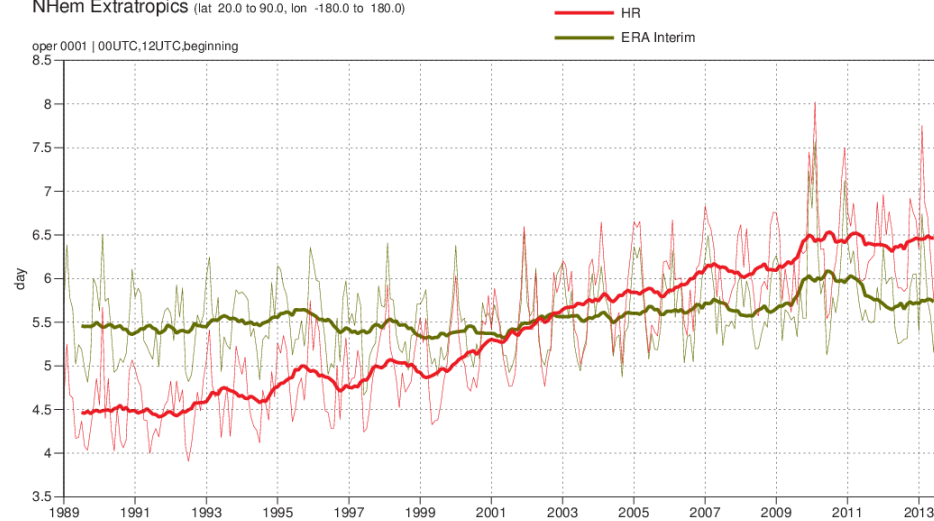
# NWP: Steady progress in forecast skill

Skill as fc day when ACC drops below 80%

HRES is operational  
ERA is EraInterim

**HRES and ERA Interim 00,12UTC forecast skill**

500hPa geopotential  
Lead time of Anomaly correlation reaching 80%  
NHem Extratropics (lat 20.0 to 90.0, lon -180.0 to 180.0)



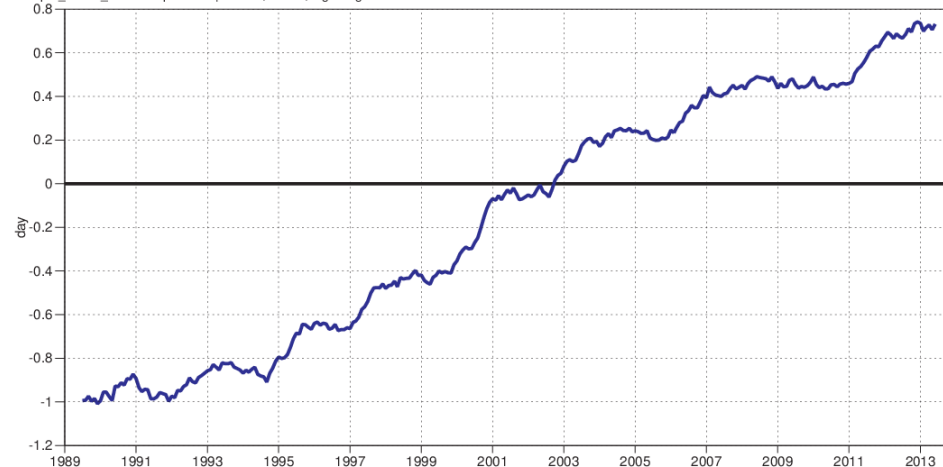
Steady progress ~  
1 day/decade

**HRES - ERA**

500hPa geopotential  
Anomaly correlation  
NHem Extratropics (lat 20.0 to 90.0, lon -180.0 to 180.0)

T+0 T+12 ... T+240

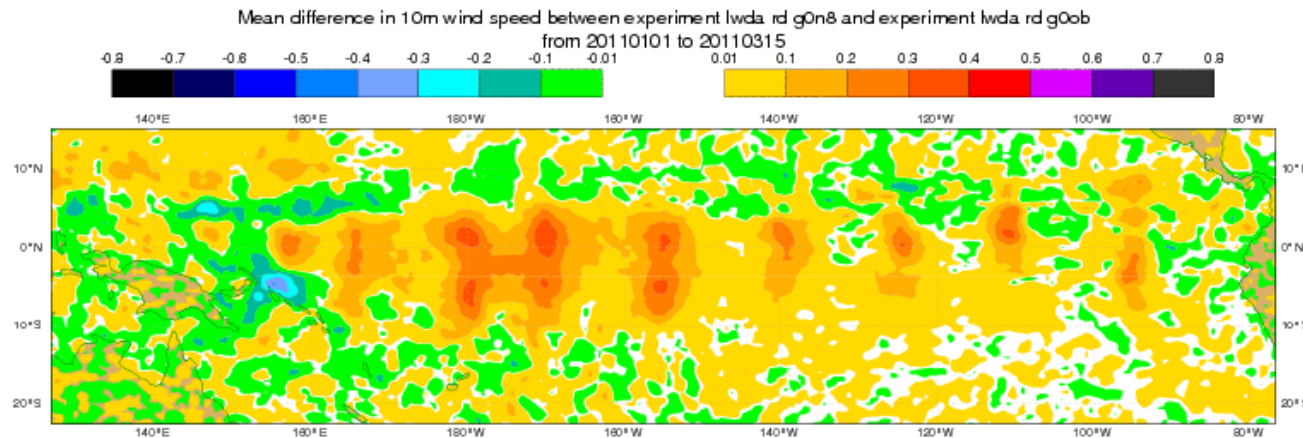
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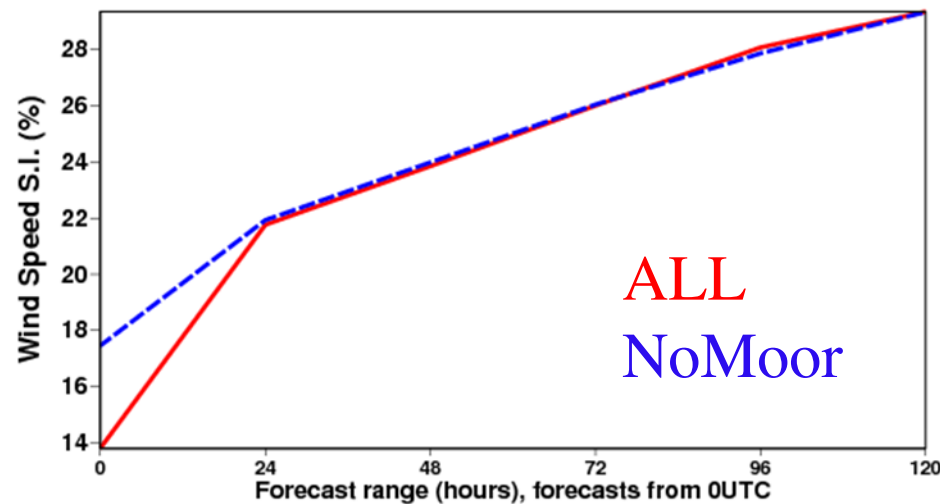
*Future forecasting  
systems will extract  
more information  
from today's  
observations*

# Short and Medium Range Weather NWP Impact of Winds from Mooring

10m winds: ALL - NoMoor



ALL has stronger winds



Information is not retained

# Summary

- **One observation contributes to many aspects of the forecasting system:** initialization, model, calibration, and verification
- **Objective evaluation is difficult**, even for the impact on the initialization and forecast.
- **Panorama for TPOS2020 is wide:** from diurnal to decadal and beyond.
- **Modelling and initializing the coupled O-A boundary layer** is becoming increasingly important.
- **Need of long continuous time series** for verification of reanalyses, extreme events/severe weather warning, and calibration of seasonal forecasts
- **Moorings** is the main observing system that currently provides information in the equatorial waveguide (surface and subsurface).
- **Model & DA errors** in both ocean and atmosphere remain a serious obstacle.
  - At the Equator
  - O-A boundary layer.

Equatorial Pacific recently in the spotlight for a reason not previously anticipated:  
the recent hiatus in surface warming.



## ★ Requirement table for SI forecasts

Variable	Accuracy	Vertical	Horizontal	Tempral
SST	0.05K	-	Global/ 0.25°	more than 20 years/ daily
Ocean Temperature	0.05K	0-250m/ 10m 250-1000m/ 50m	Tropics/ 2°×10° as the baseline	more than 20 years/ 1-5-daily
SSS	0.1PSU	-	Global/ 2°	more than 20 years/ 10-daily
Salinity	0.02PSU	0-250m/ 10m 250-1000m/ 50m	Tropics/ 2°×10° as the baseline	more than 20 years/ 1-5-daily
SSH	3cm	-	Global/ 1°	more than 20 years/ 10-daily
Currents	2cm/s	0-250m/ 20m 250-1000m/ 100m	Tropics/ 5° × 20°	more than 20 years/ 10-daily

# ★ Requirement table for Ocean forecasts

Variable	Accuracy	Vertical	Horizontal	Tempral
SST	0.05K	-	Global/ 0.1°	more than 5 years/ 3-hourly
Ocean Temperature	0.05K	0-250m/ 10m 250-1000m/ 50m	Global/ 2°	more than 5 years/ daily
SSS	0.1PSU	-	Global/ 1°	more than 5 years/ daily
Salinity	0.02PSU	0-250m/ 10m 250-1000m/ 50m	Tropics/ 2°	more than 5 years/ daily
SSH	3cm	-	Global/ 0.1°	more than 5 years/ daily
Currents	2cm/s	0-250m/ 20m 250-1000m/ 100m	several important points (including western boundary currents)	more than 5 years/ daily

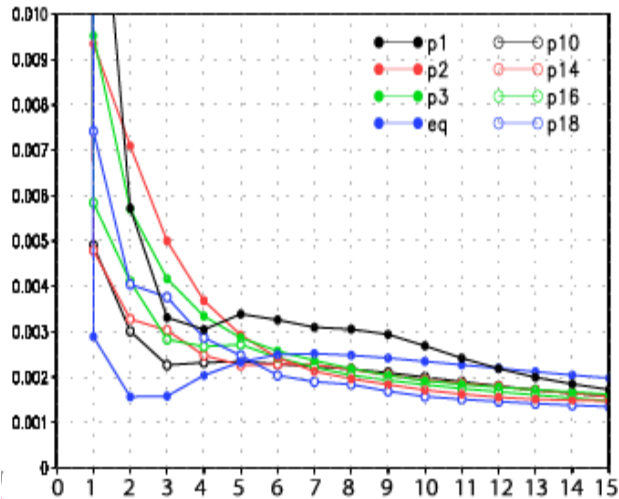
# ★ Requirement table for Ocean state estimations

Variable	Accuracy	Vertical	Horizontal	Tempral
SST	0.05K	-	Global/ 1°	more than 20 years/ 10-daily
Ocean Temperature	0.002K	0-250m/ 10m 250-1000m/ 50m 1000m-btm/ 250m	Global/ 2°	more than 20 years/ 10-daily
SSS	0.1PSU	-	Global/ 2°	more than 20 years/ 10-daily
Salinity	0.002PSU	0-250m/ 10m 250-1000m/ 50m 1000m-btm/ 250m	Tropics/ 2°	more than 20 years/ 10-daily
SSH	3cm	-	Global/ 1°	more than 20 years/ 10-daily
Currents	2cm/s	0-250m/ 20m 250-1000m/ 100m 1000m-btm/ 500m	several important points (including western boundary currents)	more than 20 years/ 10-daily

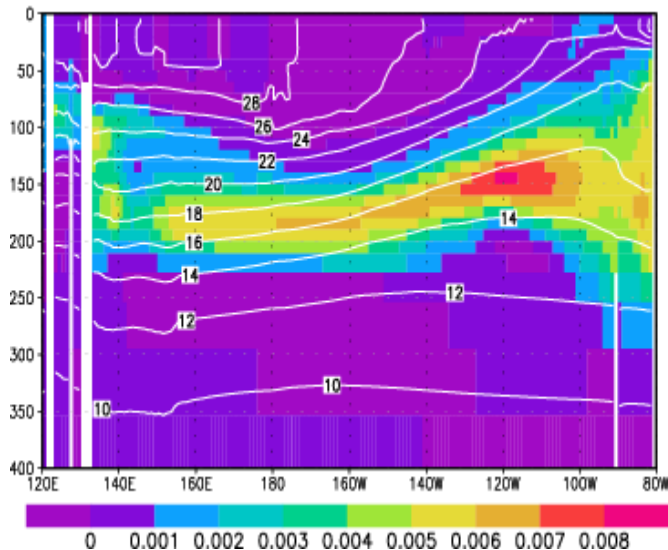
Thank you!

# ★ Analysis for the optimal repeating observation cycle

Adjoint sensitivity along equator and WHP lines at 100-m depth



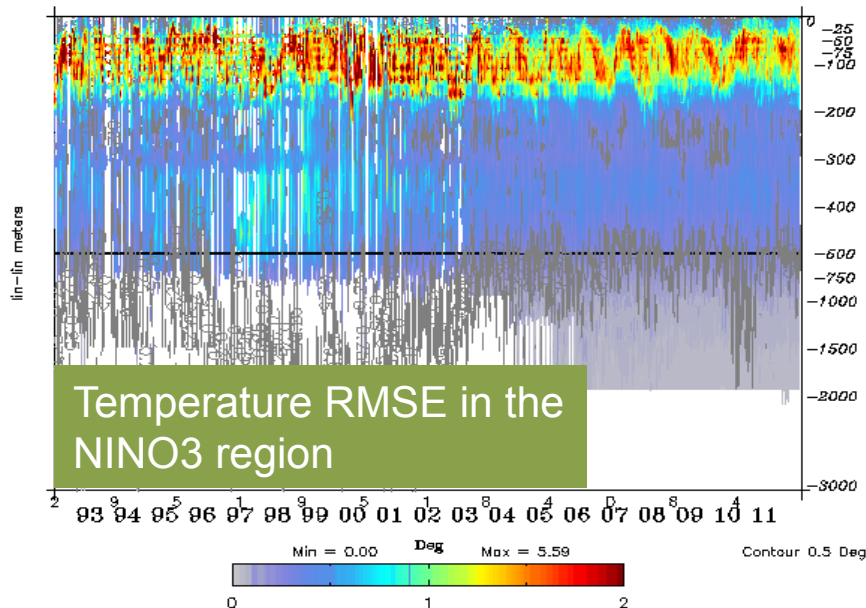
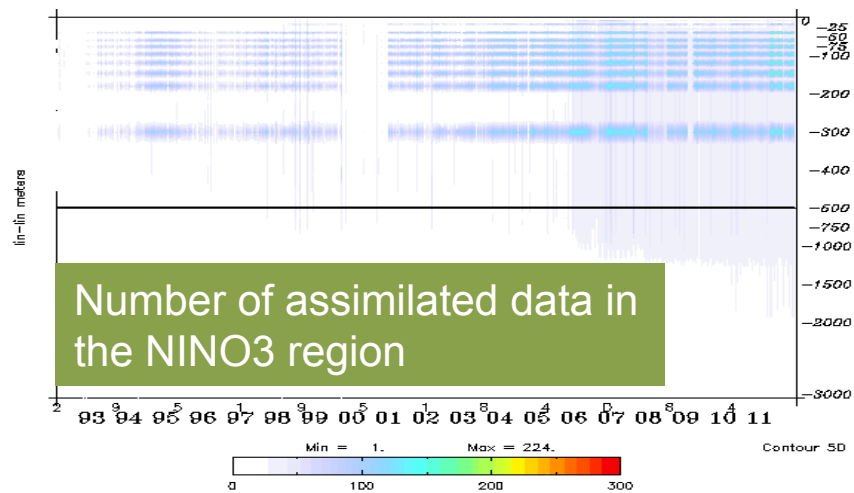
Adjoint Temp along equator -2yr



- ✓ Total **sensitivity** of the retrospective ocean state estimation **to the 100m T observations in the multiple WOCE lines** is examined through an adjoint method.
- ✓ The top panel shows that the memory of the 100m T observation is lost from 100m T field faster at the equator.
  - This indicates that **observation lines near the equator is worth repeating more intensive** than other lines.
- ✓ But it is worth noting that the memory remains mainly in the lower thermocline (150-200m depth) at the time 2 years before the observation time (bottom panel).
  - This means that the 100m T observation is effective to improve T in the lower thermocline in the retrospective estimation.
  - Frequent sampling by Moorings is important to estimate T above the thermocline.

# ★ Requirements for validations

Example of the validation for the GLORYS reanalysis in Mercator



- ✓ The long time series provided by TAO moorings are **extremely valuable to validate** long-term simulations.
- ✓ **Current measurements** by moorings are **important as independent data**.
- ✓ The multiple-parameter measurements of oceanic and atmospheric variables by moorings are important in the evaluation of the ocean state estimation systems and the corresponding heat budget analysis.
- ✓ Snapshots of the vertical section from the ship observation are useful to grab the image of the structures of TS fields and validate the DA results.