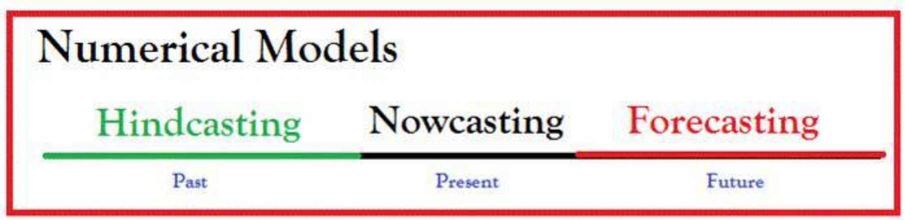
Operational Ocean analysis from Ocean data assimilation Systems

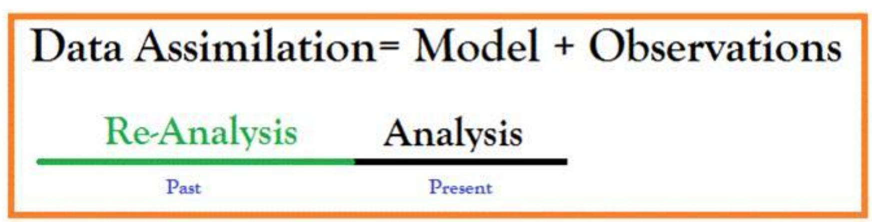
Dr. S. Sivareddy,

ESSO-INCOIS

Email: ssiva@incois.gov.in

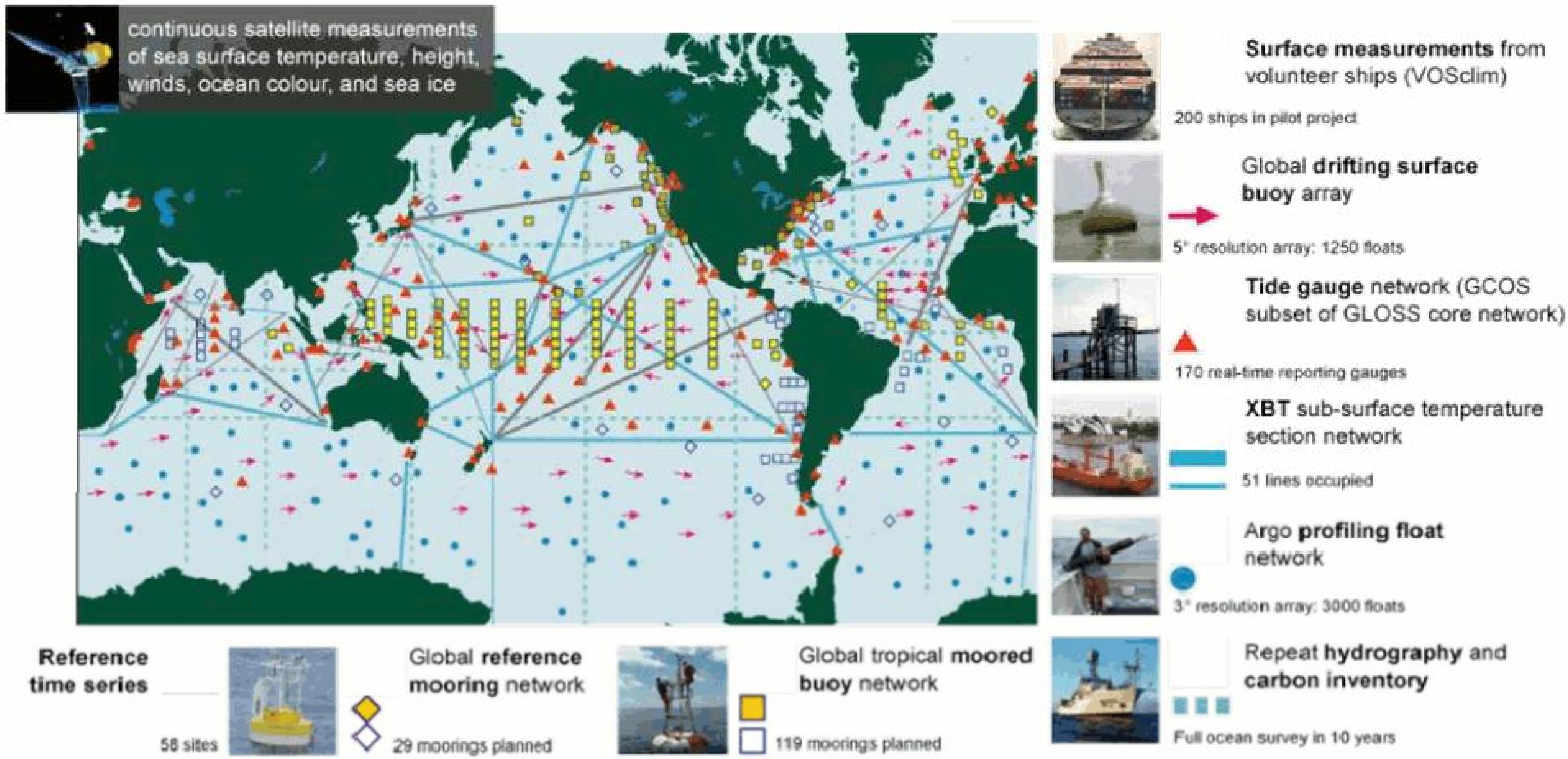
With inputs from:
Dr. Arya Paul and Mr. Deepsankar Benerjee





OTGA-INCOIS Training Course "Discovery and Use of Operational Ocean Data Products and Services" March, 2017

Ocean Observation Networks

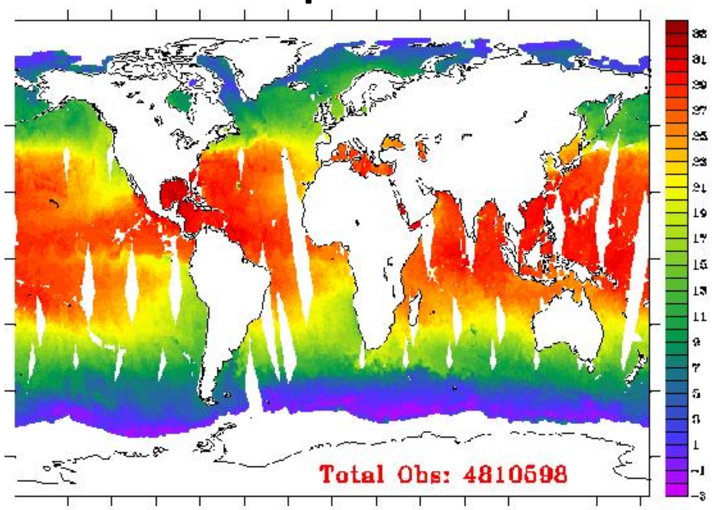


GCOS GOOS jcomm

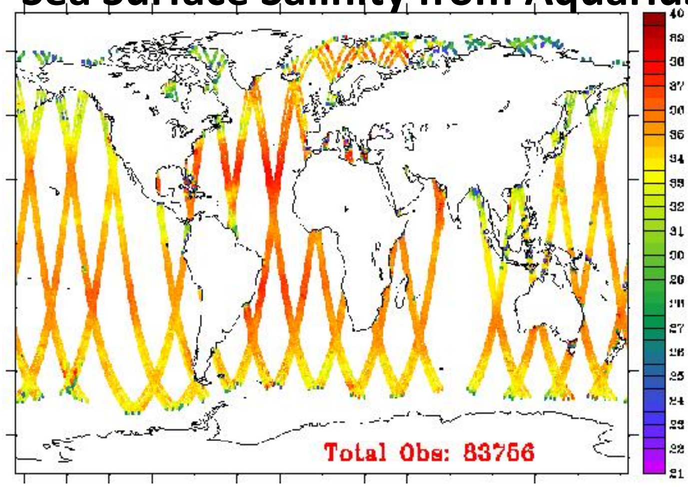
- A total of 5635 platforms are maintained globally.

Spatial Coverage from different satellites for different parameters (25th August, 2011)

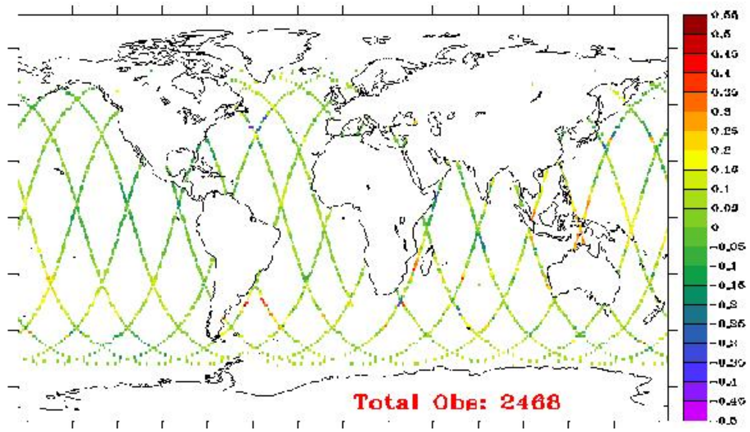
Sea Surface Temperature from AMSRE



Sea Surface Salinity from Aquarius



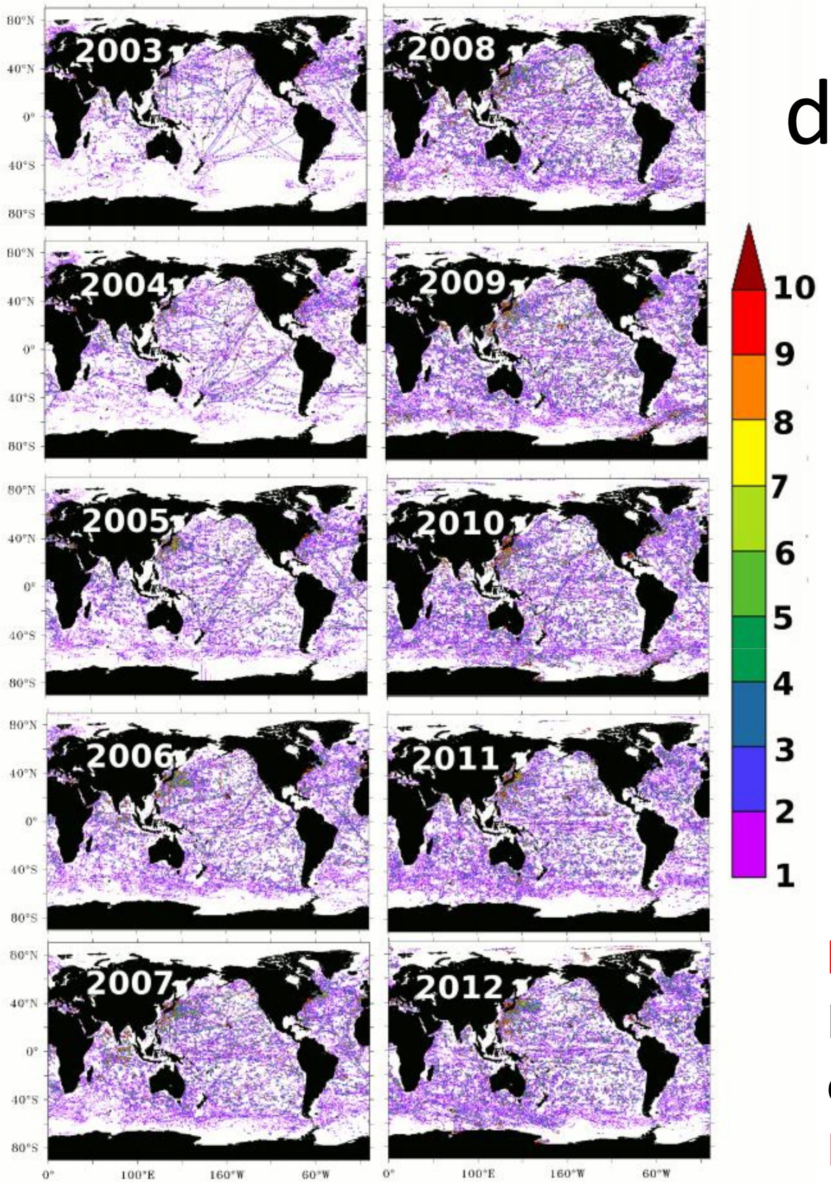
Sea Surface Height Anomaly from Altimeters

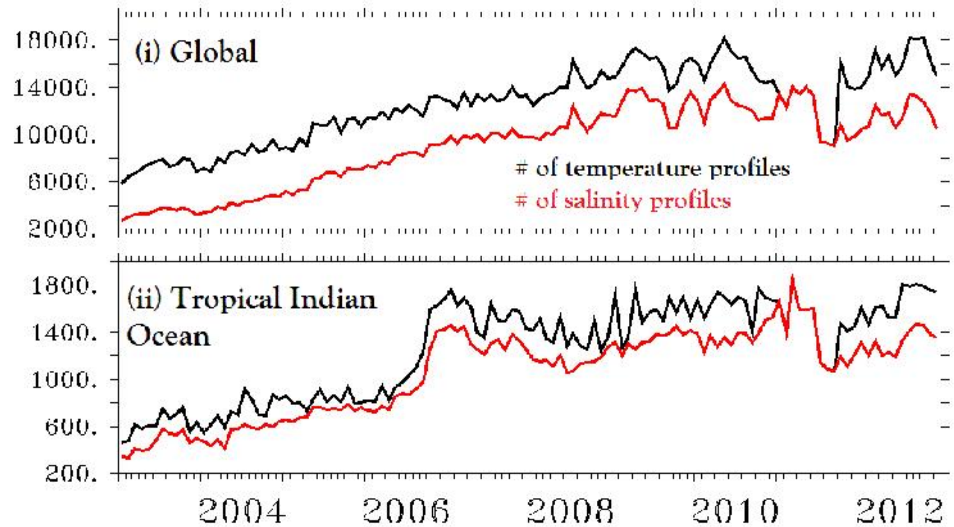


Limitation:

Cannot provide sub-surface information

Spatial coverage from different in-situ observation networks for ocean T&S profiles





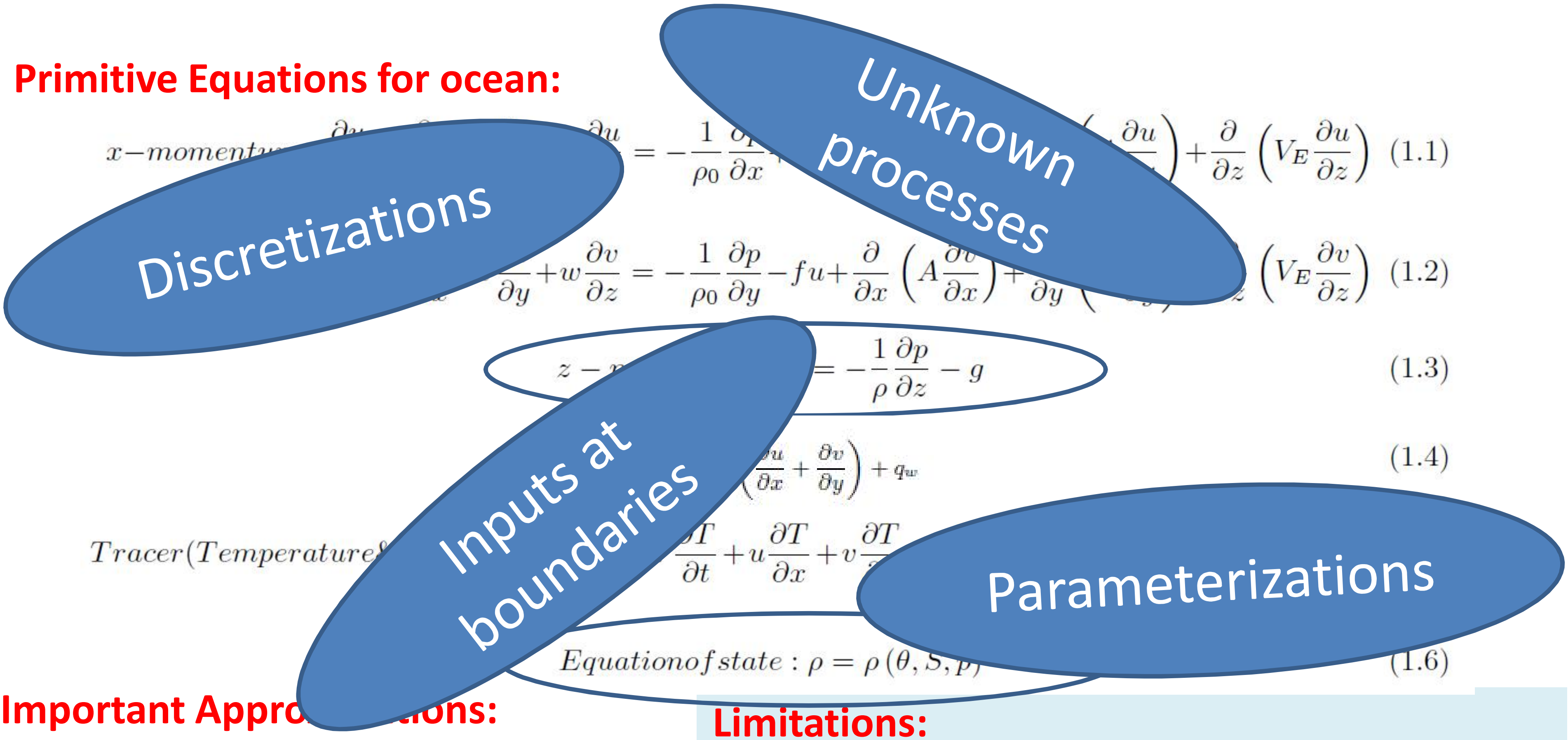
Limitations:

Impossible to observe the ocean at each and every time and location.

Most of the ocean is largely under-sampled even today.

Numerical Ocean Models

Primitive Equations for ocean:



Important Approximations:

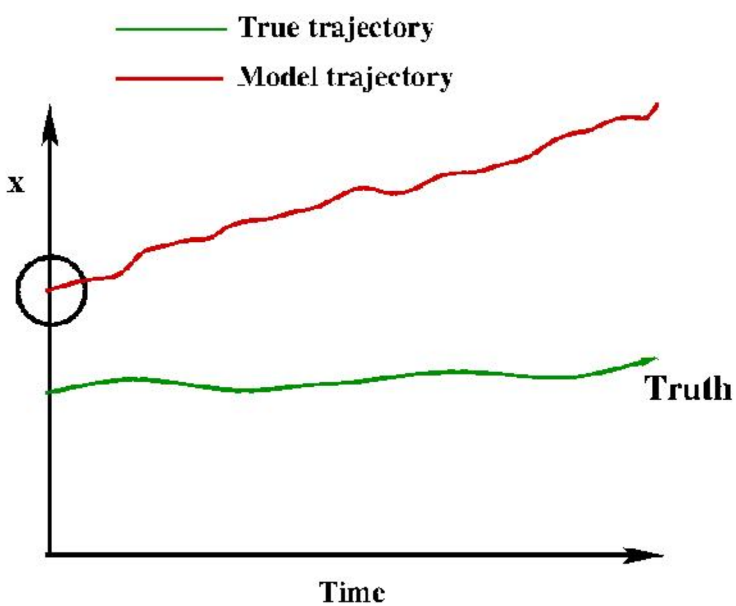
Boussinesq
Hydrostatic
Shallow-Ocean

Limitations:

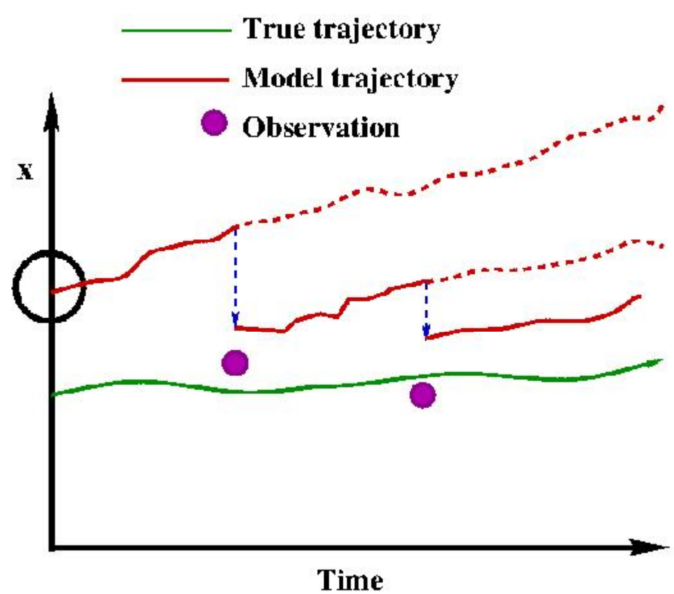
Inability to model all the ocean process.
Model errors aroused due to various approximations/discretizations

Flowchart of Data Assimilation

Definition: Data assimilation is an analysis technique in which the observed information is accumulated into the model state by taking advantage of consistency constraints with laws of time evolution and physical properties



NO CORRECTION



Truth

CORRECTION

Application: Improved solutions of the state of the ocean realized from both model and observations (temperature, salinity, SLA, and currents).

$$X^a = x^b + BH^T\left(HBH^T + R\right)^{-1}\left(Y_o - Hx^b\right)$$

$X^a --> Analysis$

$X^b --> Forecast / Background$

$Y_0 --> Observation$

B → Model background error covariance

R →Observational error covariance

H → Interpolation operator

What is the relative role of B and R

It is best understood if we work with a scalar case with H=1

Let, $R = \pm_o^2, B = \pm_b^2$

$$x^a = x^b + \pm_b^2\left(\pm_b^2 + \pm_o^2\right)^{-1}\left(y_0 - x^b\right)$$

$$\Rightarrow x^a = \frac{\pm_0^2}{\pm_0^2 + \pm_b^2}x^b + \frac{\pm_b^2}{\pm_0^2 + \pm_b^2}y_0$$

Analysis is sensitive to both model background error covariance and observational error covariance

If $\pm_b >> \pm_0$

$x^a \approx y_0$

If $\pm_0 >> \pm_b$

$x^a \approx x_b$

$$X^a = x^b + BH^T\left(HBH^T \ldots\right. \left(Y_o - Hx^b\right)$$

What is the role of B ??

X^a --> *Analysis*

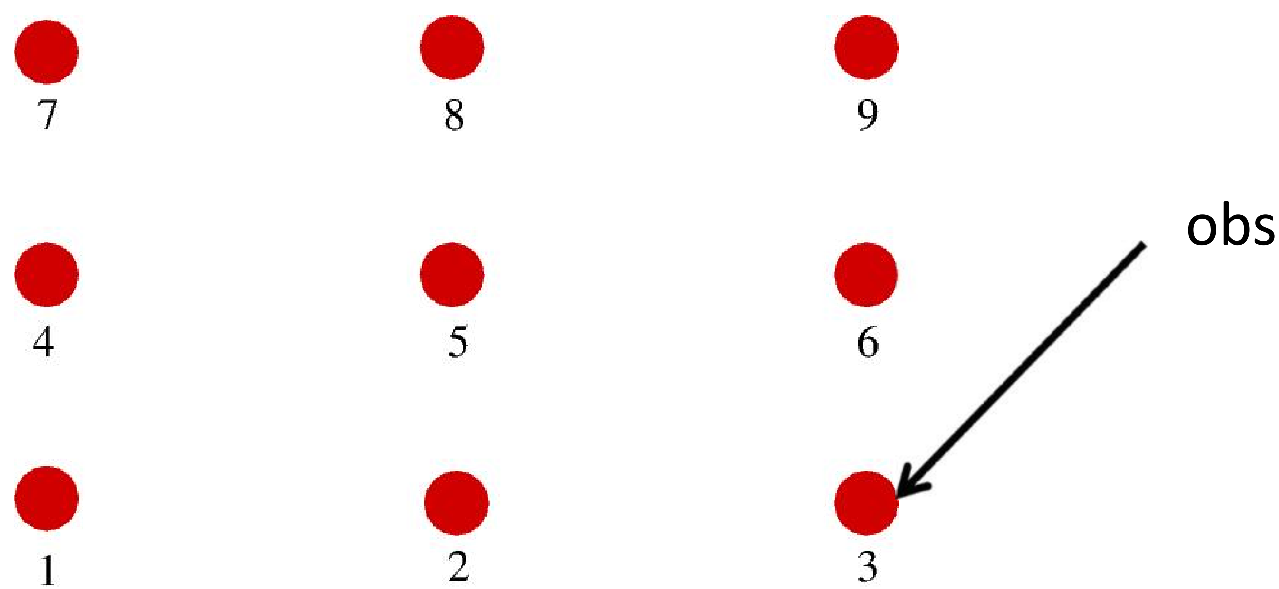
X^b --> *Forecast / B...*

Y_0 --> *Observa...*

... Model background error covariance

R → Observational error covariance

H → Interpolation operator



Under what condition will the information at grid location 3 propagate to other grid points ?

$$x^a = x^b + BH^T\left(HBH^T + R\right)^{-1}\left(y - Hx^b\right)$$

$$x^b = \begin{bmatrix} x_1^b \\ x_2^b \\ . \\ . \\ x_9^b \end{bmatrix}, \quad y = y_0, \quad H = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$R = \pm_0^2 \qquad B = \begin{bmatrix} B_{11} & B_{12} & . & . & . & B_{19} \\ B_{21} & B_{22} & . & . & . & B_{29} \\ . & . & B_{33} & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ B_{31} & B_{32} & . & . & . & B_{39} \end{bmatrix}$$

$$y - Hx^b = y_0 - \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1^b \\ x_2^b \\ . \\ . \\ x_9^b \end{bmatrix} = y_0 - x_3^b$$

$$x^a = x^b + BH^T\left(HBH^T + R\right)^{-1}\left(y - Hx^b\right)$$

$$HB = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} B_{11} & B_{12} & . & . & . & B_{19} \\ B_{21} & B_{22} & . & . & . & B_{29} \\ . & . & B_{33} & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ B_{31} & B_{32} & . & . & . & B_{39} \end{bmatrix} = \begin{bmatrix} B_{31} & B_{32} & . & . & B_{39} \end{bmatrix}$$

$$HBH^T = \begin{bmatrix} B_{31} & B_{32} & . & . & B_{39} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \\ . \\ 0 \end{bmatrix} = B_{33}$$

$$\left(HBH^T + R\right)^{-1} = \frac{1}{B_{33} + \pm_0^2}$$

$$\Rightarrow \left(HBH^T + R\right)^{-1}\left(y - Hx^b\right) = \frac{y_0 - x_3^b}{B_{33} + \pm_0^2}$$

$$x^a = x^b + BH^T\left(HBH^T + R\right)^{-1}\left(y - Hx^b\right)$$

$$\left(HBH^T + R\right)^{-1}\left(y - Hx^b\right) = \frac{y_0 - x_3^b}{B_{33} + \pm_0^2}$$

$$BH^T = \begin{bmatrix} B_{11} & B_{12} & . & . & . & B_{19} \\ B_{21} & B_{22} & . & . & . & B_{29} \\ . & . & B_{33} & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ B_{31} & B_{32} & . & . & . & B_{39} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \\ . \\ 0 \end{bmatrix} = \begin{bmatrix} B_{13} \\ . \\ . \\ . \\ B_{93} \end{bmatrix}$$

$$BH^T\left(HBH^T + R\right)^{-1}\left(y - Hx^b\right) = \begin{bmatrix} B_{13} \\ . \\ . \\ . \\ B_{93} \end{bmatrix} \frac{\left(y_0 - x_3^b\right)}{\left(B_{33} + \pm_0^2\right)}$$

$$\begin{bmatrix} x_1^a \\ x_2^a \\ . \\ . \\ x_9^a \end{bmatrix} = \begin{bmatrix} x_1^b \\ x_2^b \\ . \\ . \\ x_9^b \end{bmatrix} + \begin{bmatrix} B_{13} \\ B_{23} \\ . \\ . \\ B_{93} \end{bmatrix} \frac{\left(y_0 - x_3^b\right)}{\left(B_{33} + \pm_0^2\right)}$$

$$x_k^a = x_k^b + \left(\frac{y_0 - x_3^b}{B_{33} + \pm_0^2} \right) B_{k3}$$

B propagates information from one site to another !!!

Data Assimilation Techniques

Nudging:

Simply adds a correction term to the prognostic equation of inerest (example: SST equation)

$$\frac{\partial X}{\partial t} = K(X_o - X)$$

Limitation: Observation should exactly be on the model space.

Optimal Interpolation:

Gets correction at each grid point separately based on model and observational error covariance. The technique depends largely on the de-correlation lengths. Model error covariance is

$$X^a = X^b + BH^T (HBH^T + R)^{-1} \left(Y_o - HX^b\right)$$

Limitation: Corrections at a grid point is independent from other grid point which can lead to discontinuities in the solution. There is absolutely no scope for correction if there are no observations within the de-correlation length scales.

Data Assimilation Techniques

Variational Methods (3D-VAR and 4D-VAR):

Gets correction at each grid point based on a cost function that connects for the whole domain. The technique ensures smoothness in the solutions.

$$3D-VAR: J(X) = \frac{1}{2}(X - X^b)^T B^{-1}(X - X^b) + \frac{1}{2}(HX - Y_o)^T R^{-1}(HX - Y_o)$$

$$4D-VAR: J(X) = \frac{1}{2}(X - X^b)^T B^{-1}(X - X^b) + \frac{1}{2}\sum_{i=1}^{n}(HX - Y_o^i)^T R^{-1}(HX - Y_o^i)$$

Limitation: Model error covariance is static. In reality, they change with time and state of the ocean.

Kalman Filters :

Model error covariance that is required to obtain correction evolves with the model.

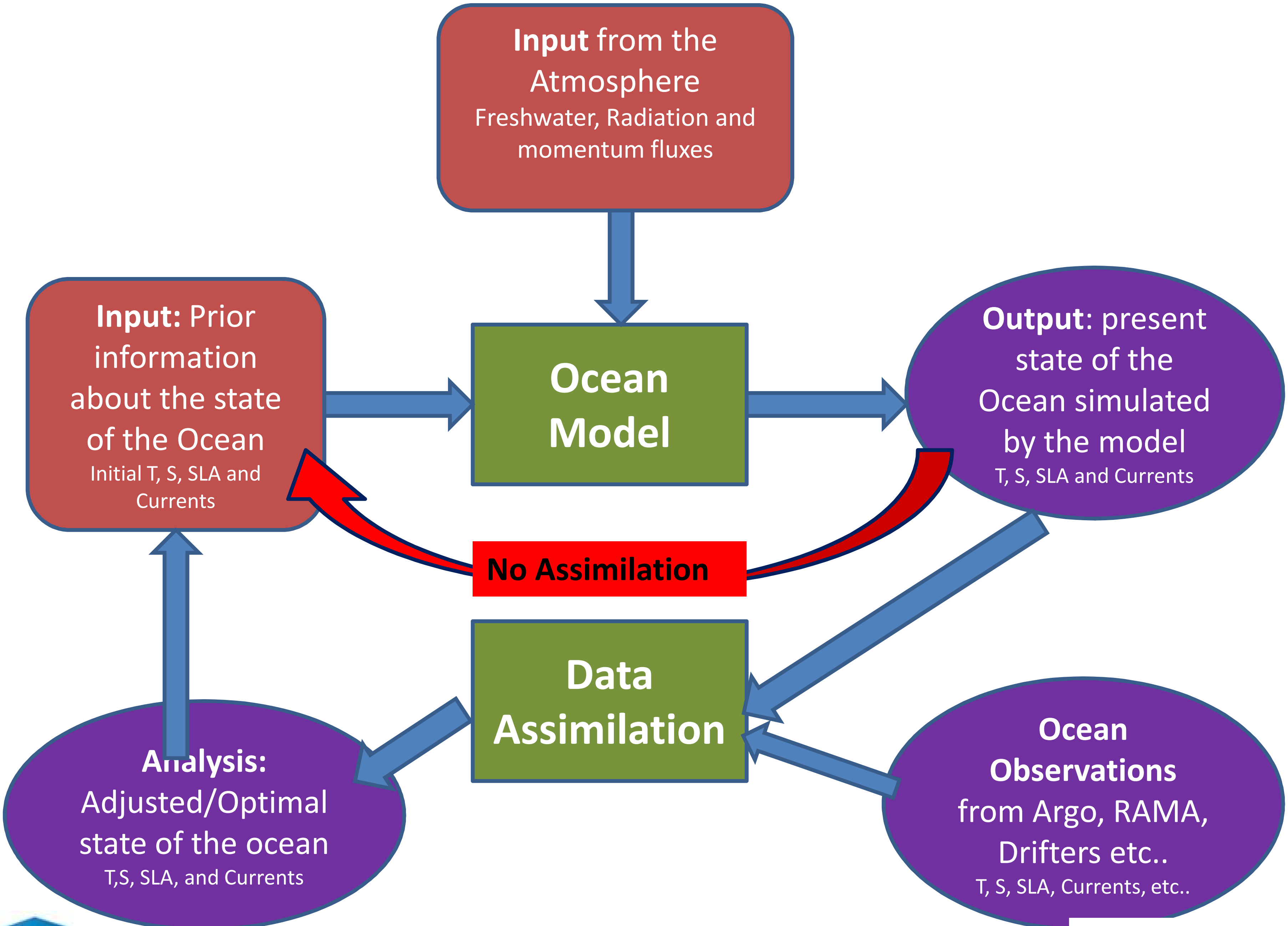
$$X^a = X^b + P^a H^T R^{-1}\left(Y_o - HX^b\right)$$
$$P^a = \left[I + P^b H^T R^{-1} H\right]^{-1} P^b$$

Limitations: Pure Kalman filters can not be applied to ocean systems. Ensemble methods that use the flavour of Kalman filters are popular in literature. They largely depends on initial ensemble and inflation parameter that is unphysical.

Limitations of Assimilation Schemes

Difficulty in prescribing the behavior of model errors, observational errors (instrument + representation)

Doesn’t implicitly conform with the model dynamics. It can lead to dynamically inconsistent ocean states



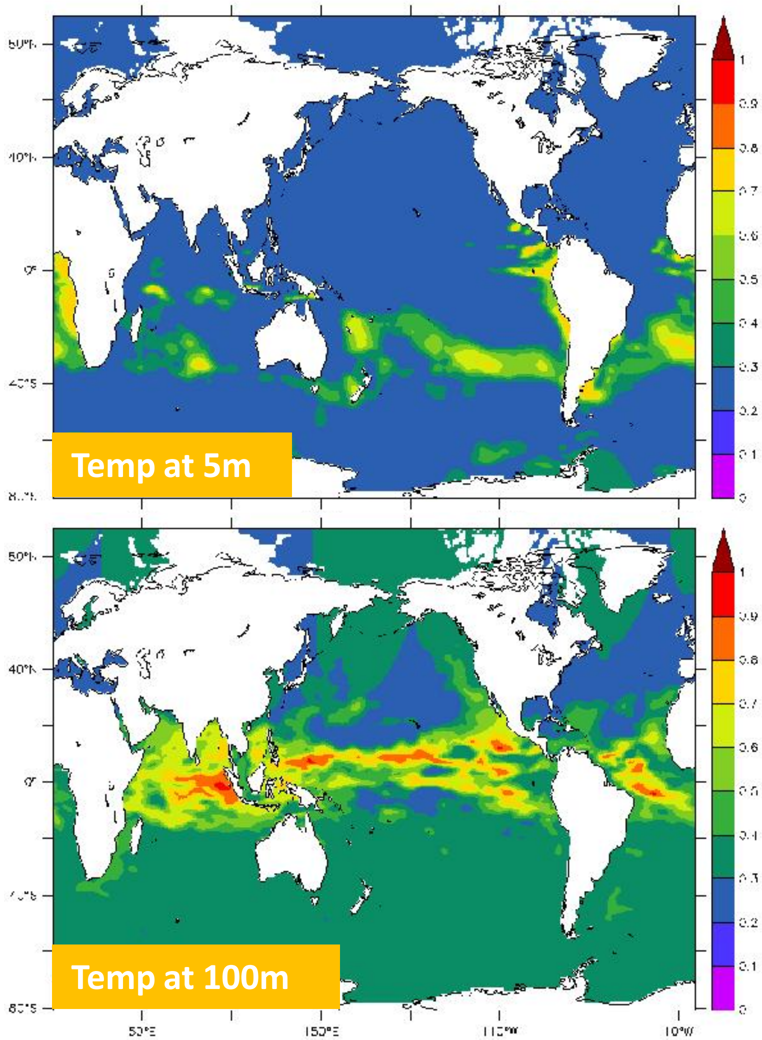
Input from the Atmosphere
Freshwater, Radiation and momentum fluxes
Input: Prior information about the state of the Ocean
Initial T, S, SLA and Currents
Ocean Model
Output: present state of the Ocean simulated by the model
T, S, SLA and Currents
No Assimilation
Data Assimilation
Analysis: Adjusted/Optimal state of the ocean
T,S, SLA, and Currents
Ocean Observations from Argo, RAMA, Drifters etc..
T, S, SLA, Currents, etc..

Ocean Data Assimilation systems At INCOIS

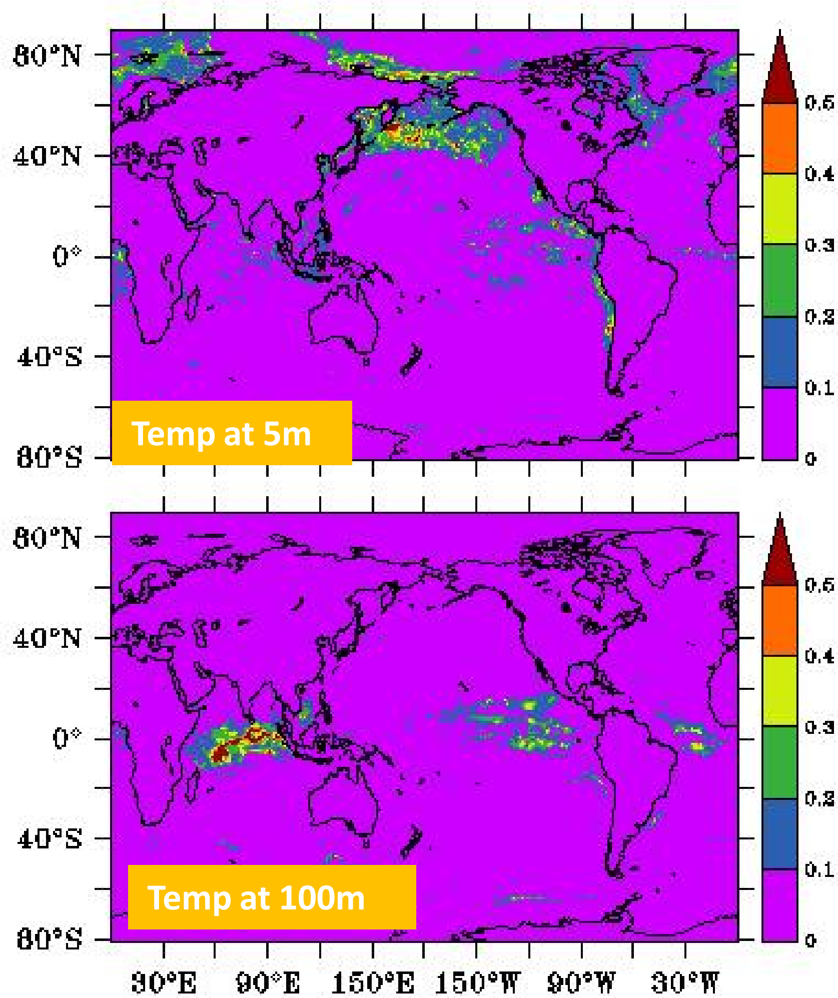
	INCOIS-GODAS	LETKF-NEMO	LETKF-MOM	LETKF-ROMS
OGCM	MOM-4.0	NEMO	MOM-4.1	ROMS-3.6
Assimilation Scheme	3D-VAR	LETKF	LETKF	LETKF
Domain	Global	Global	Global	Indian Ocean
Assimilation capabilities	T&S profiles	SLA and T&S profiles	SST, SSS, SLA and T&S profiles	SST, SSS, SLA and T&S profiles
Status	Operational	Toy Model	Experimental	Experimental
Original source	Adopted from NCEP	Adopted from University of Maryland	Joint efforts between University of Maryland and INCOIS	Indigenous development
Reference	Ravichandran et al., 2013 Sivareddy, 2015	Sluka et al., 2016	--	--

Model Errors set in INCOIS-GODAS and LETKF-MOM

INCOIS-GODAS



LETKF-MOM

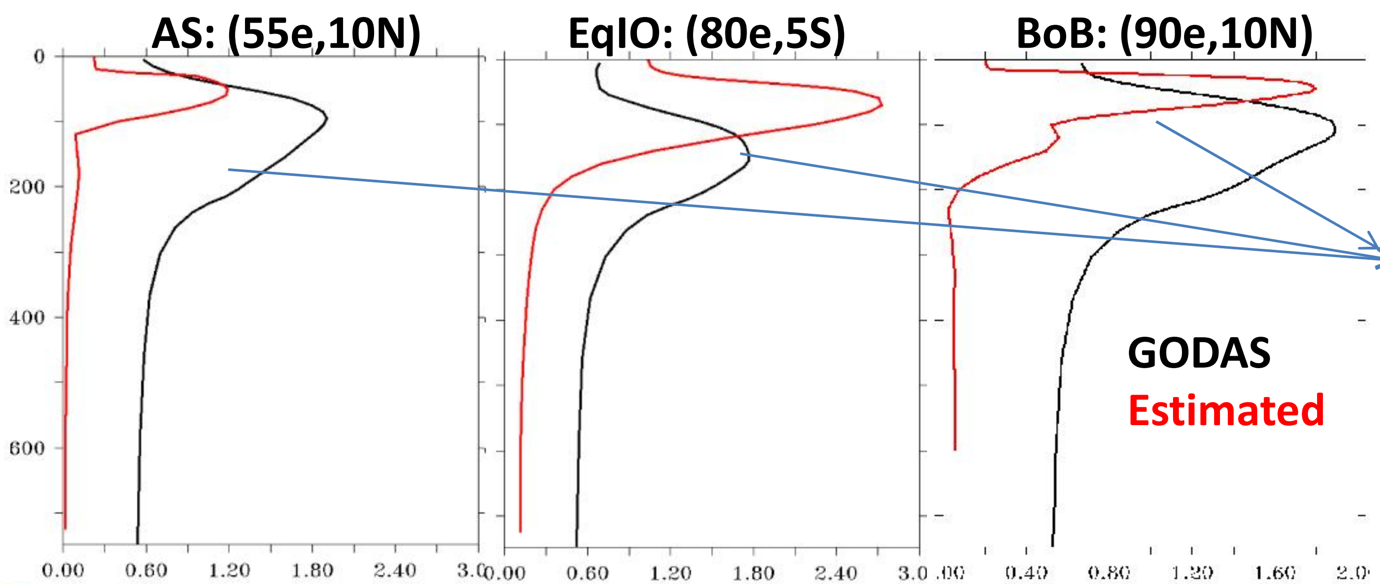


Observational Errors from high resolution simulations

In **INCOIS-GODAS, Observational error is estimated based on local vertical gradient** (e.g. local vertical tempearature gradient)

In LETKF-MOM and LETKF-ROMS **observational error is estimated based on high** resolution outputs from ROMS

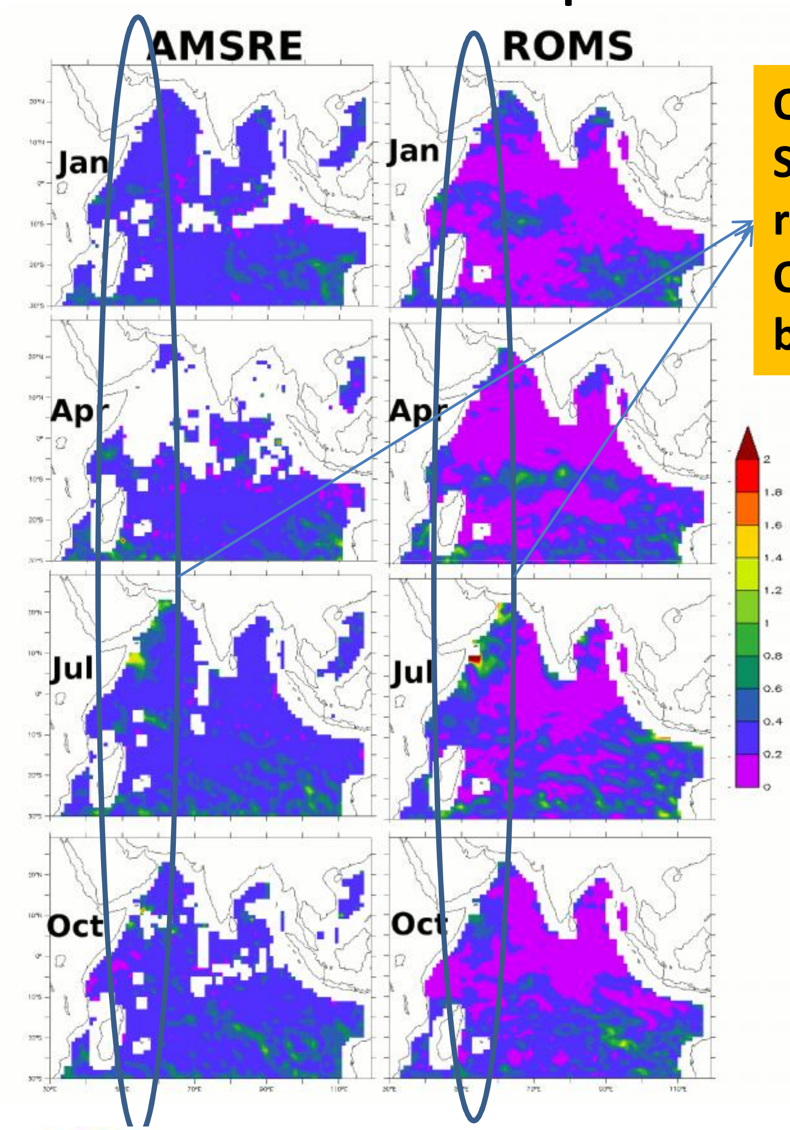
$$OE = \frac{1}{(\Delta i \times \Delta j)} \sum_{ii=i,\, jj=j}^{ii=i+\Delta i,\, jj=j+\Delta j} \left(H\,\overline{X_{ii,jj}} - X_{ii,jj} \right)^2 \qquad \overline{X} = \frac{1}{(\Delta i \times \Delta j)} \sum_{ii=i,\, jj=j}^{ii=i+\Delta i,\, jj=j+\Delta j} X_{ii,jj}$$



Structure and magnitudes of Estimated OEs are comparable to INCOIS-GODAS

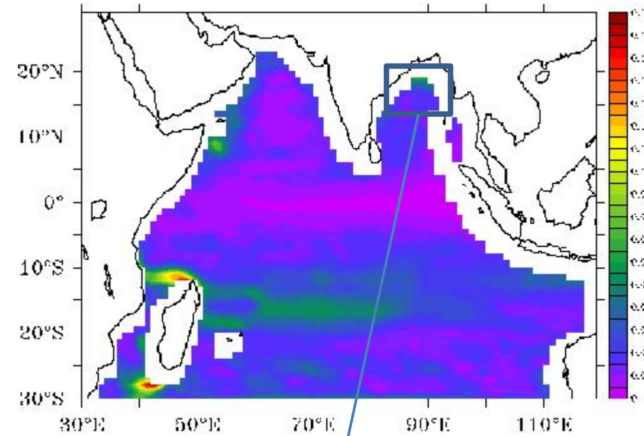
Observational Errors

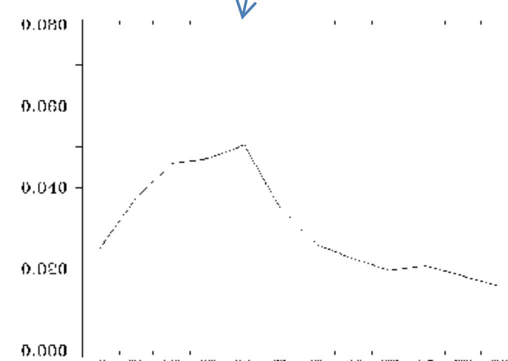
OE for Sea Surface Temperature



Observed Seasonality in OEs is reasonably picked by OE product that is based on ROMS

OE for SSHA based on ROMS





Operational set up of INCOIS-GODAS

Model used : MOM 4 (GFDL)

Domain: Global

Resolution: 50 km zonal and 25 km meridional, 40 vertical levels.

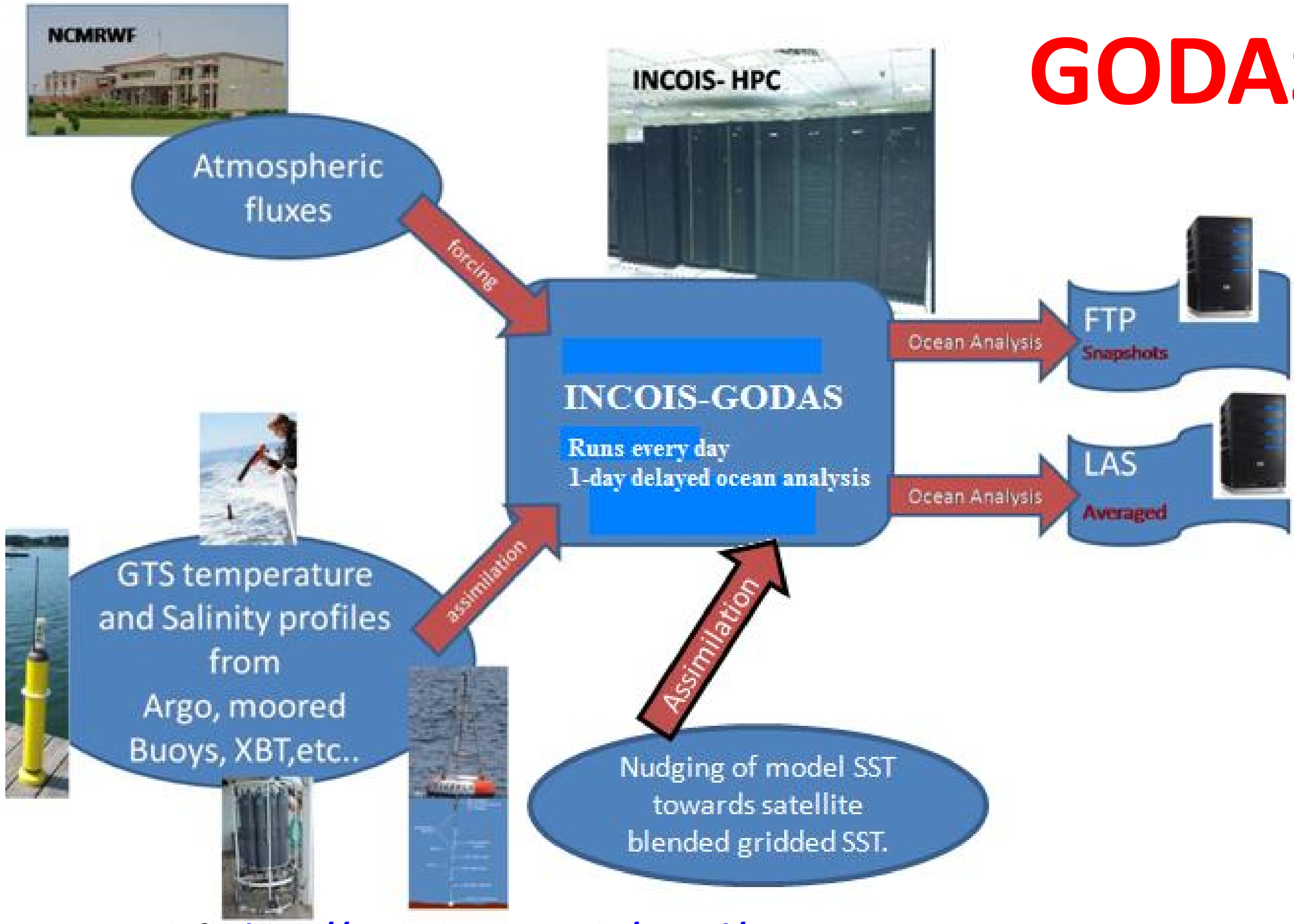
Atmospheric forcing: Fluxes from Global Assimilation Forecast System (GFS)- T574L64 run at NCMRWF.

Data assimilation scheme: 3D VAR

Parameters assimilated: Temperature and salinity profiles from Argo, XBT and RAMA moorings

Relaxation: OISST-V2 [Reynolds, 2007]

Outputs: Temperature, Salinity, SSH, and Currents



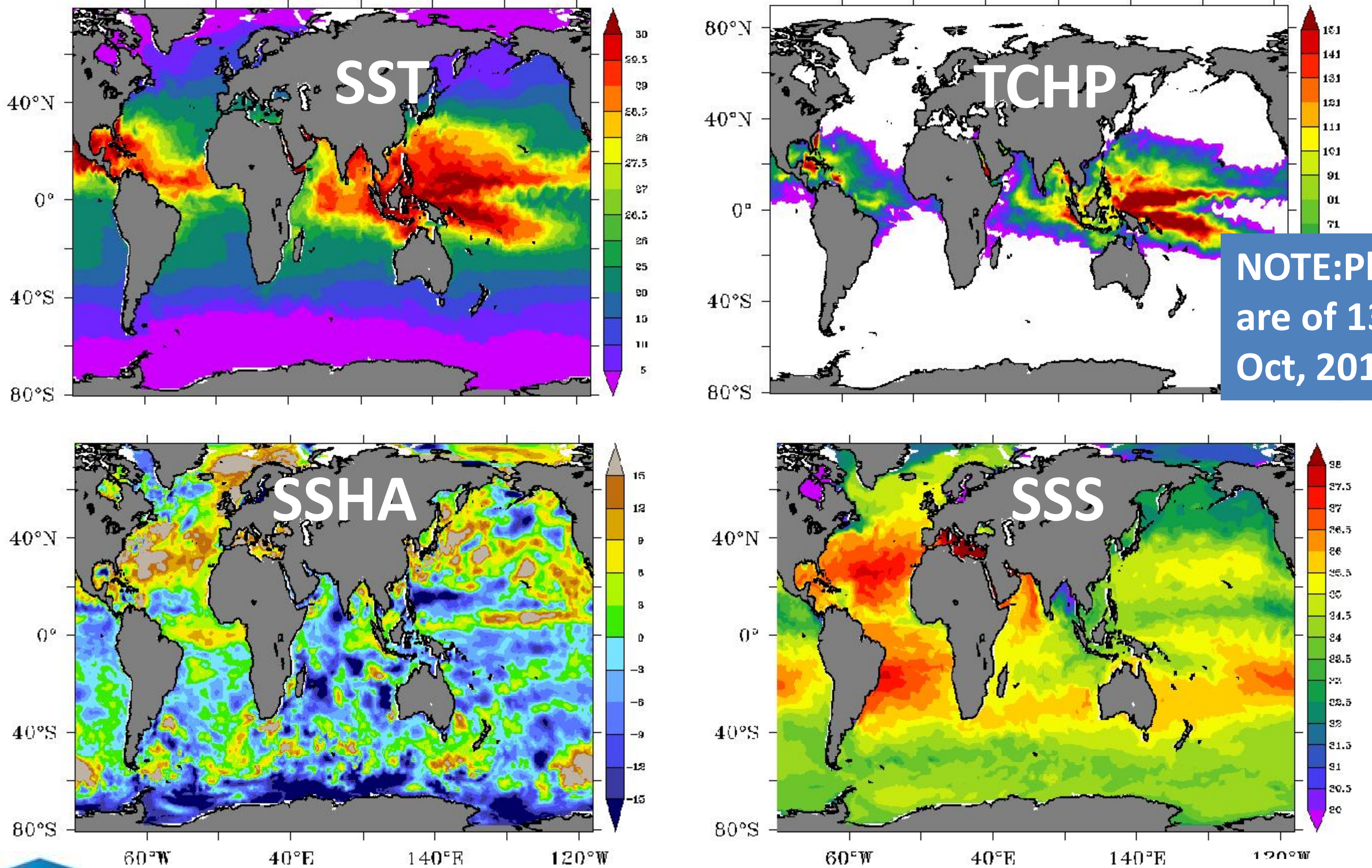
For more info: http://www.incois.gov.in/portal/GODAS

References:

1) Ravichandran et al. , 2013, Ocean Modelling

2) Sivareddy et al., 2015, PhD thesis

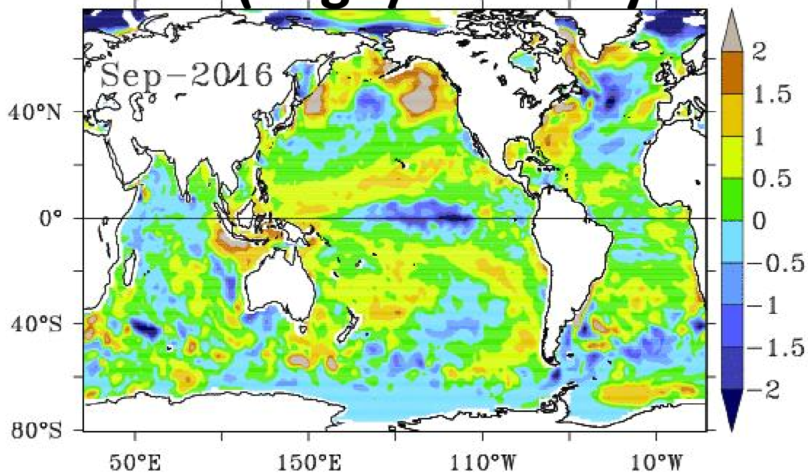
Real time (1-day delay) updates of the Global Ocean from INCOIS-GODAS: 2D fields



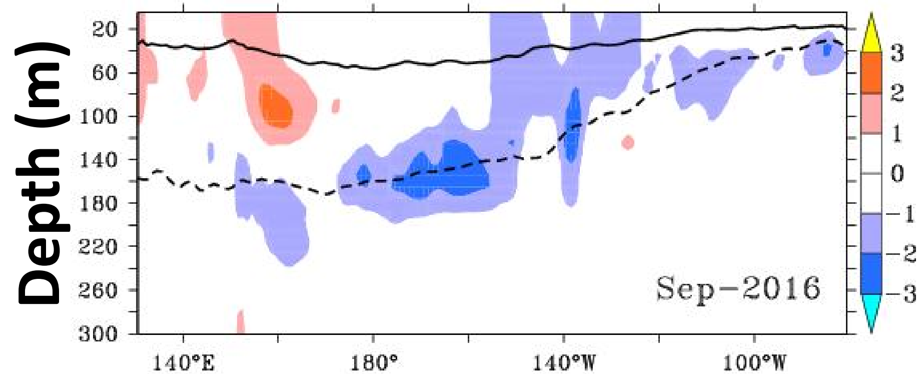
NOTE:Plots are of 13th Oct, 2016

Climate Indices from INCOIS-GODAS

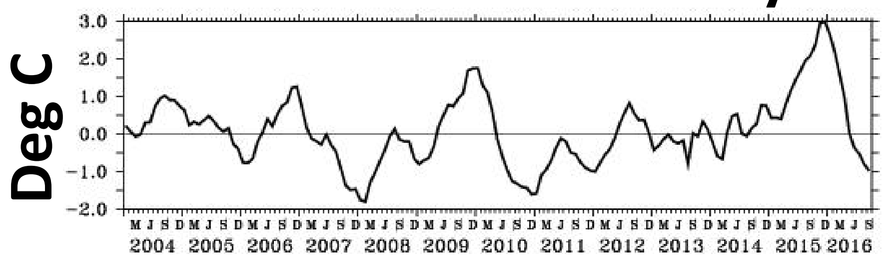
SST (degC) anomaly



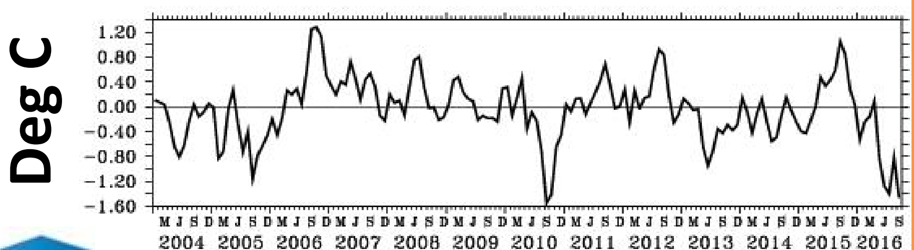
Temperature anomaly (deg C) averaged over 5S-5N latitudes



NiNO 3.4 SST anomaly



IOD index



Monthly updates of climate indices are available by 10th of each month.
Service is started in April, 2014.
The information is being disseminated from the INCOIS web site
www.incois.gov.in/portal/ElNino

Users of INCOIS-GODAS analysis

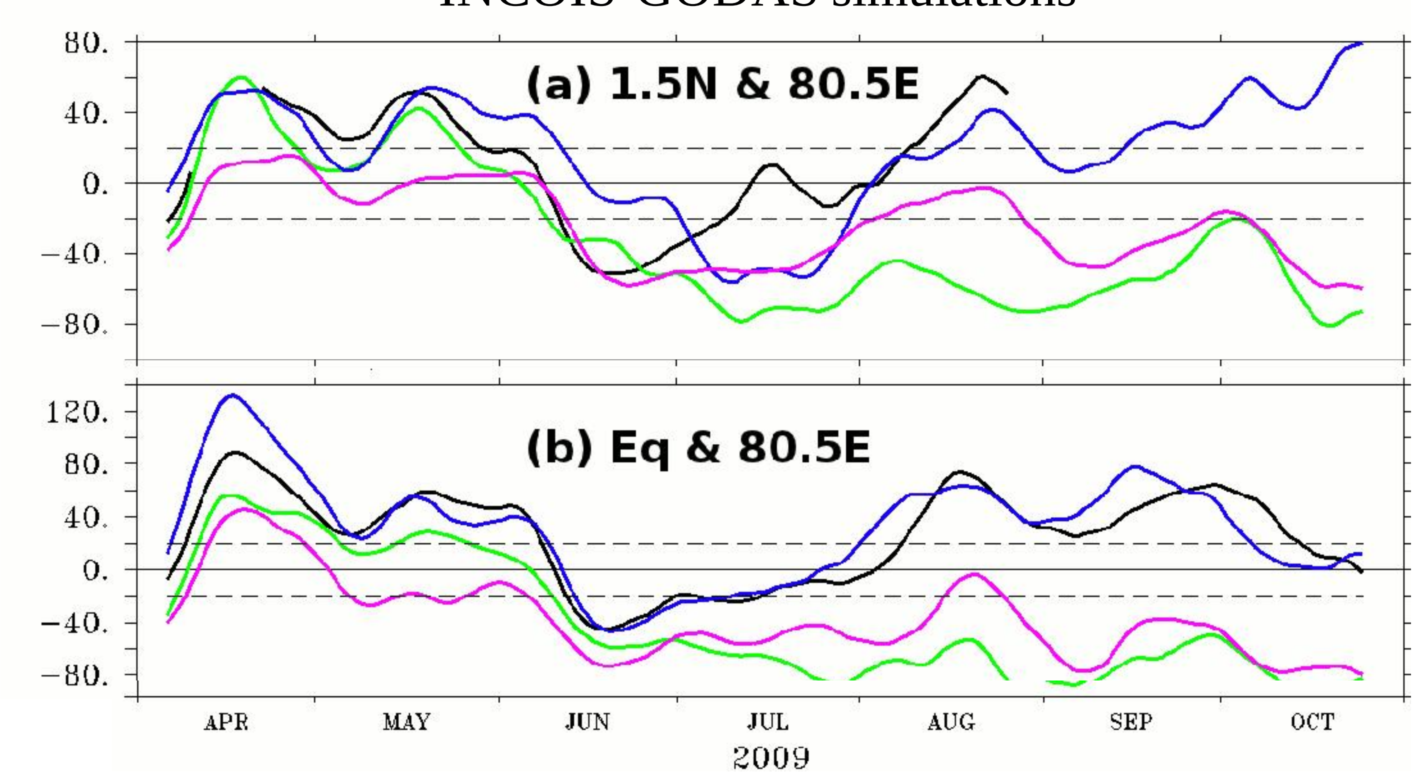
- Analysis are used as initial and boundary counditions to operational ROMS at INCOIS
- Ocean initial conditions are provided to IITM, Pune for CFS-V2
- Global maps of SST and SST anomalies are provided to IMD-Pune
- Climate indices are used in MoES-ENSO bulletins
- Researchers across globe

Ocean Re-analysis from INCOIS-GODAS

- Forcing
  - Improved atmospheric forcing from NCMRWF GFS-T574L64 that is available at 4 times daily temporal and 0.25 x 0.25 spatial resolutions
  - Improved wind forcing from scatterometers
  - Inter-annual monthly river discharge to improve seasonal cycles in the Head BoB.
- Assimilation
  - Assimilates delayed mode temperature and salinity profiles only from Argo and ship-based networks to avoid spurious assimilation shocks from moored buoys.
  - Relaxes model SST towards Reynolds SST
- Outputs
  - 3D fields of T, S, zonal and meridional currents, vertical velocity
  - 2D fields of SSHA and MLD
  - Available at 4 times daily resolution

Wind forcing from pure scatterometer winds improves ocean model simulations

Zonal surface currents (cm/s) from RAMA observation and INCOIS-GODAS simulations



RAMA observation

QSCAT forcing (pure scatterometer)

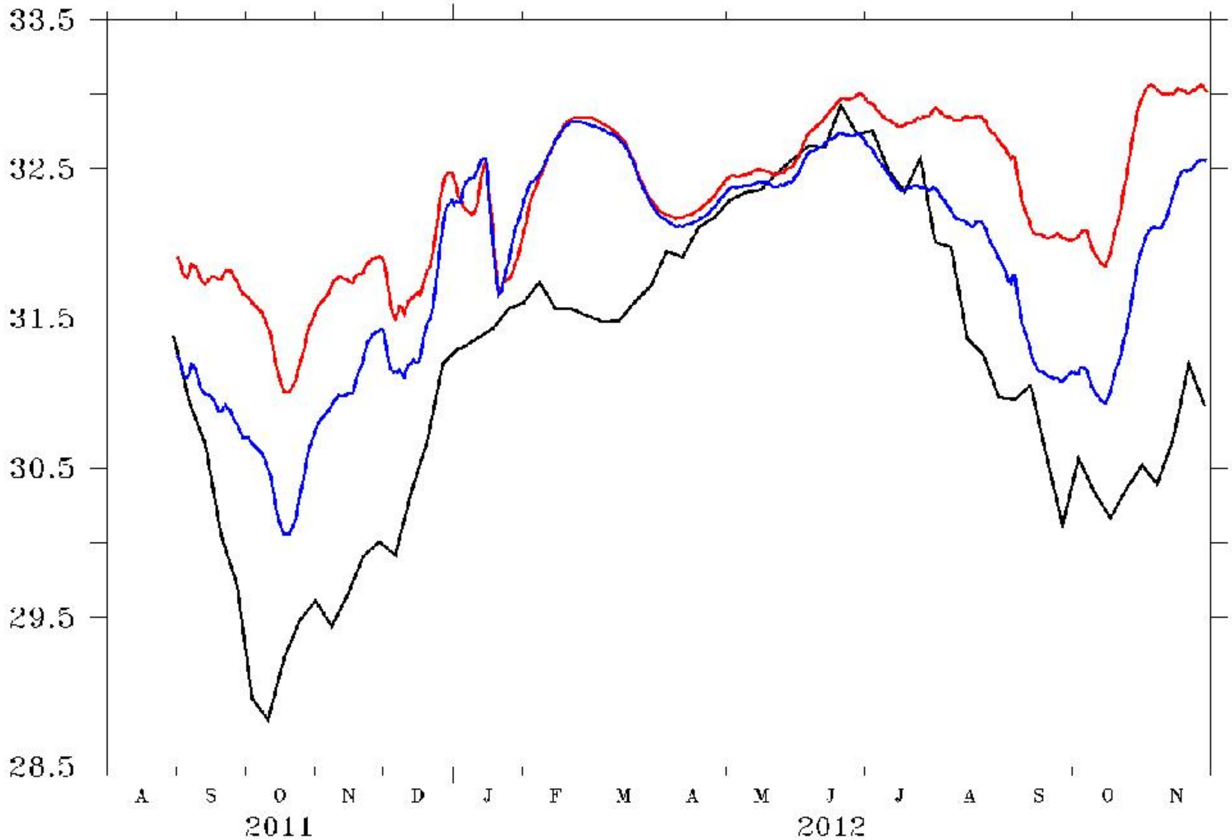
NCEP-R2 forcing (pure model)

DASCAT forcing (scatterometer + model blended)

Sivareddy et al., 2015. Assessing the impact of various wind forcing on INCOIS-GODAS simulated ocean currents in the equatorial Indian Ocean. *Ocean Dynamics*, 65 (9-10), pp. 1235-1247.

River runoff estimated from altimeter measurements improves salinity simulations in INCOIS-GODAS

Sea surface salinity averaged over north BoB



Aquarius observation

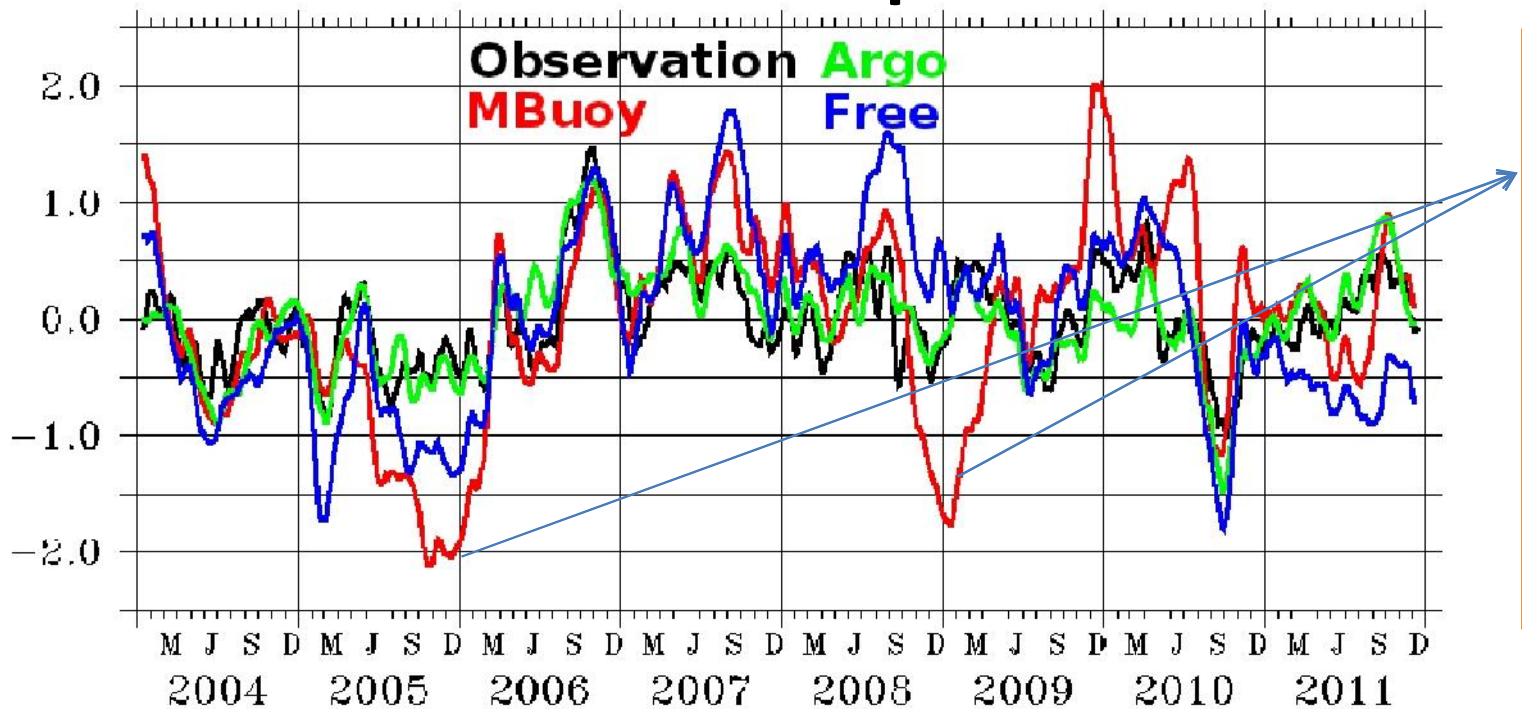
Simulation based on climatological river runoff

Simulation based on Altimeter derived inter-annual monthly river runoff

Sivareddy, S., 2015. A study on global ocean analysis from an ocean data assimilation system and its sensitivity to observations and forcing fields, Ph.D. thesis, Andhra University.

Tropical Mbuoy observations causes spurious assimilation shocks: Demonstration

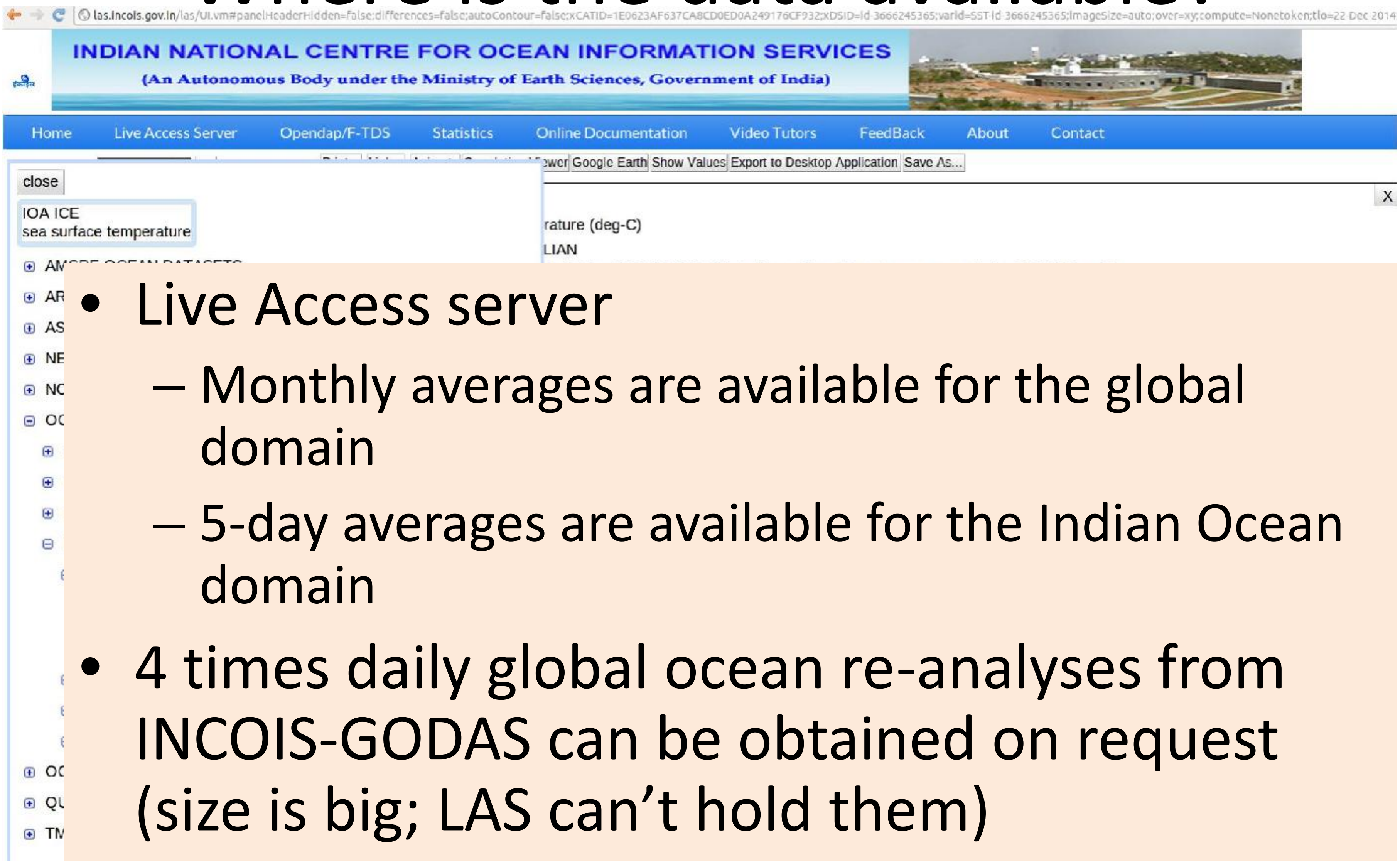
Indian Ocean Dipole index



Mbuoy exp Wrongly interpreted neutral IOD as strong –ve IOD years. Importantly, the simulation is worse than Free exp.

S. Sivareddy, Arya Paul, Travis Sluka, M Ravichandran and Eugenia Kalnay (2017), The pre-argo ocean reanalysis may be seriously affected by the spatial coverage of moored-buoys, under revision in Nature Scientific Reports.

Where is the data available?



- Live Access server
  - Monthly averages are available for the global domain
  - 5-day averages are available for the Indian Ocean domain
- 4 times daily global ocean re-analyses from INCOIS-GODAS can be obtained on request (size is big; LAS can't hold them)

Thank You

Theme: Model validation

Estimated parameters

- Mixed layer Depth
  - Definition: Mixed-layer is the layer between the ocean surface and a depth usually ranging *between 25 and 200m*, where the density is about the same as at the surface. The mixed-layer owes its existence to the mixing initiated by waves and turbulence caused by the wind stress on the sea surface.
  - MLD is estimated based on the method suggested by Sprintall and Tomczak, 1992 by setting delta T to 0.8.
- Depth of 20 degree isotherm
  - The depth of 20C isotherm from the surface is broadly used as the thermocline depth for tropical ocean studies (Meyers 1979; Kessler 1990; Vialard and Delecluse 1998; Durand and Delcroix 2000; Meinen and McPhaden 2000; Fedorov and Philander 2001; Chepurin et al. 2005; Sourav and Arun, 2012) because the 20C isotherm is located near the center of the main thermocline.
  - The mechanism of variation 20◦C isotherm depth (D20) is important to study as it indicates the oceanic upwelling and downwelling processes and indicates the thermocline variability of the ocean (Haijun and Wang 2008). Braganza (2008) and Rao and Behera (2005) explain that there are cases where changes in the thermocline depth may act as a precursor to subsequent changes at the surface during strong upwelling, and this will cause potential cooling of the surface temperature. During the case when upwelling is not strong enough to influence the surface, it acts upon the bottom of the mixed layer.

Statistical parameters

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$$

$$Bias = \overline{X} - \overline{Y}$$

$$\pm_X = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (X_i - \overline{X})^2}$$

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (X_i - Y_i)^2}$$

$$Correl = \frac{\sum_{i=1}^{n} \left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\left(n - 1\right)\pm_X \pm_Y}$$

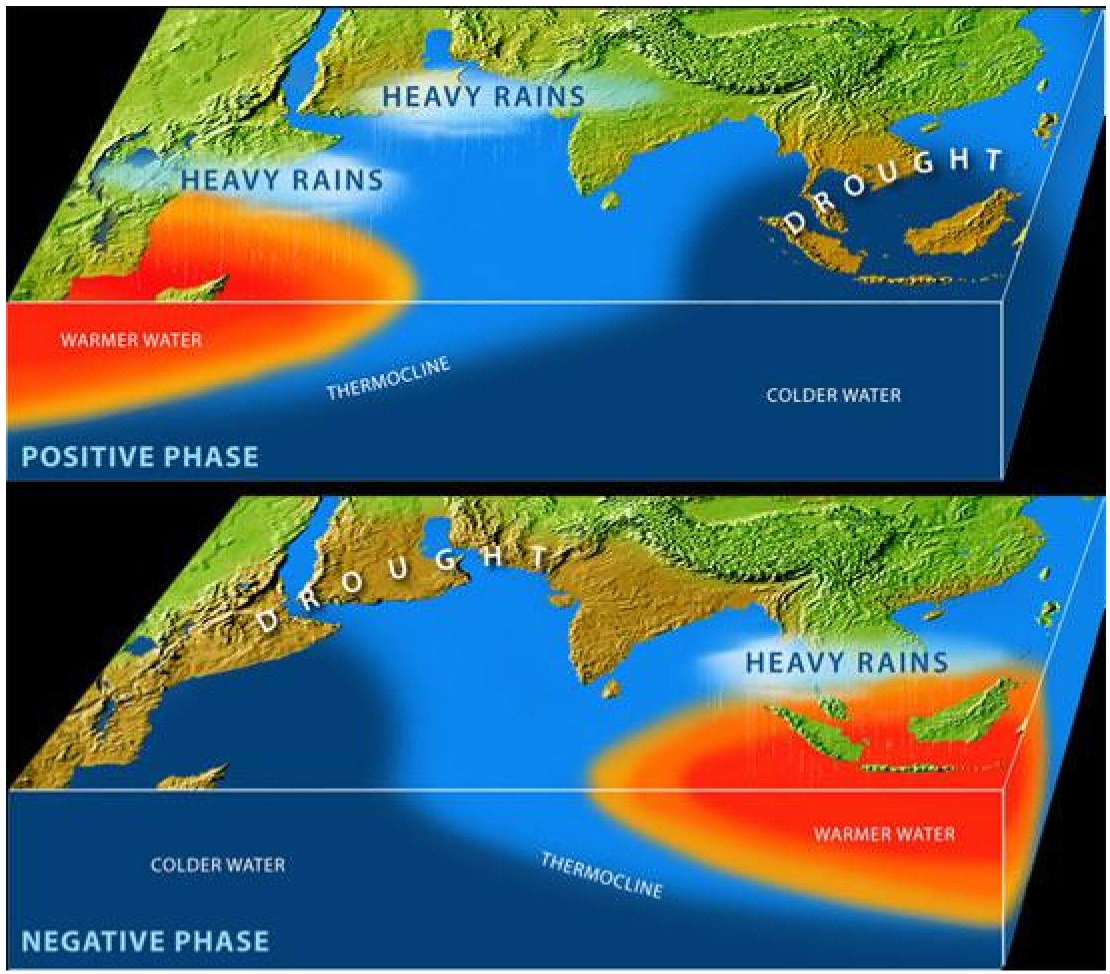
Data Sets

- Time series measurements from RAMA buoy network
  - Temperature
    - Daily averages
    - Available at depths 1.5, 5, 15, 25, 50, 75, 100, 125,150, 200, 250, 300, 500, 750 m
  - Currents
    - Daily averages
    - Available at 10m depth
  - Source: www.pmel.noaa.gov/tao
  - Reference: McPhaden et al. (2009b)
- REYNOLDS SST:
  - Satellite and in-situ blended level-4 gridded SST product
  - Daily averages at 0.25 X 0.25
  - Source: ftp.emc.ncep.noaa.gov
  - Reference: Reynolds et al. (2007)
- OSCAR:
  - Ocean Surface currents (0-30m average) derived from satellite measurements of winds, SSHA and SST
  - 5-day averages at 1/3 X 1/3
  - Source: www.oscar.noaa.gov
  - Reference: Bonjean and Lagerloef (2002)

Theme: Climate Indices

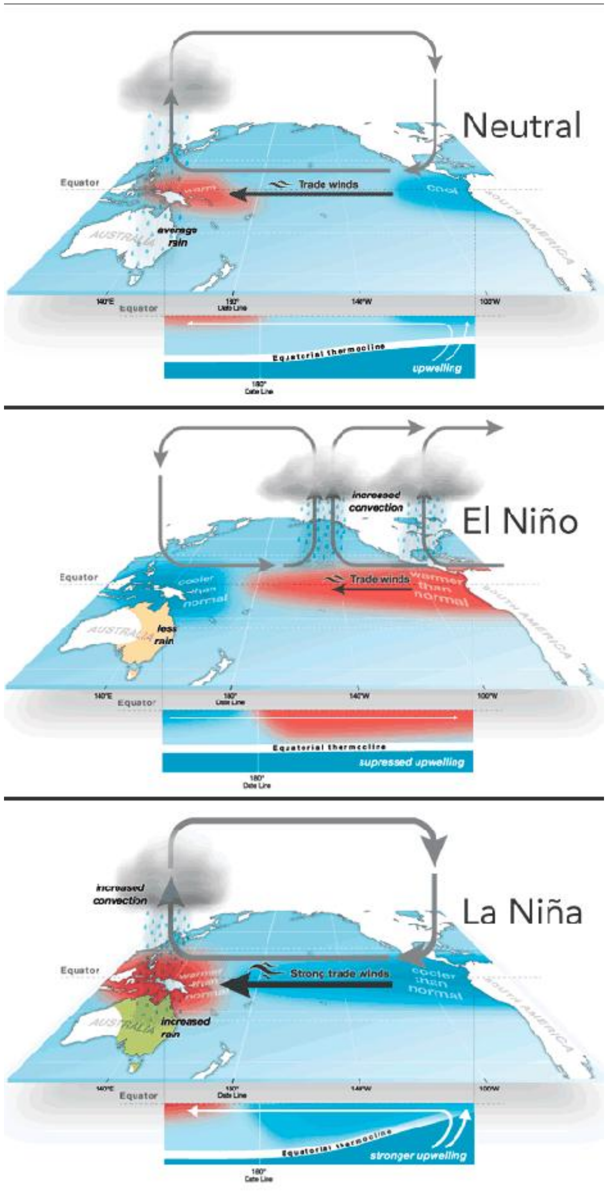
Indian Ocean Dipole

The Indian Ocean Dipole (IOD) is defined by the difference in sea surface temperature between two areas (or poles, hence a dipole) – a western pole in the Arabian Sea (western Indian Ocean) and an eastern pole in the eastern Indian Ocean south of Indonesia. The IOD affects the climate of India and other countries that surround the Indian Ocean Basin, and is a significant contributor to rainfall variability in this region.

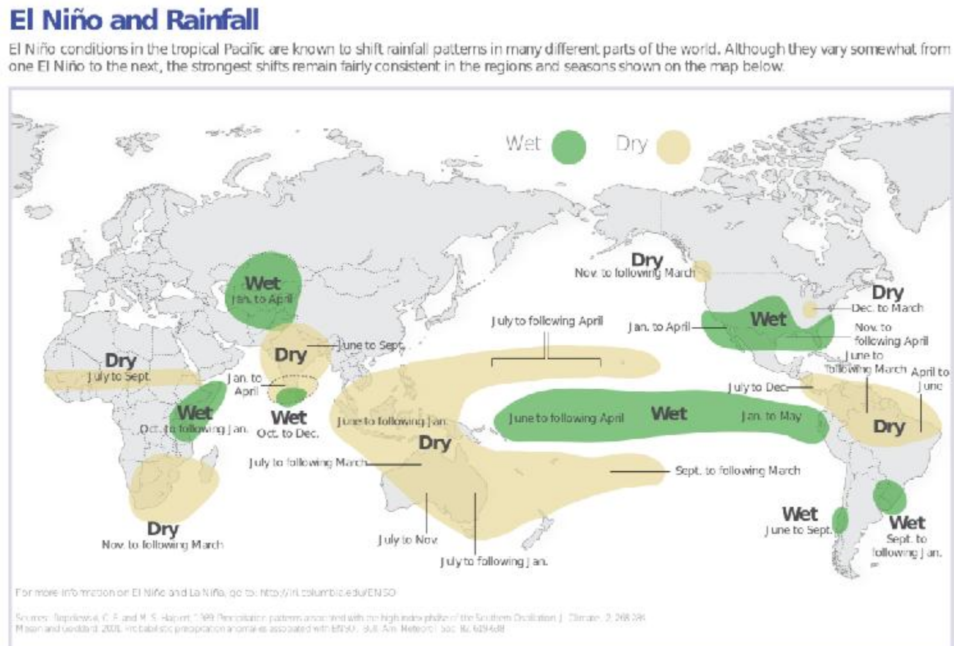


Source: www.meted.ucar.edu

ElNino

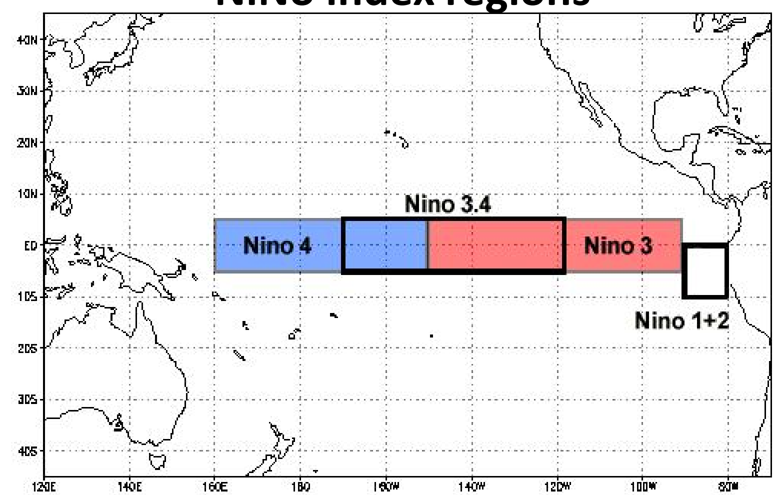


Images from the [Australian Bureau of Meteorology](https://www.bom.gov.au).



Source: www.climate.gov

NiNo index regions



Source: www.ncdc.noaa.gov