Remote Sensing of the Earth System: Challenges & Way Ahead

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IEEE-GRSS Kolkata Chapter and Centre for Soft Computing Research

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Approach

- Introduction to Big Data
- Big Data in the Earth System
- Remote Sensing Applications
- Current Challenges in Remote Sensing
- The way forward

Big Data & Data Analytics

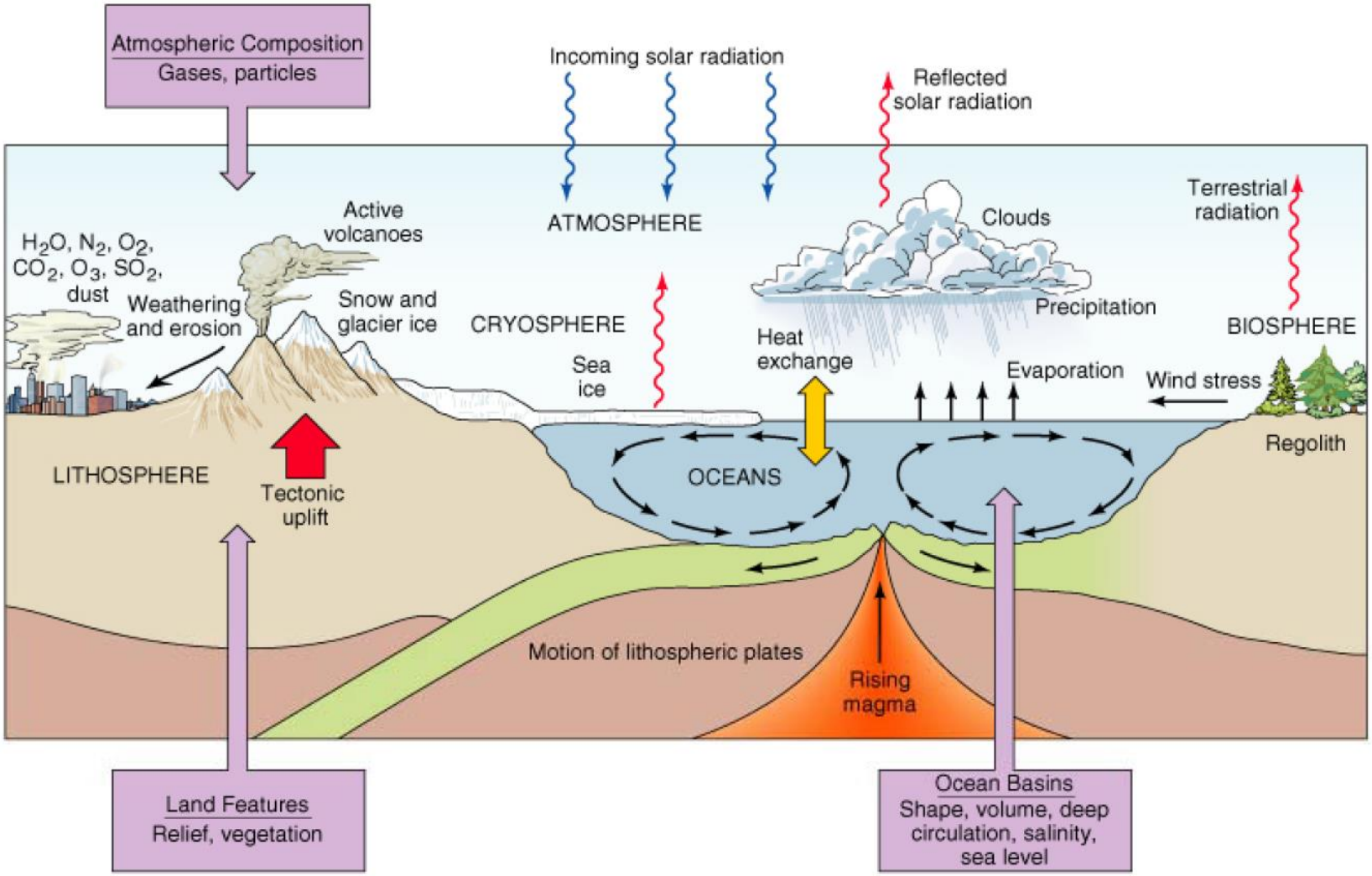
Big Data is a high-volume and high-velocity and/or high-variety information assets that demand cost-effective, innovative forms of information processing to enable enhanced insight, decision-making, and process automation.

Data Analytics is the science of examining raw data with the purpose of finding patterns and drawing conclusions about that information by applying an algorithmic or mechanical process to derive insights.

Refs:

- Baumann et al. (2015), Big Data Analytics for Earth Sciences: the EarthServer approach, *International Journal of Digital Earth*, 9(1), 3-29, http://dx.doi.org/10.1080/17538947.2014.1003106.
- https://www.gartner.com/technology/home.jsp

The Earth's climate system is quite complex



System is highly non-linear due to multiple interactions

The Earth System: Essential Climate Variables (ECVs)

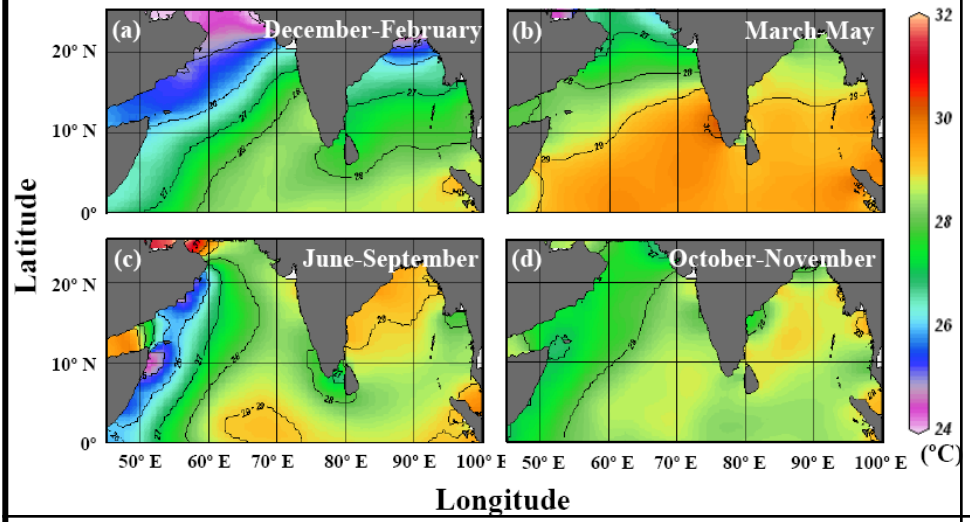
Domain	Essential Climate Variables (50)
Atmospheric (over land, sea and ice)	**Surface:** [1] Air temperature, Wind speed and direction, Water vapour, Pressure, Precipitation, Surface radiation budget. **Upper-air:** [2] Temperature, Wind speed and direction, Water vapour, Cloud properties, Earth radiation budget (including solar irradiance). **Composition:** Carbon dioxide, Methane, and other long-lived greenhouse gases [3], Ozone and Aerosol, supported by their precursors [4].
Oceanic	**Surface:** [5] Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Surface current, Ocean colour, Carbon dioxide partial pressure, Ocean acidity, Phytoplankton. **Sub-surface:** Temperature, Salinity, Current, Nutrients, Carbon dioxide partial pressure, Ocean acidity, Oxygen, Tracers.
Terrestrial	River discharge, Water use, Groundwater, Lakes, Snow cover, Glaciers and ice caps, Ice sheets, Permafrost, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (FAPAR), Leaf area index (LAI), Above-ground biomass, Soil carbon, Fire disturbance, Soil moisture.

[1] Including measurements at standardized, but globally varying heights in close proximity to the surface.
[2] Up to the stratopause.
[3] Including nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), and perfluorocarbons (PFCs).
[4] In particular nitrogen dioxide (NO_2), sulphur dioxide (SO_2), formaldehyde (HCHO) and carbon monoxide (CO).
[5] Including measurements within the surface mixed layer, usually within the upper 15m.

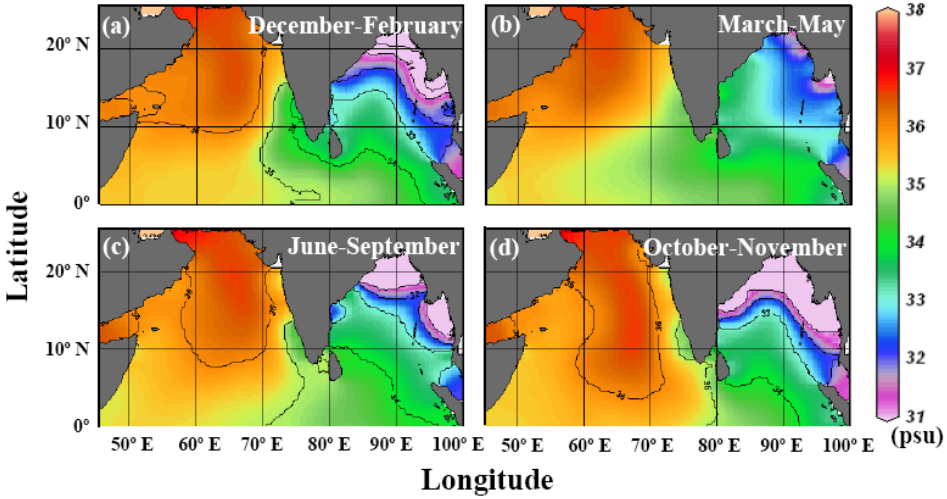
Source: UNFCC & IPCC

Complexities in the North Indian Ocean

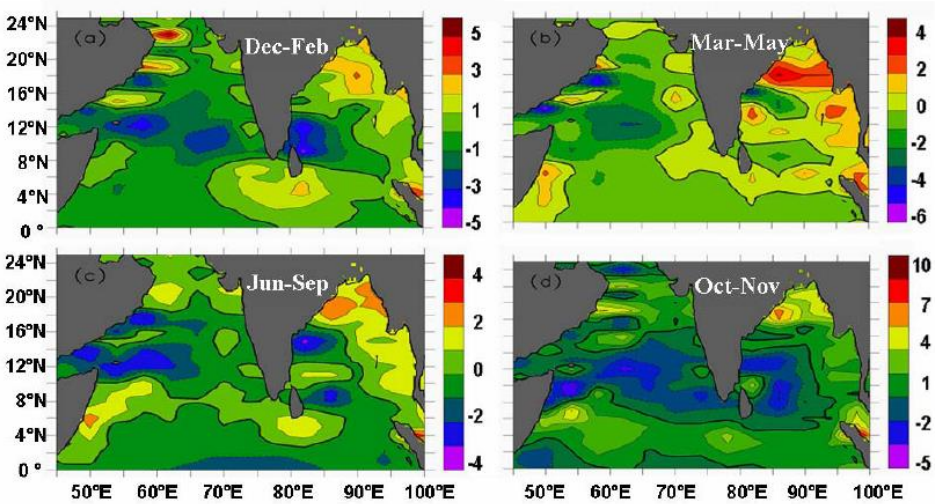
Seasonal SST Climatology



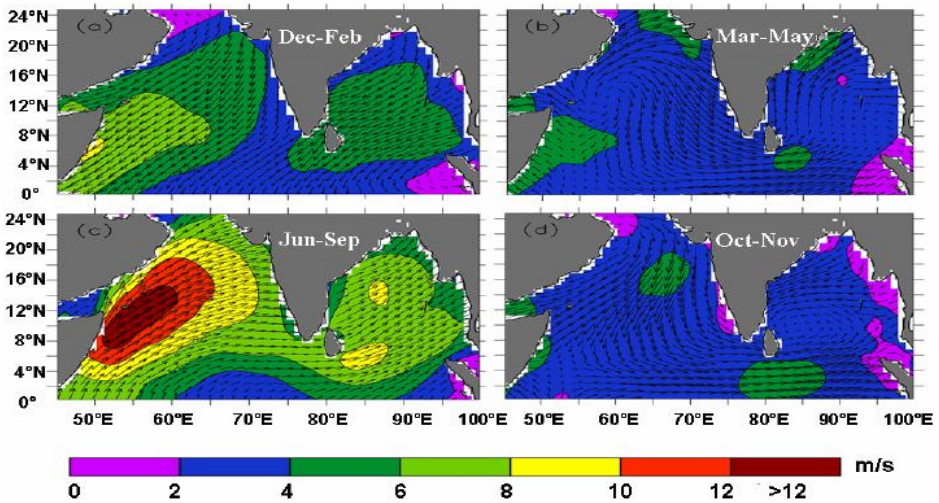
Seasonal SSS Climatology



Seasonal Sea Surface Height Anomaly

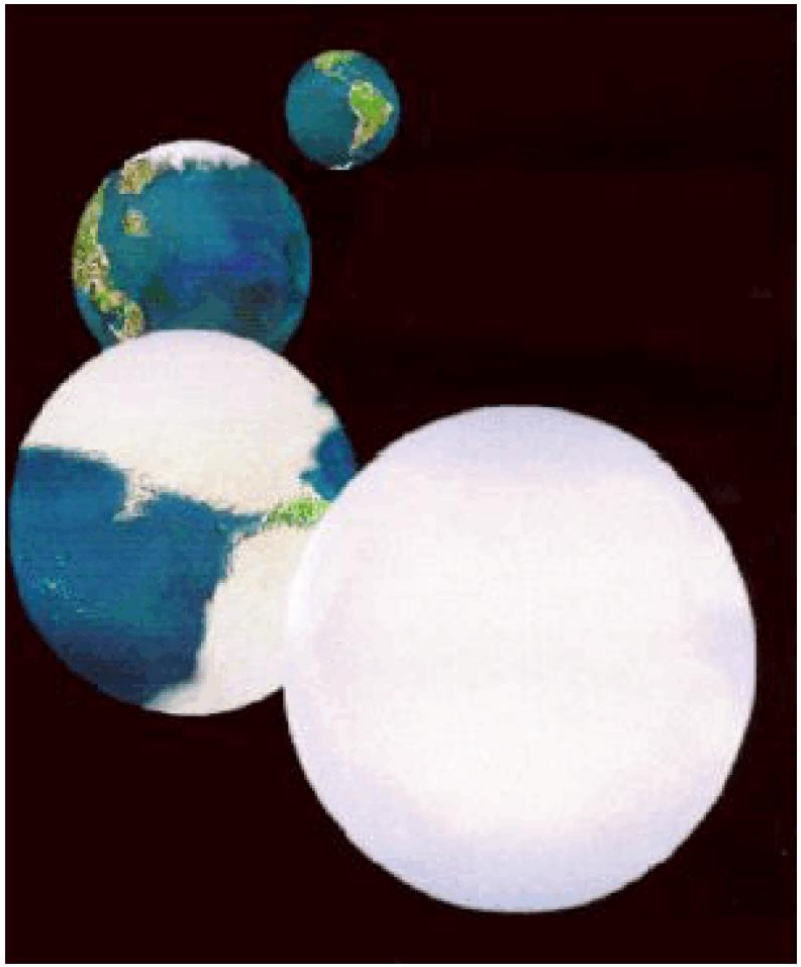


Wind Speed Climatology

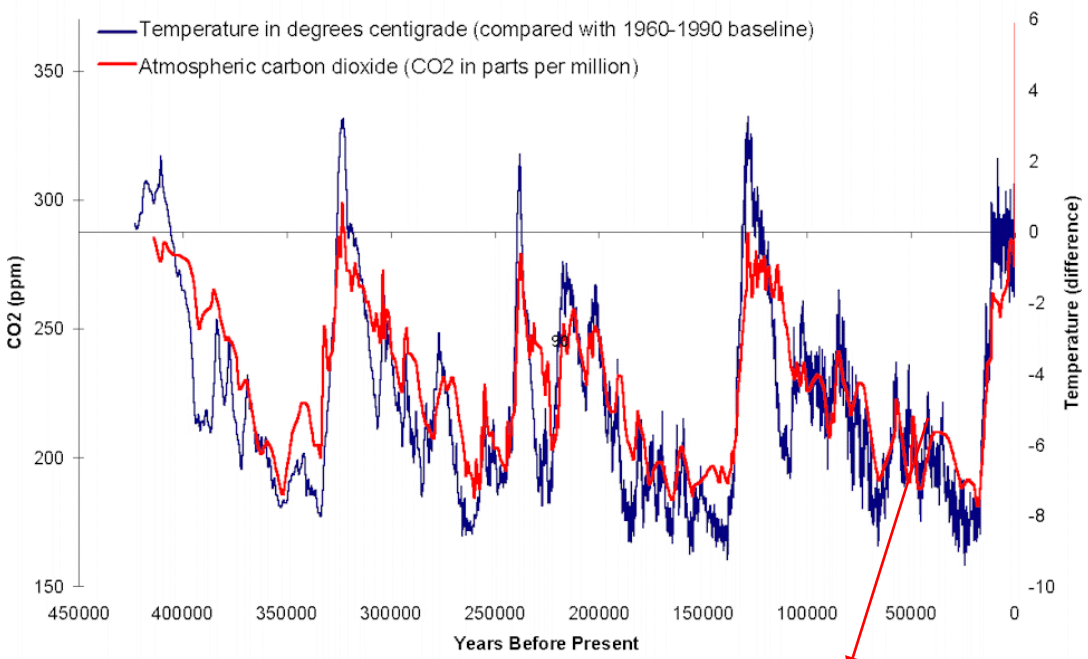


Source: Swain, 2009

Transitioning between Ice-free & Ice-covered Earth



Climate is Always Changing!



Changes are of the order of 50,000 years!

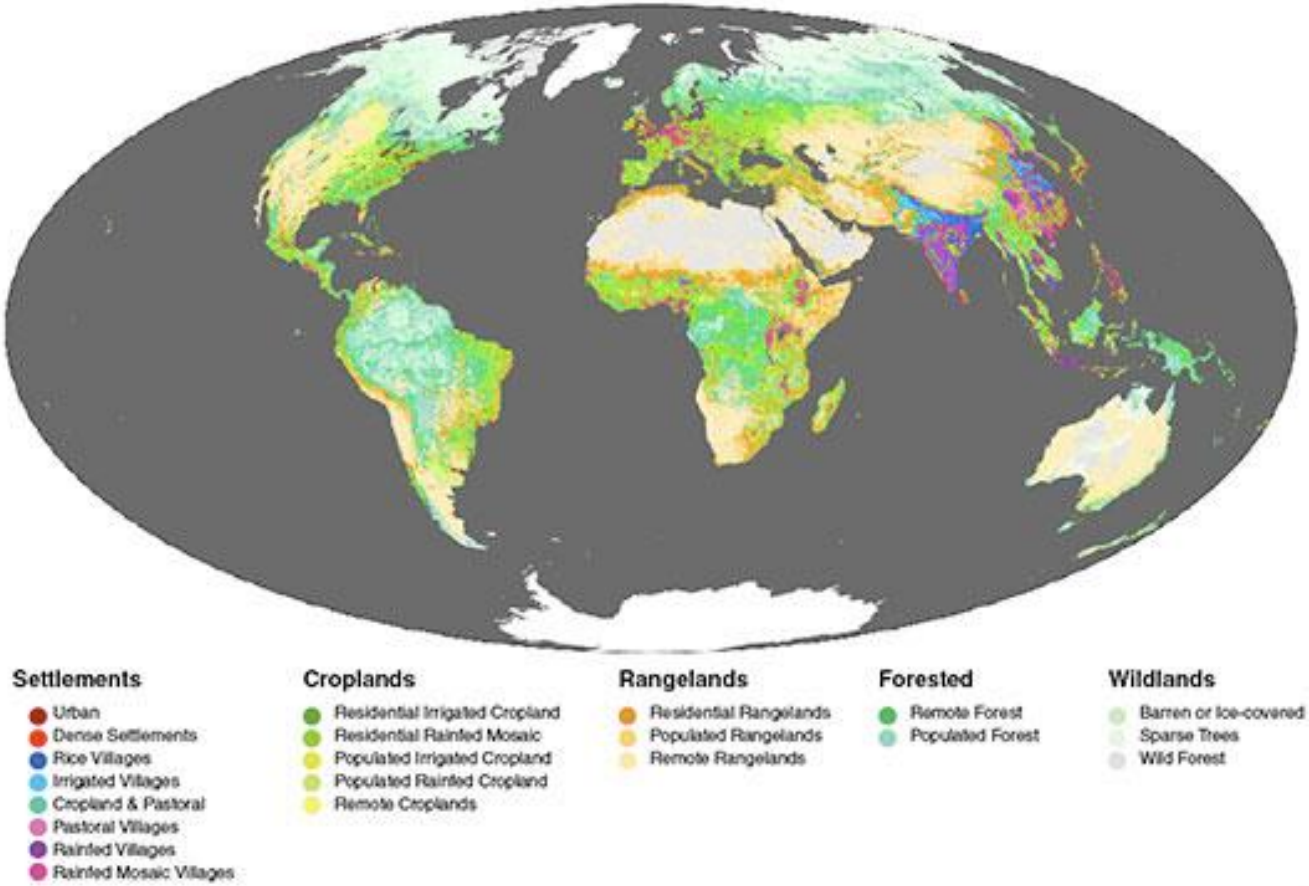
A few degrees doesn't seem much!!!

Temperature Change ~ +/- 6 degrees

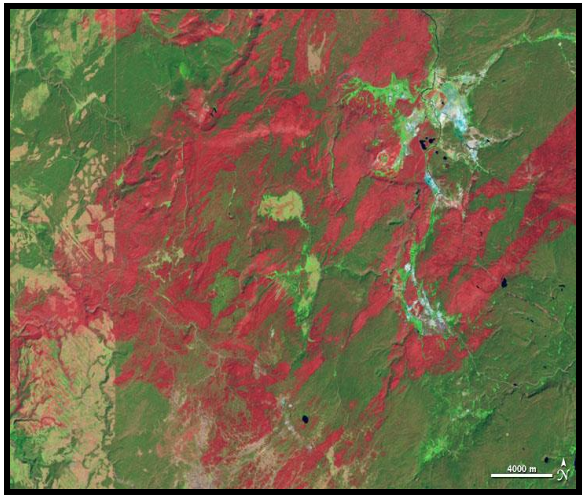
The difference between an ice age and ice-free age is only this!

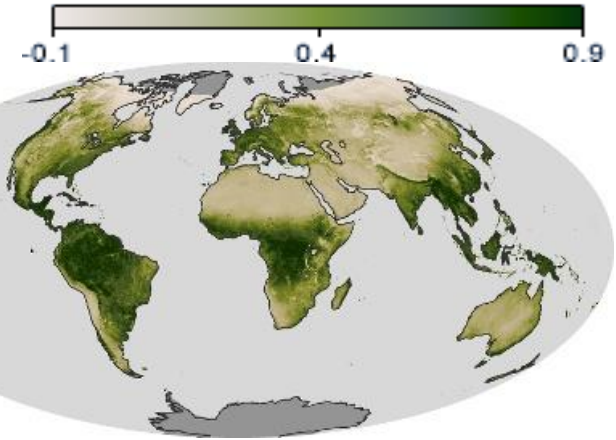
Calls for continuous high spatio-temporal resolution multi-parameter observations (Big Data !!)

(i) Monitoring Surface Changes: Vegetation



Land Cover





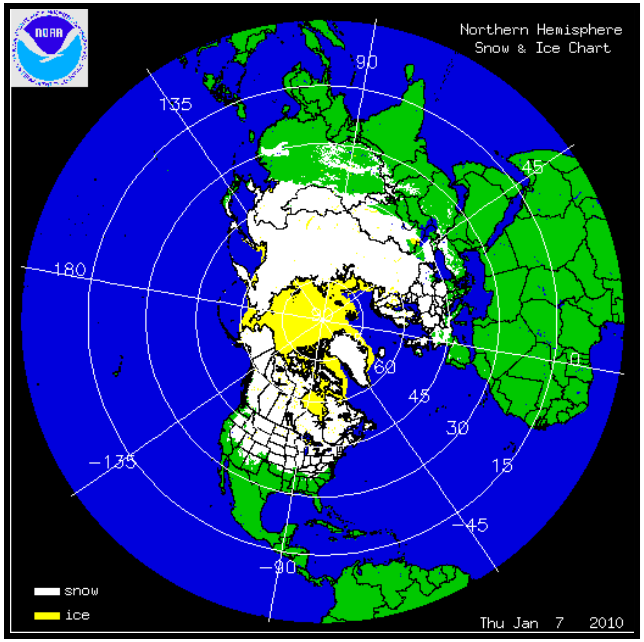
Vegetation NDVI (2007)

Data: MODIS

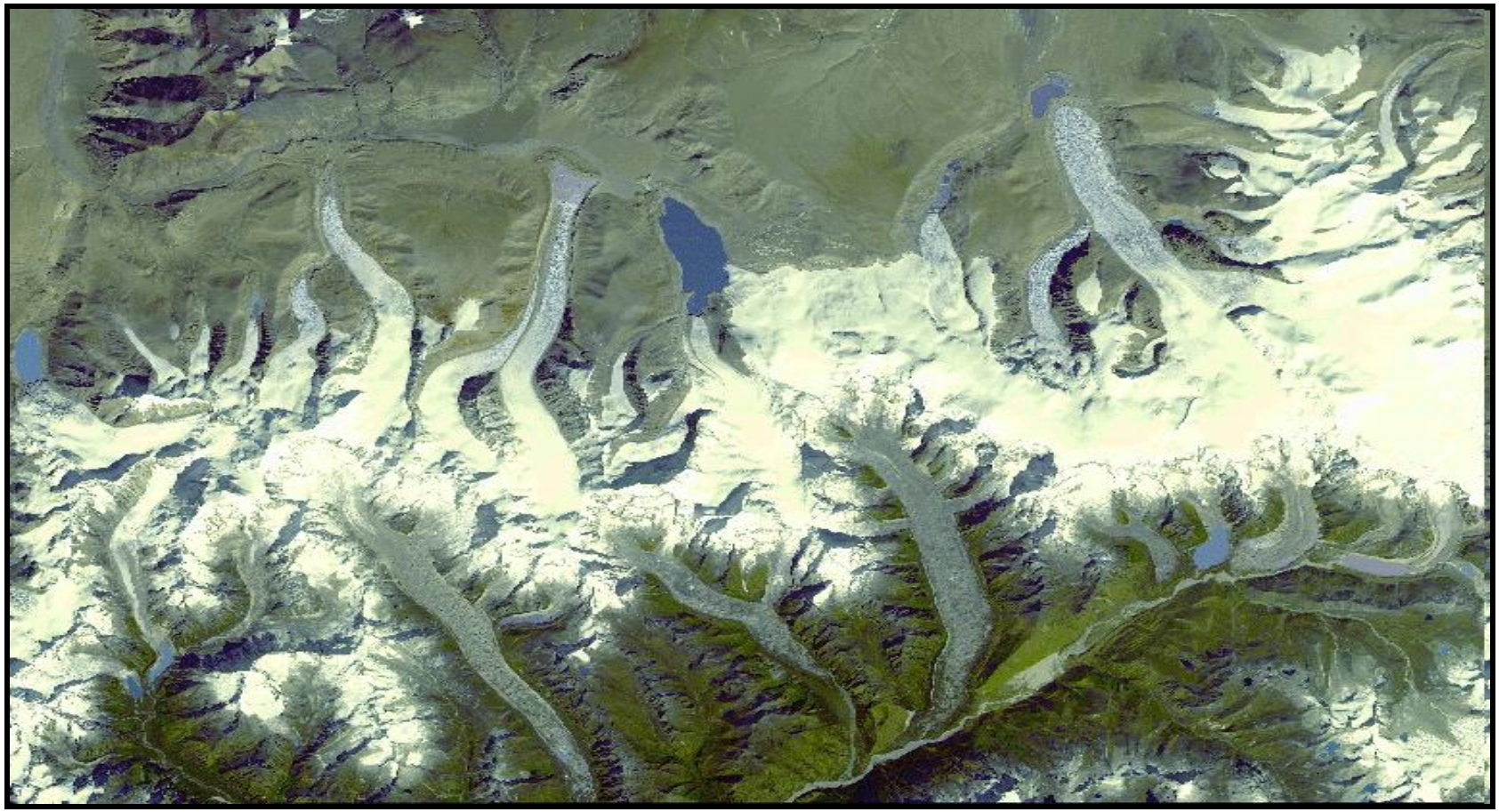
(ii) Monitoring Surface Changes: Snow Cover

The 28 year trend in snow extent derived from visible and passive microwave satellite data indicates an annual decrease of approx.

1 to 3 % per decade with greater deceases of approx. 3 to 5 % during spring and summer.



(iii) Monitoring Surface Changes: Glacial Retreat



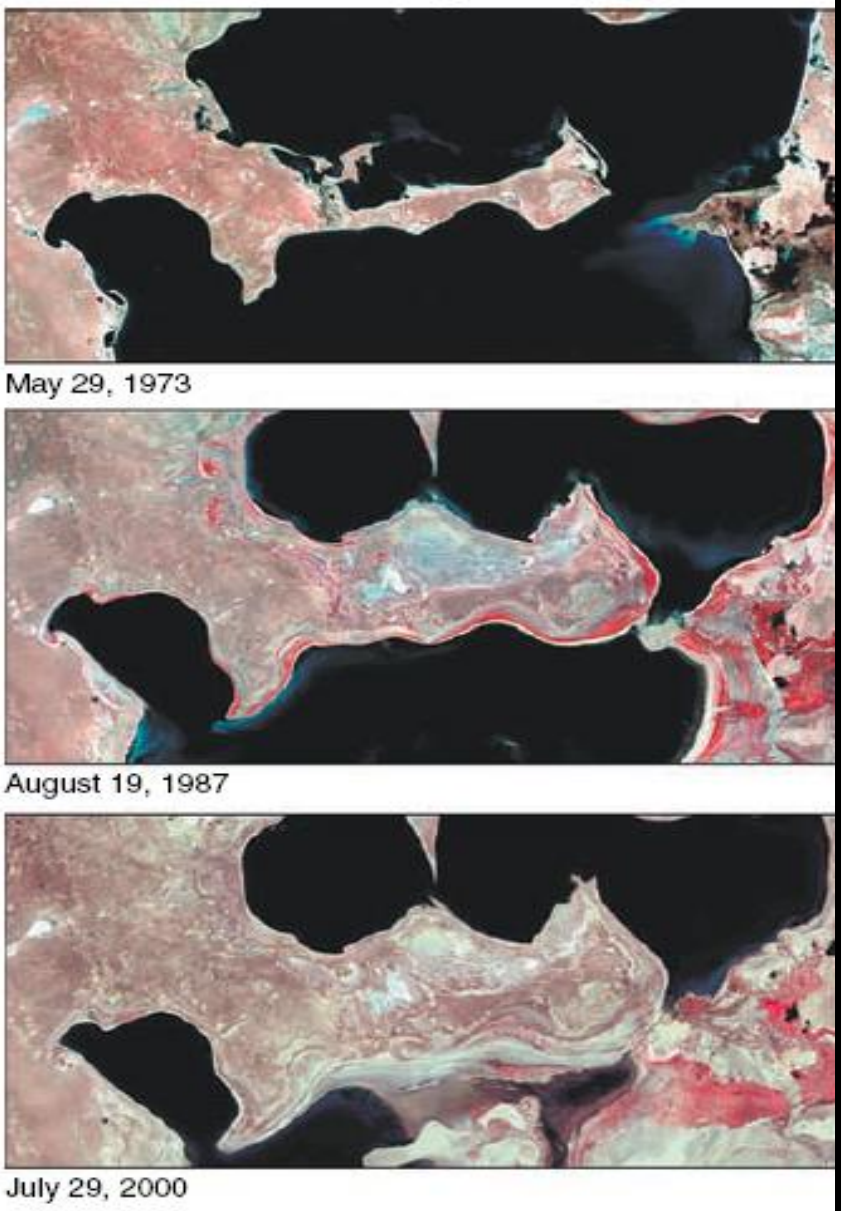
ASTER image of the Himalaya mountains documents glacier stagnation & lake formation (2001)

(Advanced Space borne Thermal Emission & and reflection Radiometer - instrument flown on NASA's Terra satellite)

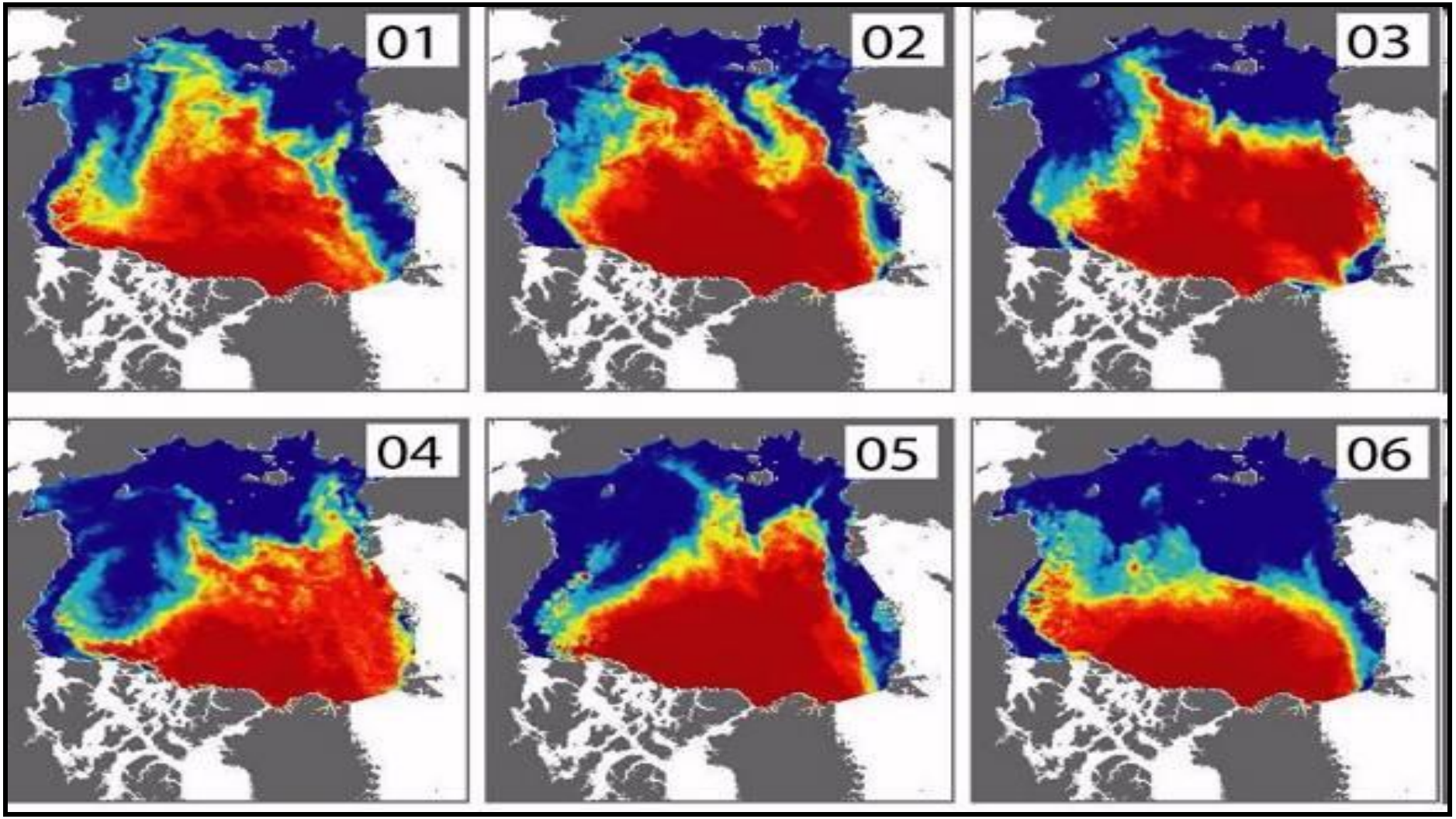
(iv) Monitoring Surface Changes: Desertification

The disappearance of the Aral Sea, as seen by Landsat satellite during the period 1973 to 2000.

Over this period, more than 60% of the lake vanished, replaced with a dry, dusty plain.

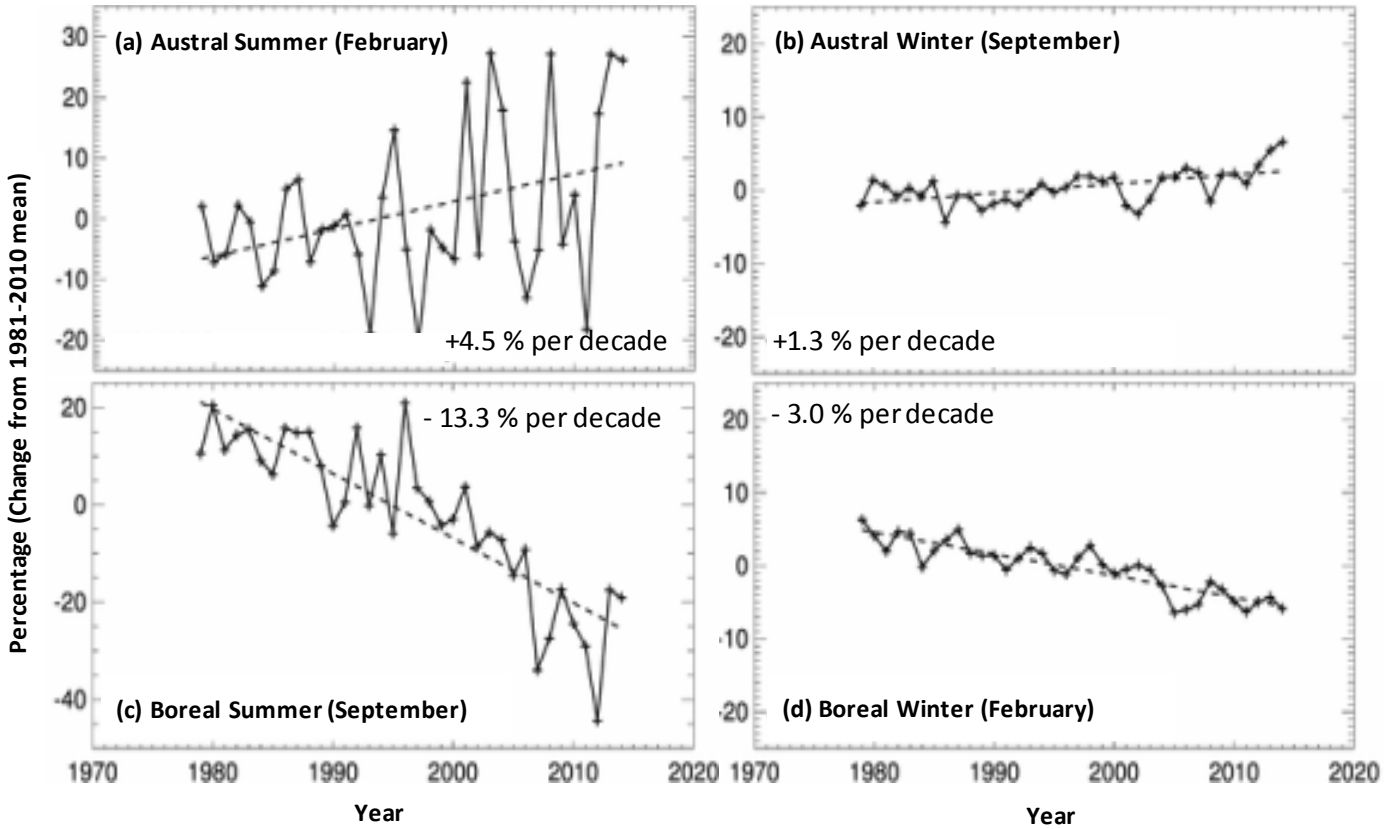


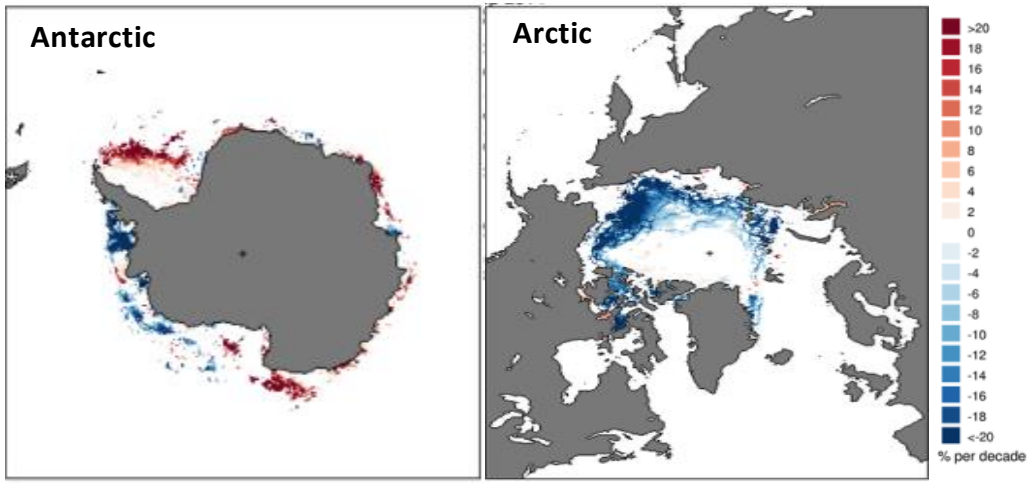
(v) Monitoring Surface Changes: Arctic Sea Ice



Satellite studies indicate Arctic sea ice cover is declining annually

Sea Ice Cover: NH and SH

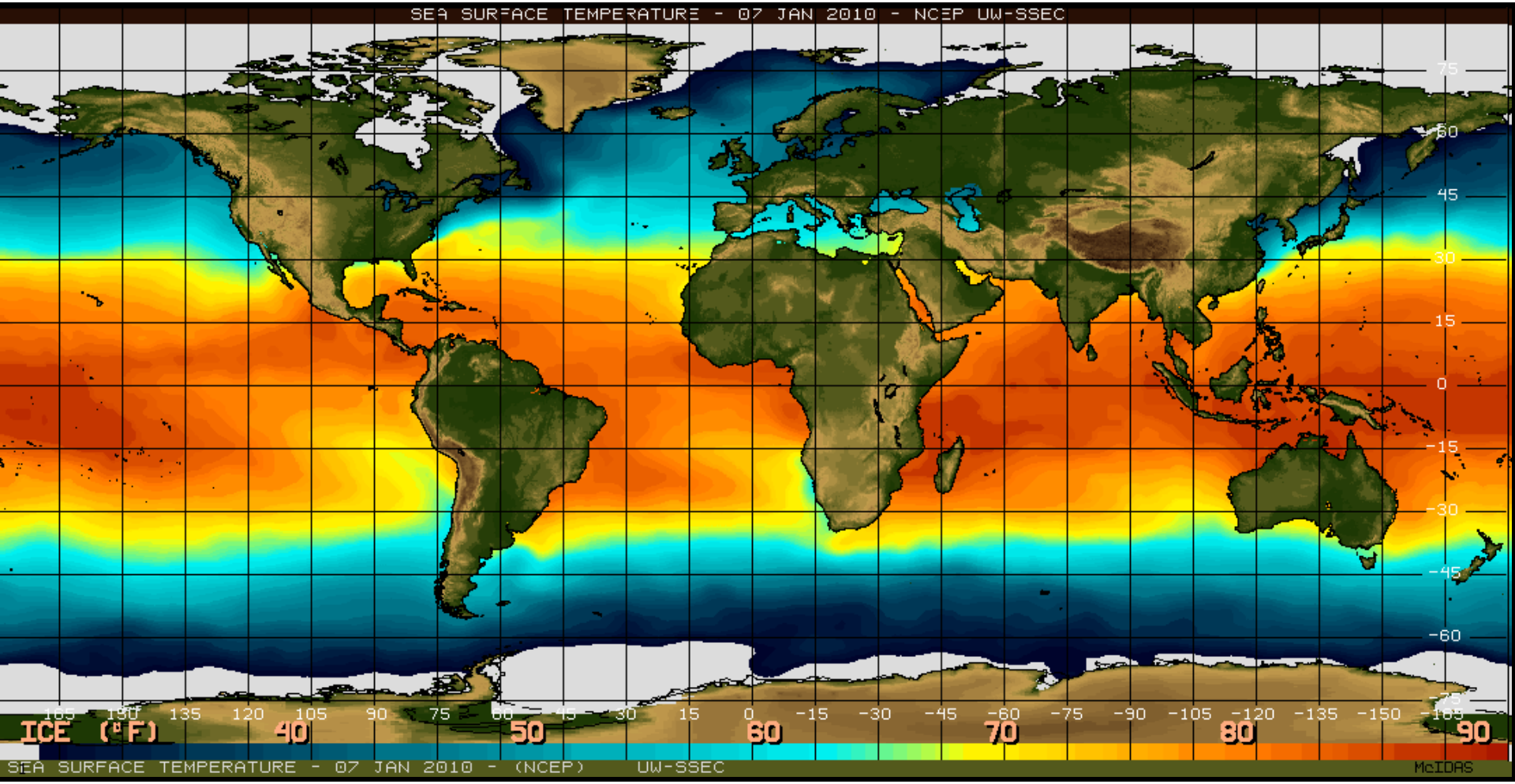




Over 30 years period for sea ice cover:

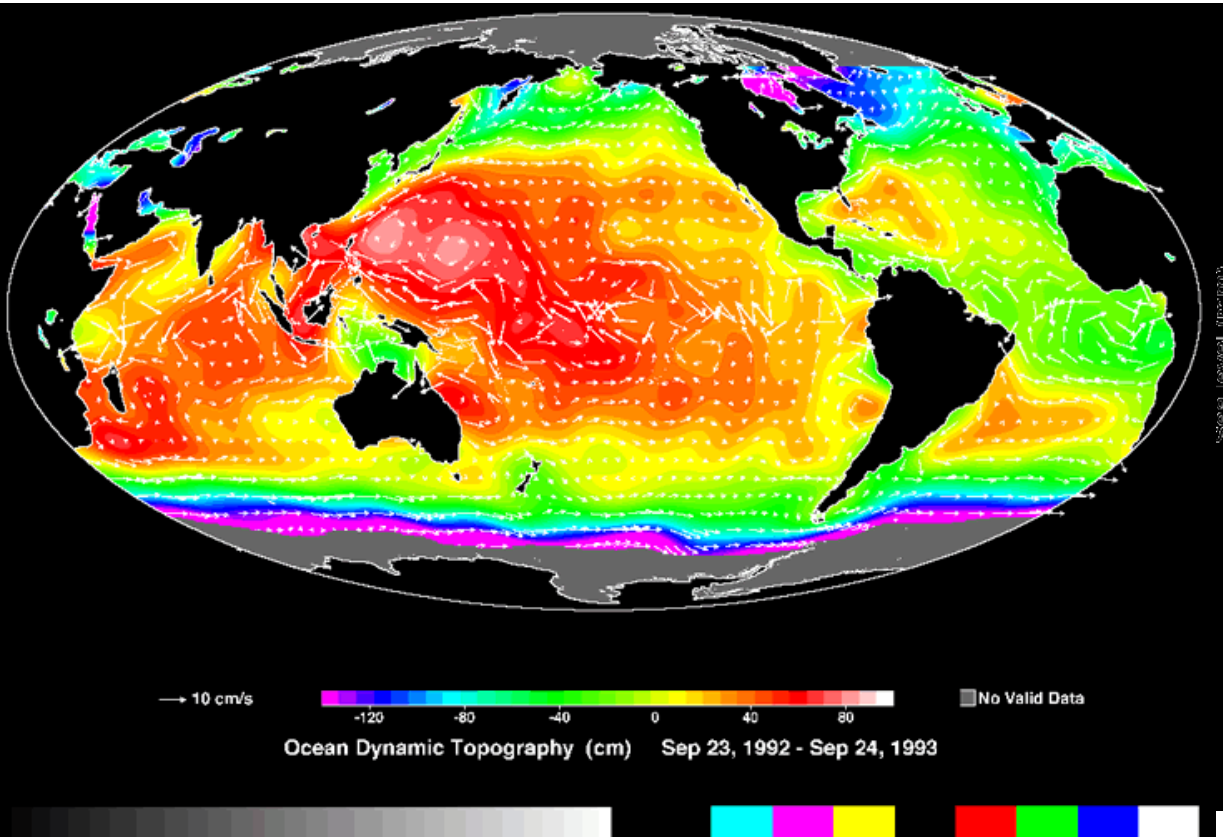
- Continuous downward trend both during the summer (-13.3 % per decade) and winter (-3.0 % per decade) periods over the Arctic region
- Increasing trend of 4.5 % per decade for summer and 1.3 % per decade during winter periods over the Antarctic region

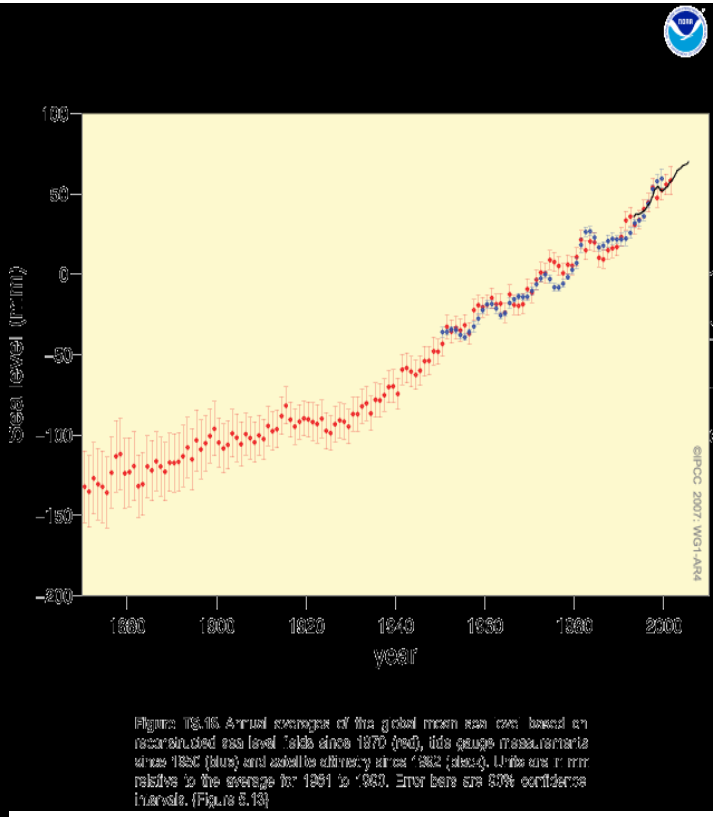
(vi) Monitoring Oceanic Changes: Sea Surface Temperature



Source: http://www.ssec.wisc.edu/data/sst/

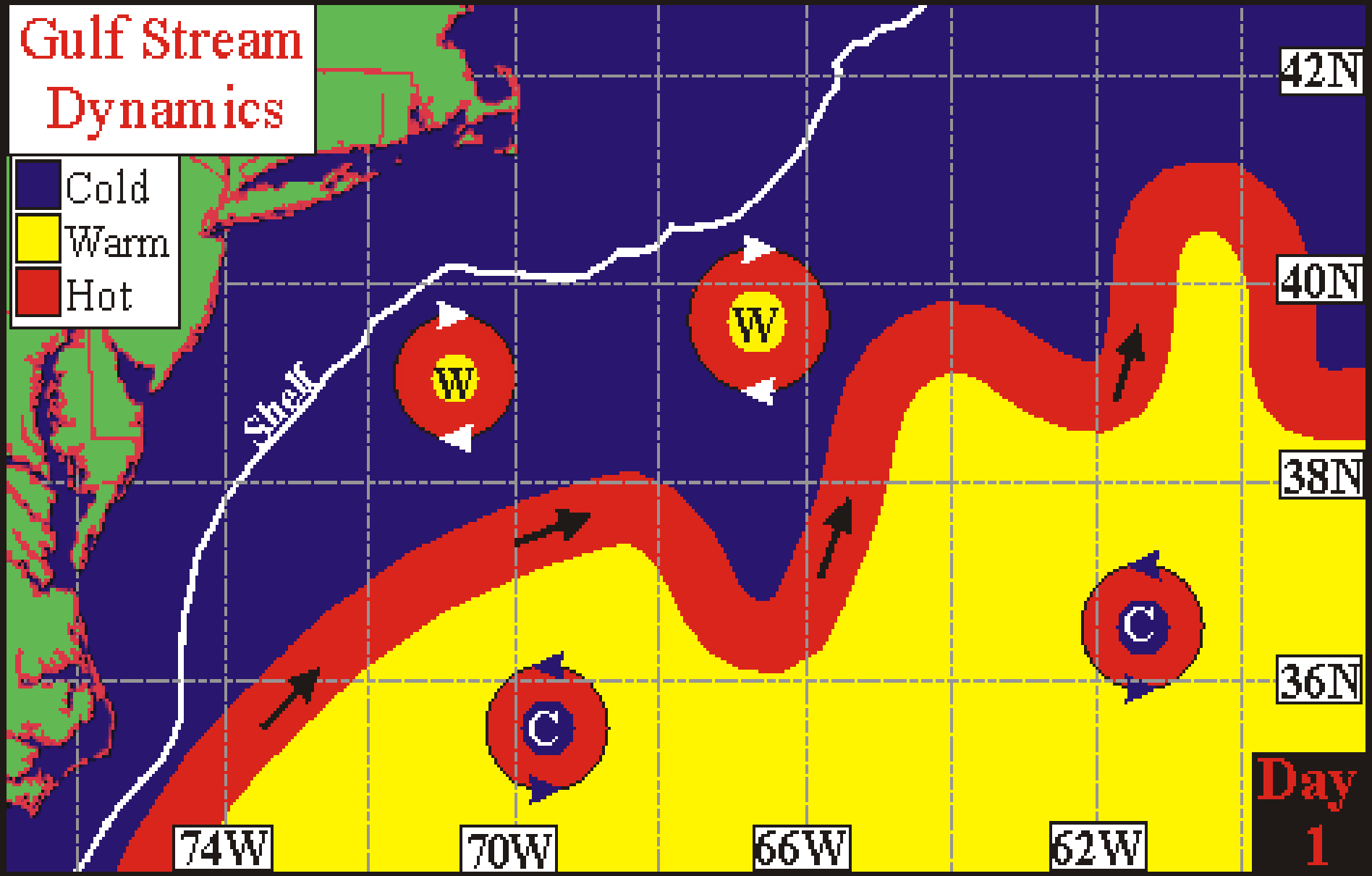
(vii) Monitoring Oceanic Changes: Sea Level Rise



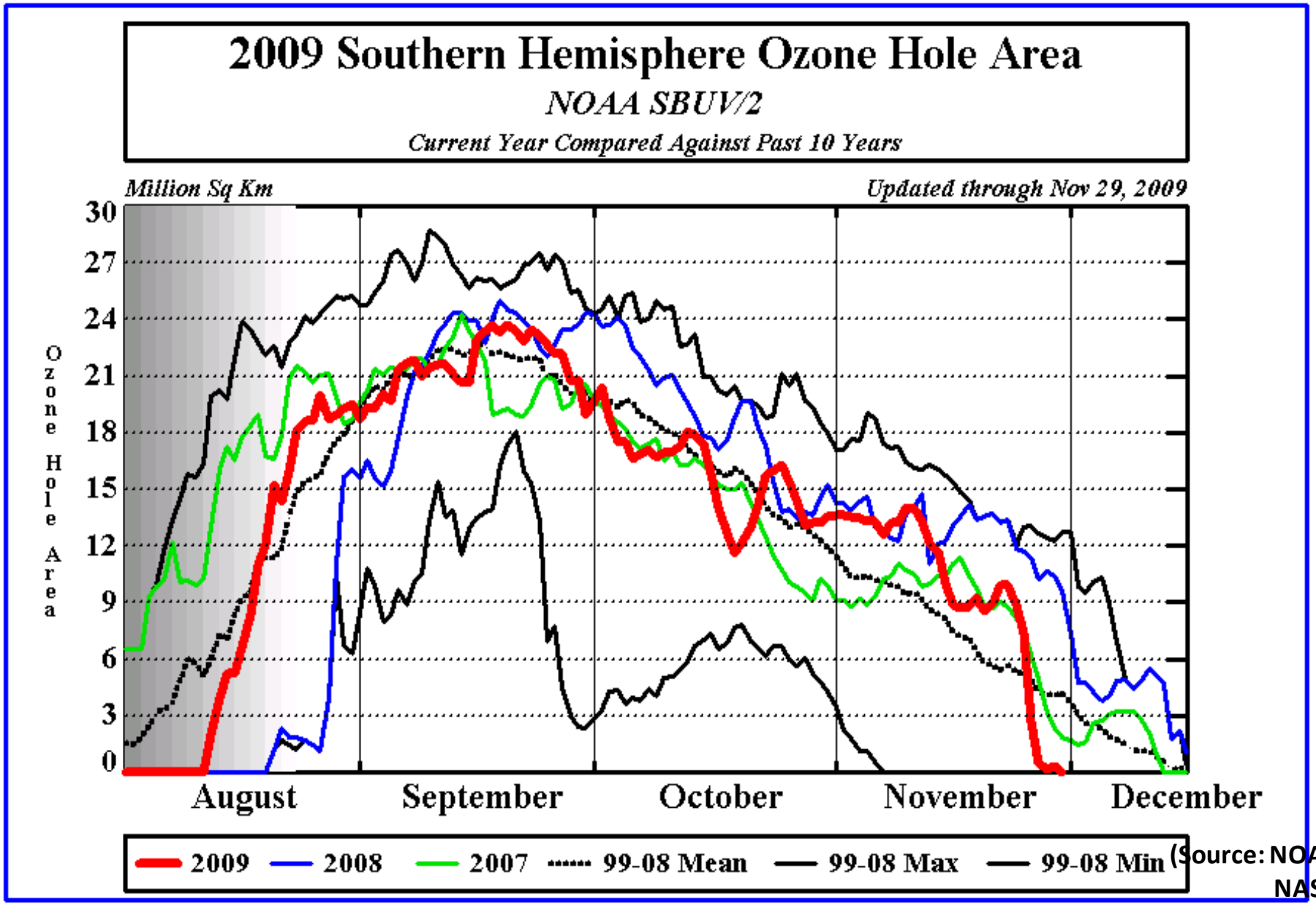


Altimeters on satellites provided the first detailed picture of global sea level and now track its change **(Source: NOAA/NASA)**

(viii) Monitoring Ocean Circulations: Ocean Eddies

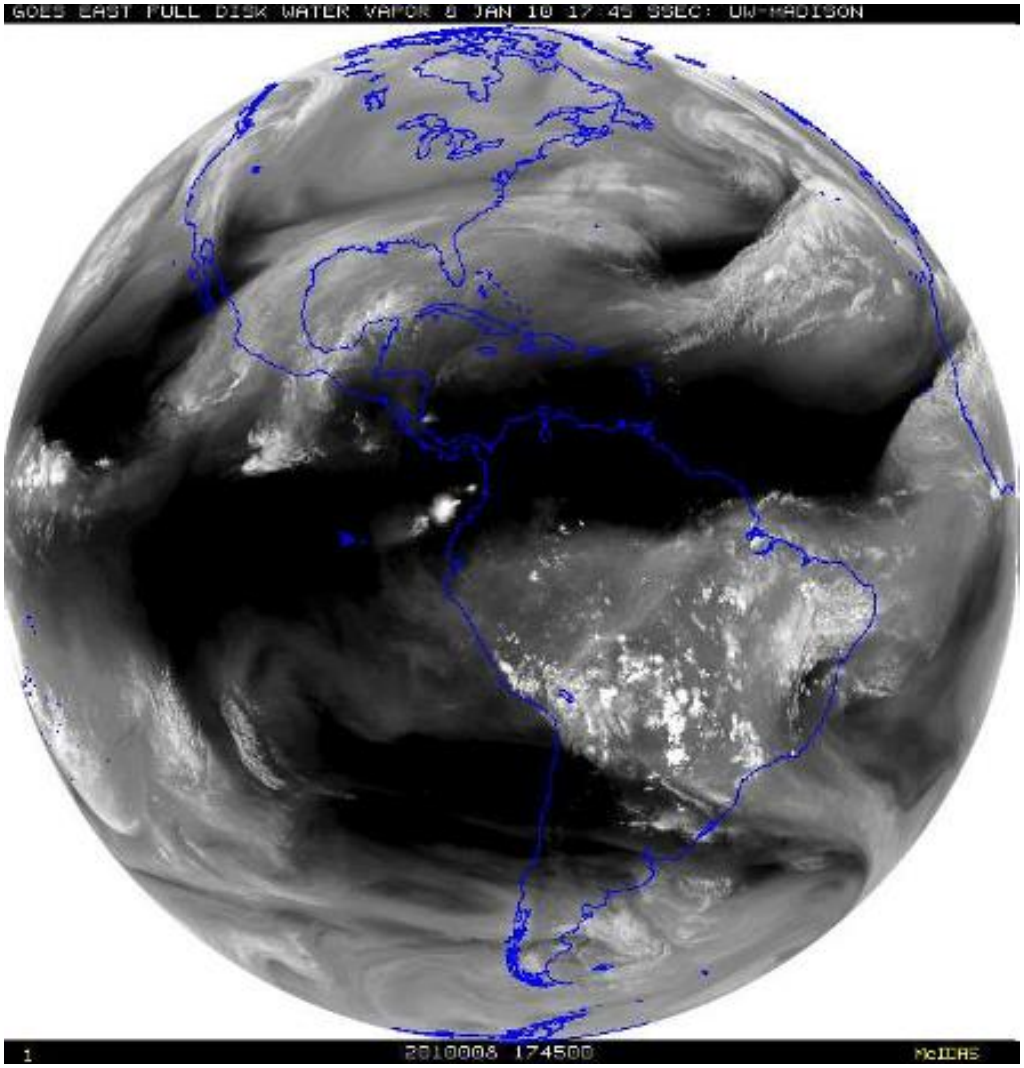


(ix) Monitoring Atmospheric Changes: Ozone Hole



(Source: NOAA/ NASA)

(x) Monitoring Atmospheric Changes: Water Vapour

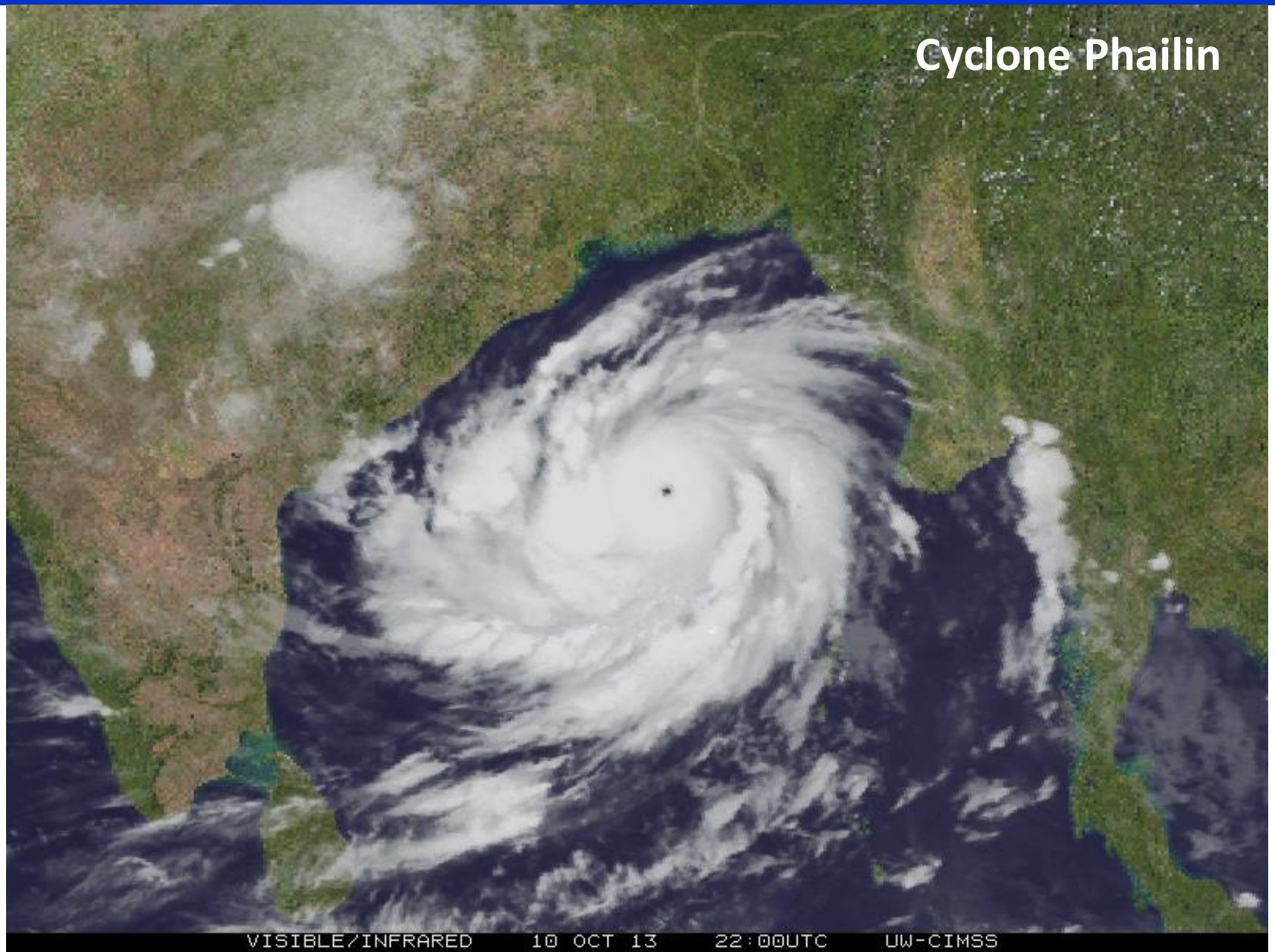


Warmer temperatures enable an increase in atmospheric water vapor (H_2O - the most abundant greenhouse gas)

(xi) Monitoring Land-Atmosphere Exchanges: Volcanoes

Source: www.geo.mtu.edu

(xii) Monitoring Air-Sea Interactions: Cyclones



Data Requirements

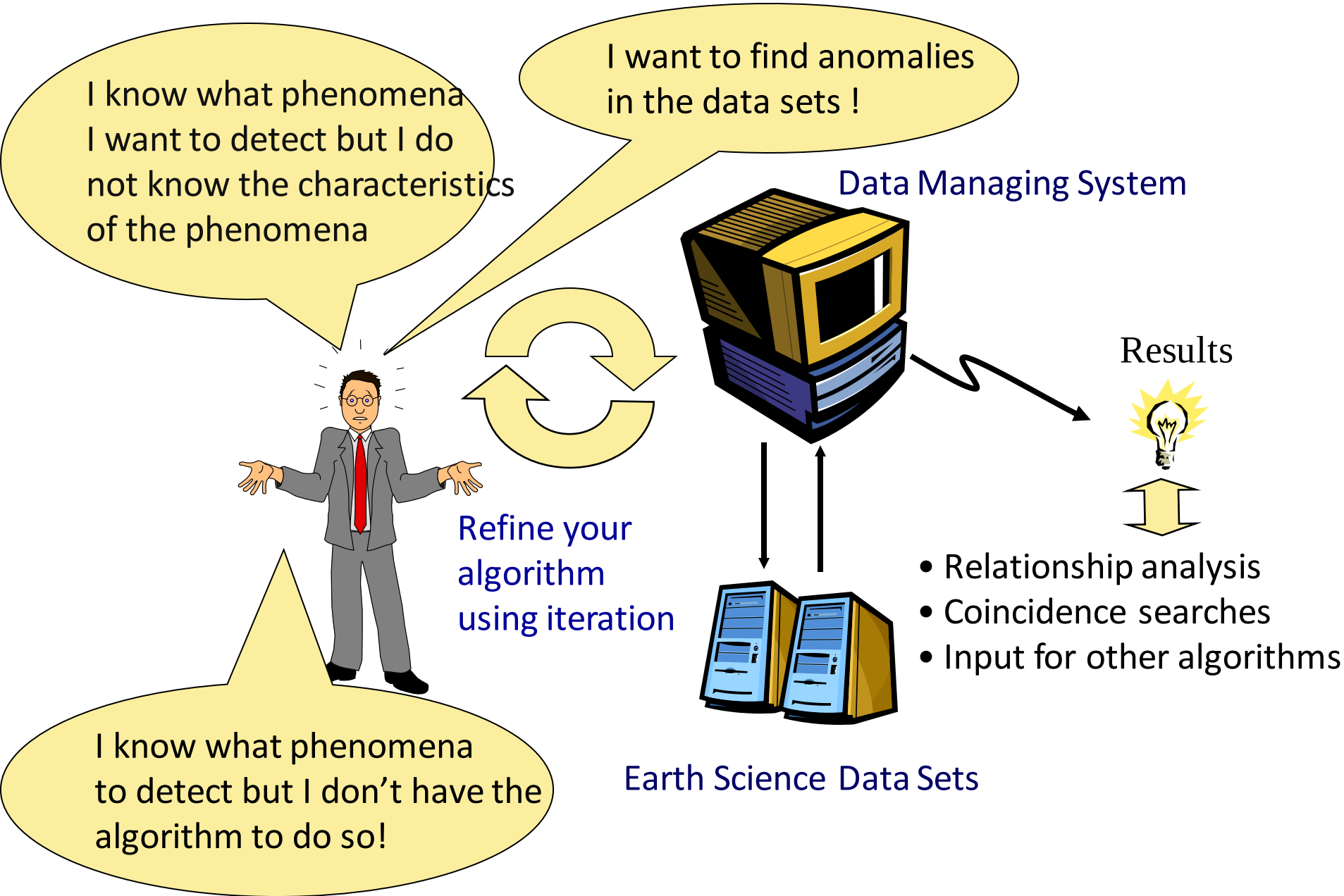
- High Resolution Global *in situ* Observations (spatial and temporal)

- Long term Satellite based imagery (multiple resolutions and wavelengths)

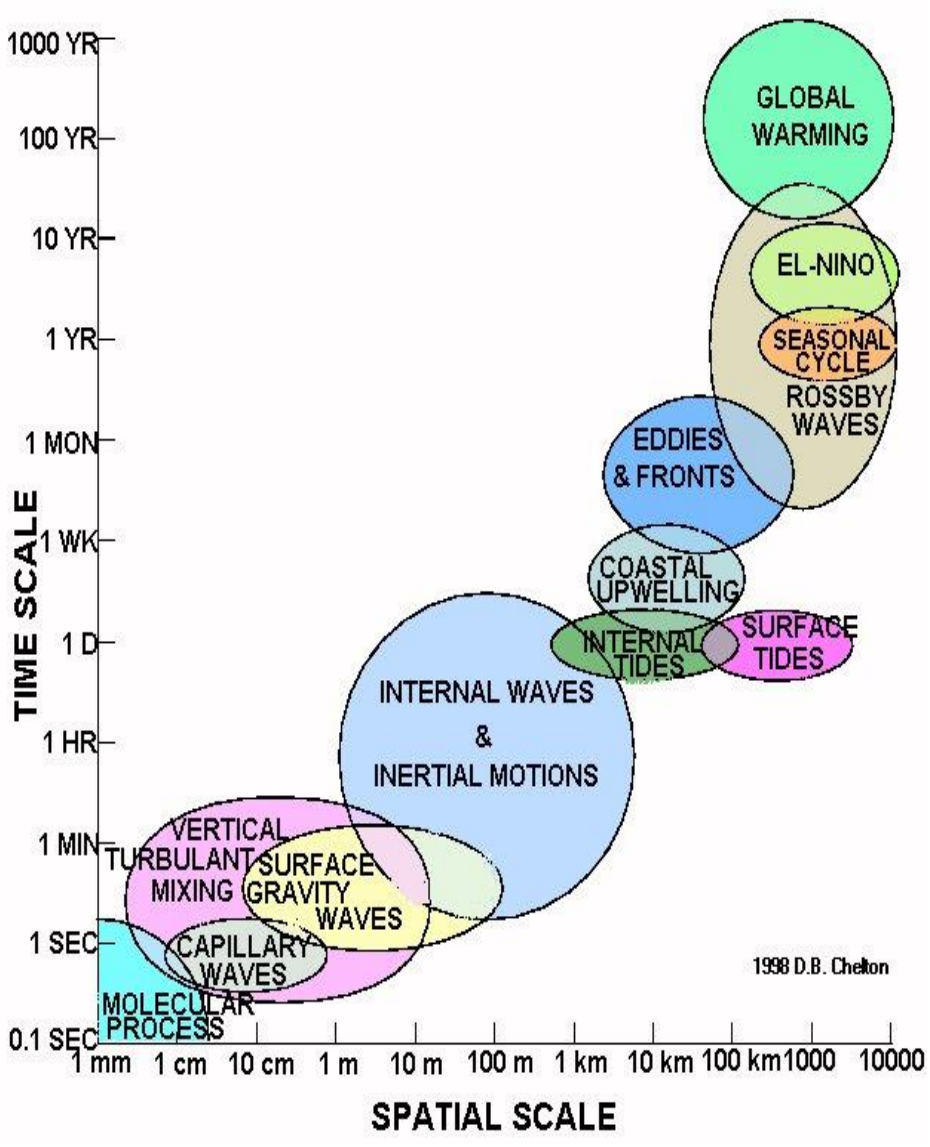
- Multi-dimensional bulk data analysis & modeling

- Data Intensive and High Computational Prowess
  - Data Mining Techniques
  - Genetic Algorithms
  - Artificial Neural Networks
  - EOFs / Fractals, etc……

Known Event / Large Data



Ocean Parameters/Processes



- Ocean Surface Winds
- Waves (wind/internal/swell waves)
- Ocean Currents/Circulation
- Oceanic Rings/Eddies/Gyres
- Tides
- Fronts
- Upwelling
- Mixed Layer Dynamics
- Air-Sea Interaction
- El-Nino
- Morpho-dynamic changes
- Photosynthesis

Oceanography Applications

Altimeters

SARAL AltiKa: 35.75 GHz (Ka-band)

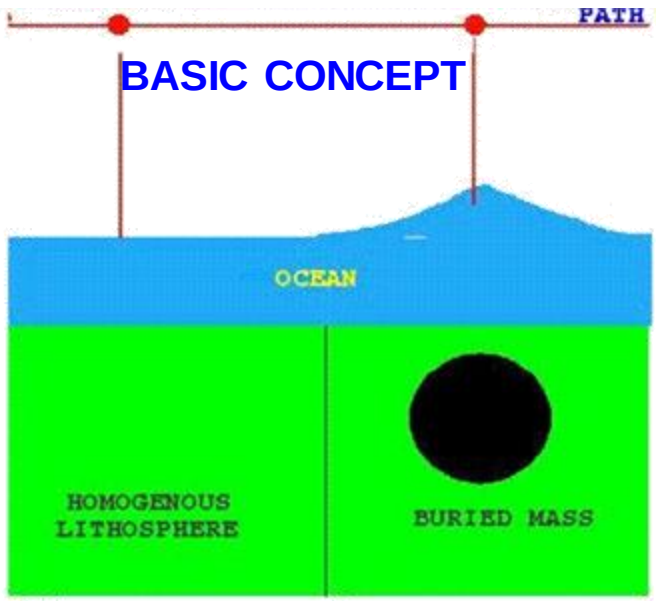
Scatterometers

Scatsat-1: 13.515 GHz (Ku-band)

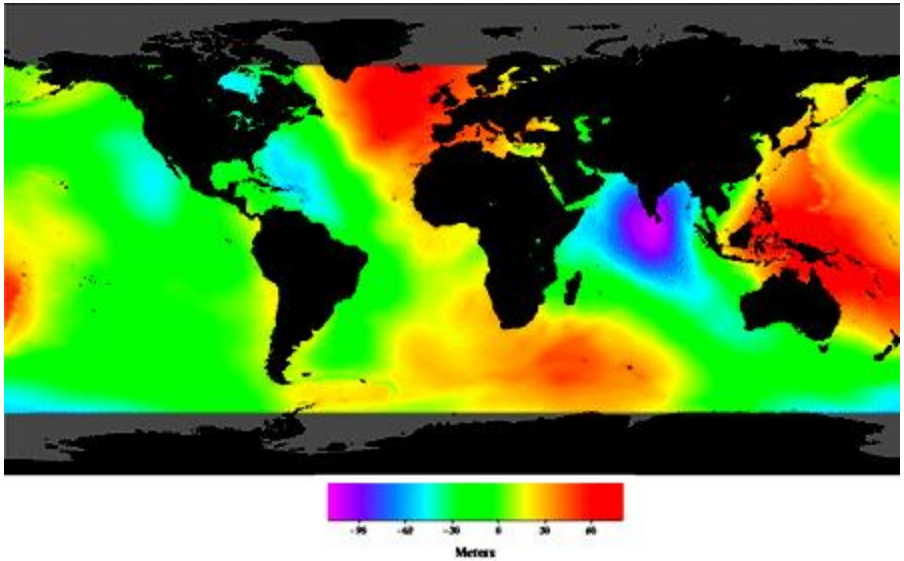
Microwave Bands

Bands	Frequency (Wavelength)
P	0.3 – 1 GHz (30 – 100 cm)
L	1 – 2 GHz (15 – 30 cm)
S	2 – 4 GHz (7.5 – 15 cm)
C	4 – 8 GHz (3.8 – 7.5 cm)
X	8 – 12.5 GHz (2.4 – 3.8 cm)
Ku	12.5 – 18 GHz (1.7 – 2.4 cm)
K	18 – 26.5 GHZ (1.1 – 1.7 cm)
Ka	26.5 – 40 GHz (0.75 – 1.1 cm)

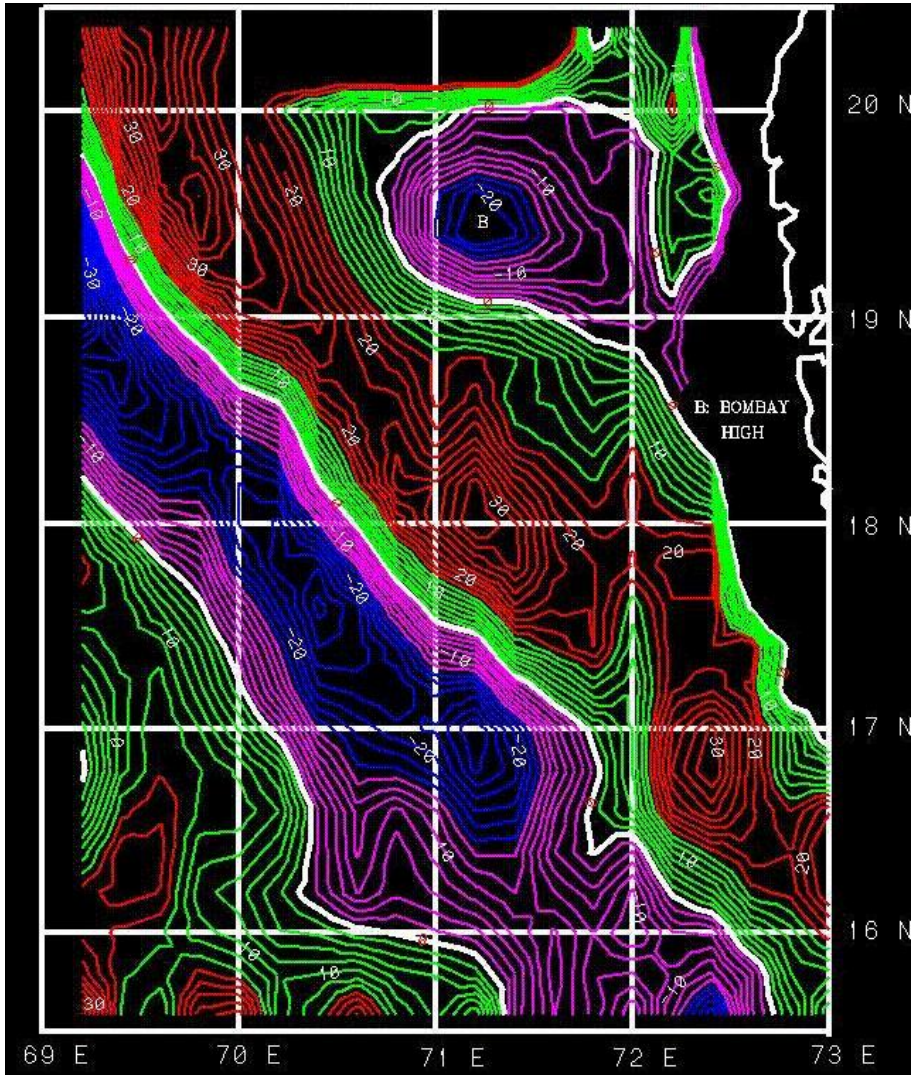
Satellite Altimetry for Geoid and Gravity Anomaly



GEOID

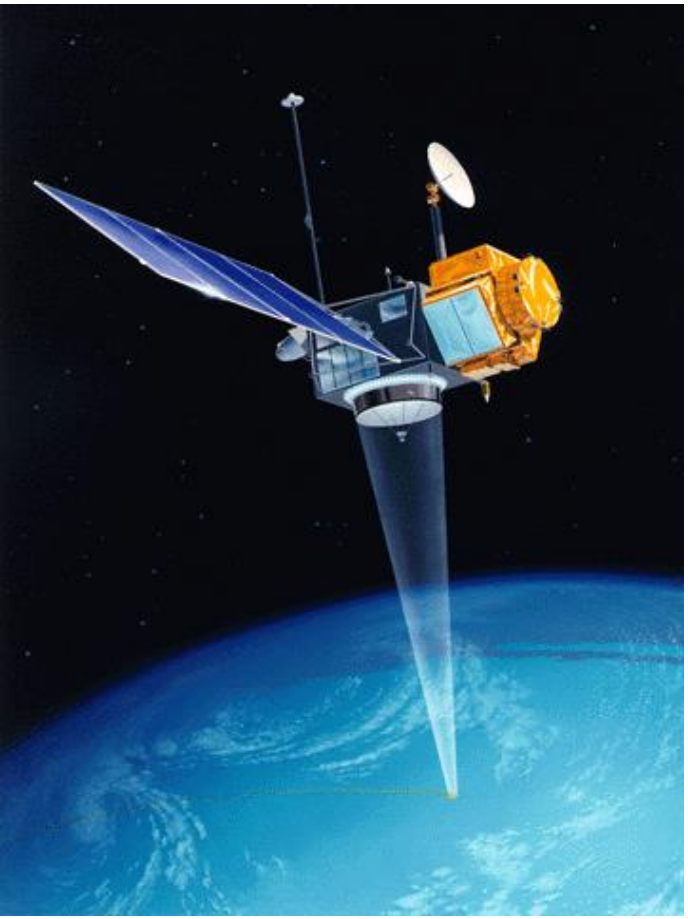


FREE-AIR GRAVITY ANOMALY AT BOMBAY HIGH



Courtesy: ISRO

Satellite Altimetry of Sea Surface Topography



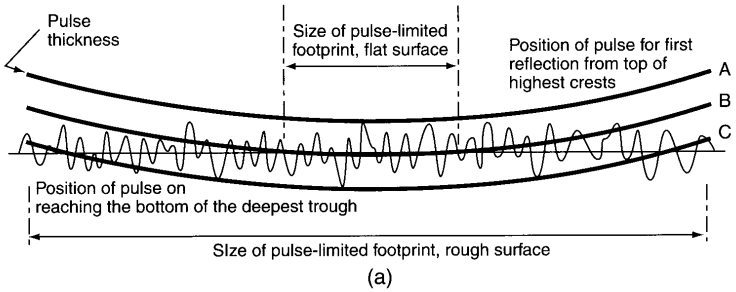
Satellite altimeters are radars, which transmit short pulses toward the earth beneath them.

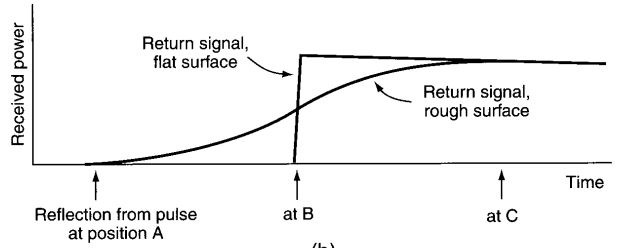
The return time of the pulse after reflection at the earth's surface is measured, and this yields the height of the satellite.

Altimeters:

ERS-1, ERS-2, TOPEX/Poseidon, Jason-1,2, SARAL/AltiKa satellites.

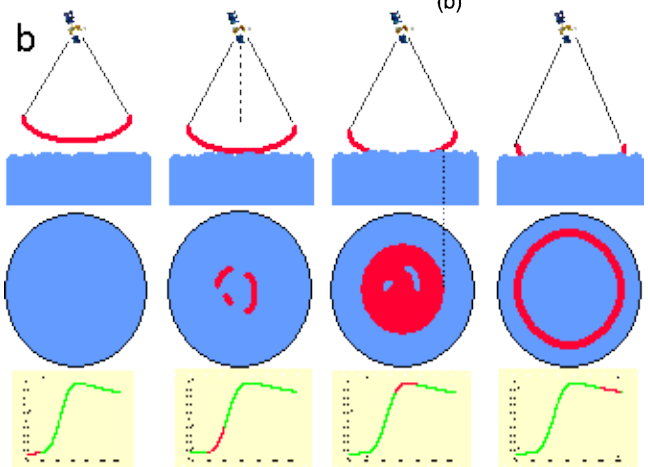
Basic principle of Satellite Altimetry



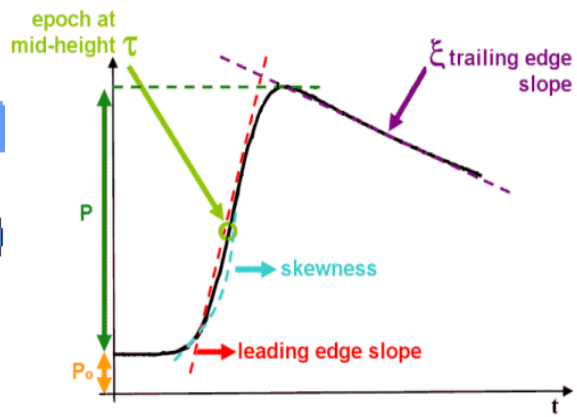


Sea surface is rough rather than flat. So the first reflection of energy commences when the leading edge of the pulse reaches the topmost crests of the waves, earlier than for the flat surface.

But the reflected energy does not achieve its maximum until the trailing edge reaches the lowest wave trough.



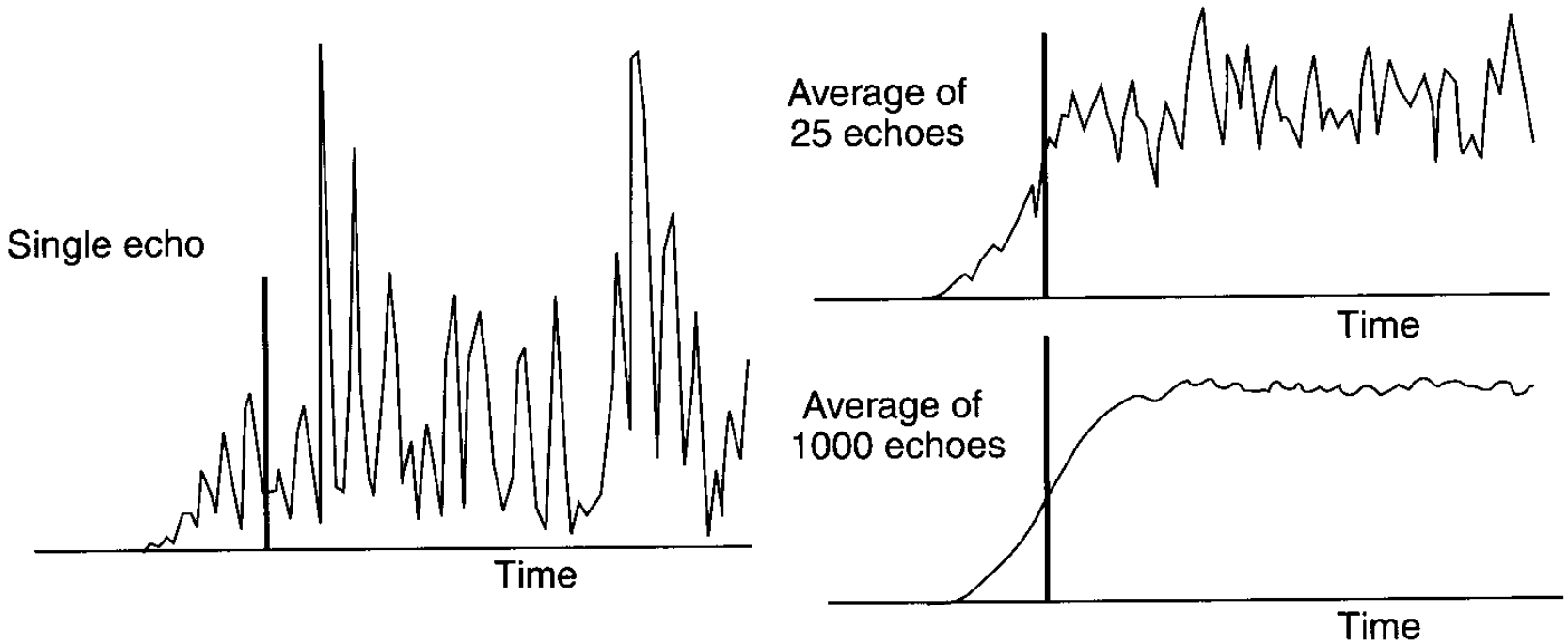
Footprint of the signal and its echo



The waveform of the echo signal

In this way, the altimeter is able to average out the effect of the ocean waves. This parameter is called a **Significant Wave Height (SWH)**

Basic principles Contd …



As a result of random distribution of the ocean wave facets at any instant, each individual return signal is very noisy, but averaging many successive pulses can reduce this.

Properties - JA2_IPS_2PdP160_192_20121112_022238_20121112_031851.nc

General | Attributes

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File Type: HDF4, size=35514K, groups=1, datasets=220

Group Members

Number of members: 220

Name	Type
time	Dataset
meas_ind	Dataset
wvf_ind	Dataset
time_20hz	Dataset
lat	Dataset
lon	Dataset
lon_20hz	Dataset
lat_20hz	Dataset
surface_type	Dataset
alt_echo_type	Dataset
rad_surf_type	Dataset
rad_distance_to_land	Dataset
qual_alt_1hz_range_ku	Dataset
qual_alt_1hz_range_ku_mle3	Dataset
qual_alt_1hz_range_c	Dataset
qual_alt_1hz_swh_ku	Dataset
qual_alt_1hz_swh_ku_mle3	Dataset
qual_alt_1hz_swh_c	Dataset
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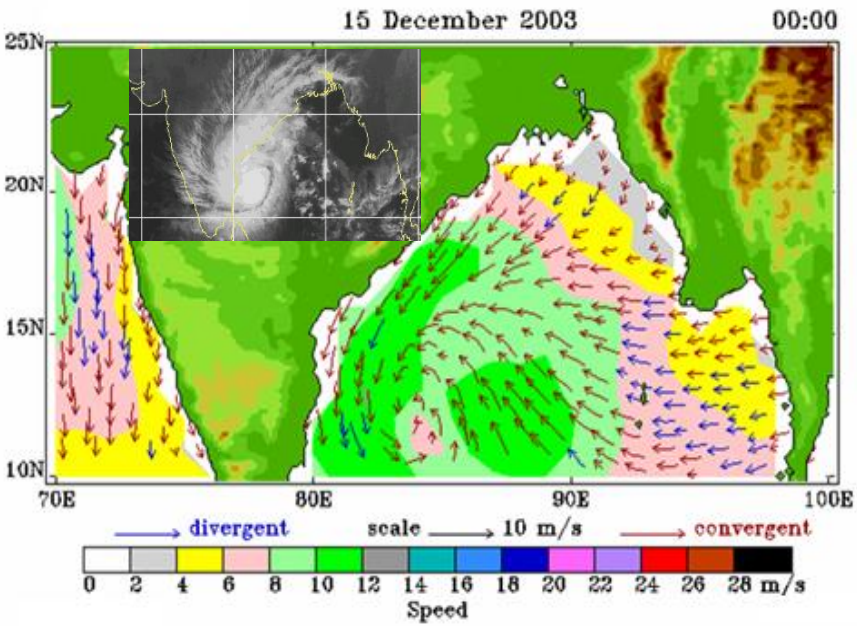
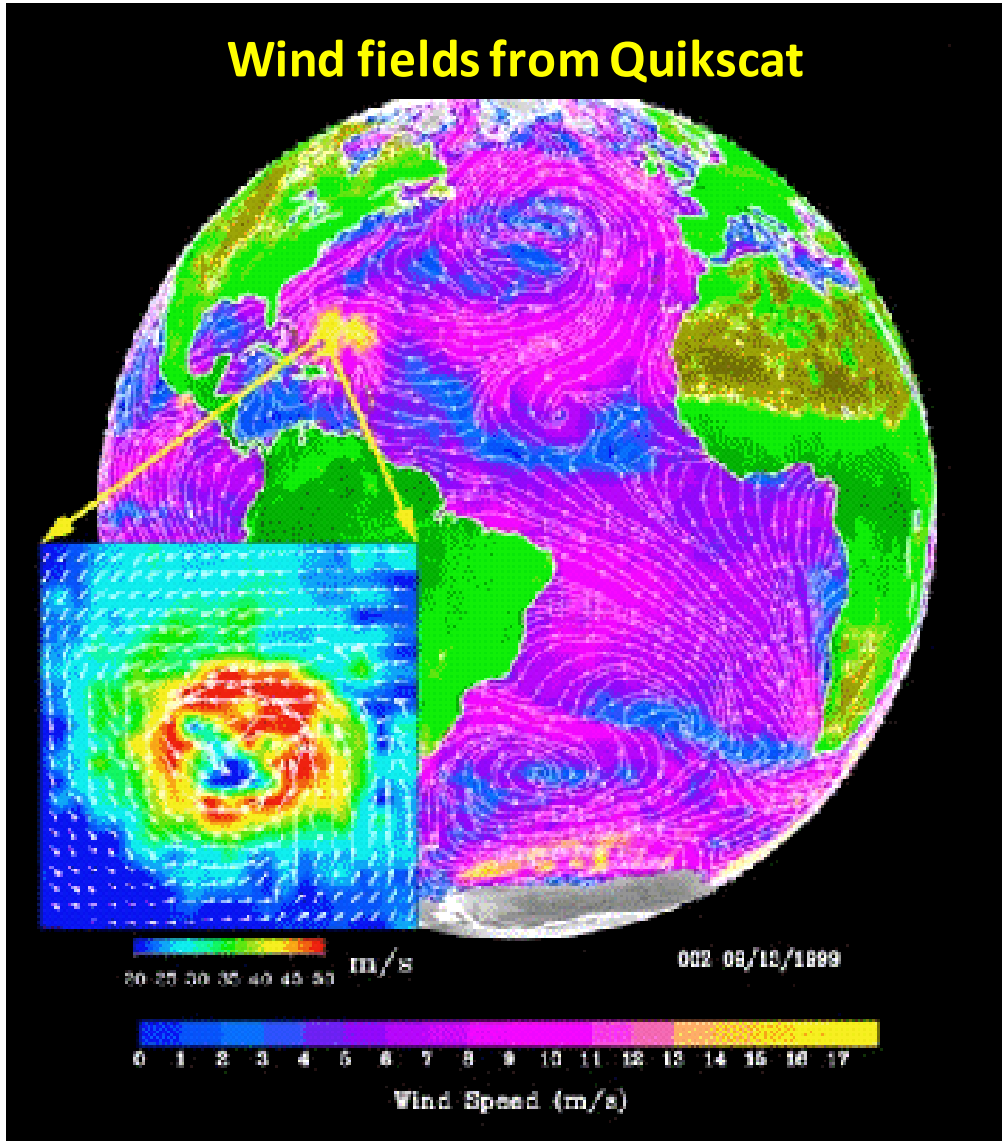
Close

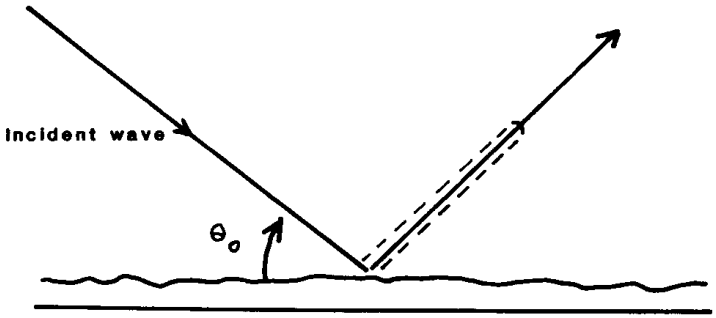
Scatterometer Winds Applications

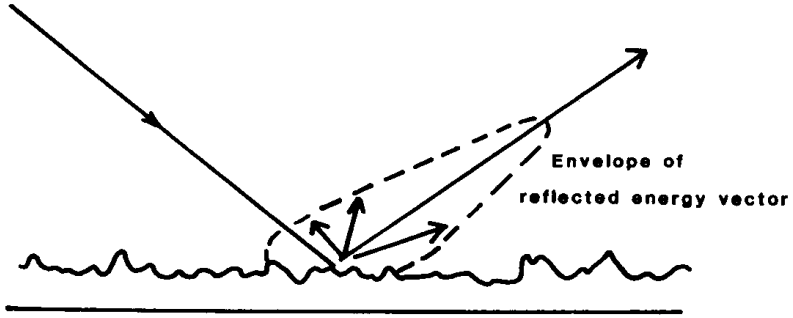
- Generation of surface waves
- Shipping safety and efficiency
- Oil platform operations
- Storm surges
- Upwelling
- Coupled Ocean-Atmosphere General Circulation Models
- Cyclone studies

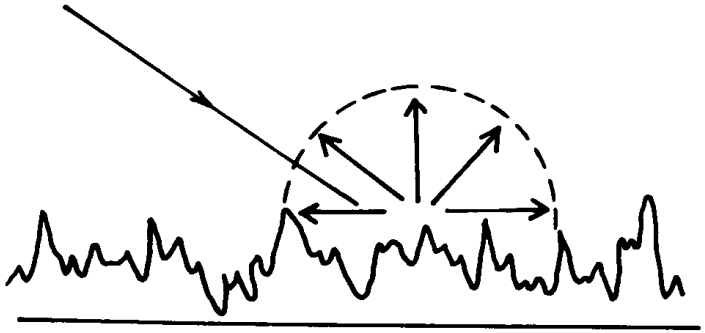




Sea Surface Roughness: (Oblique-viewing)



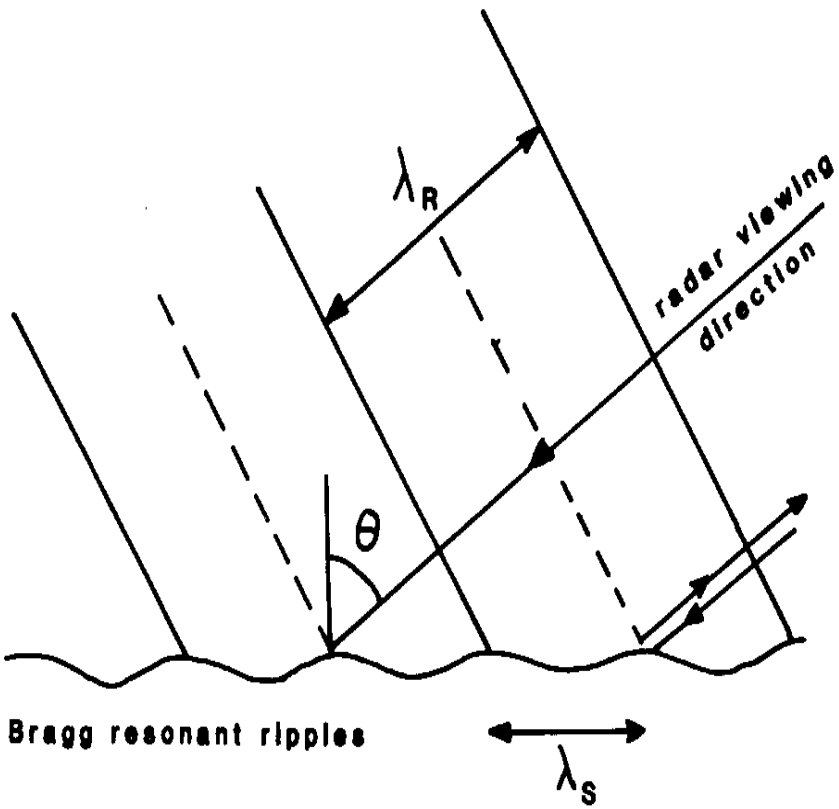




Microwave scatterometer is based on the principle of the resonant Bragg scattering.

For a smooth surface, oblique viewing of the surface with active Radar yields virtually no return. If the surface is rough, significant backscatter occurs.

Sea Surface Roughness Contd ……..



The interference of scattering from many different parts of the surface results in a reinforcement of scattering from periodic structures in the surface roughness which have suitable wavelengths, and destructive interference of all other reflections.

$(2\ d\ \mathrm{Sin}\theta = n\ \lambda)$

Computation of Wind based Upwelling Index (UI)

- Ekman transport is considered as the wind based UI (a function of alongshore wind stress and Coriolis parameter) computed as:

Alongshore wind stress (τ_l) = $\rho_a C_d \boldsymbol{V_l} (U^2 + V^2)^{1/2}$

where: ρ_a = Air density (1.225 kg m^{-3})

C_d = Drag coefficient (1.43×10^{-3})

$\boldsymbol{V_l}$ = Upwelling favourable wind

U = Zonal Wind

V = Meridional Wind

Computation of Upwelling Index Contd…

$$V_l = -(\text{lat}/\text{abs(lat)})\,(U \cos(\theta - \pi/2)) + (V \sin(\theta - \pi/2)$$

where, θ is the angle defined by an unitary vector normal to the shoreline and pointing seaward (*following Cropper et al. 2014; Varela et al. 2015*)

- Ekman transport: $M_e = \tau_l / f$ (Bakun, 1973)
- Ekman pumping velocity: $W_e = curl\, \tau_l / (\rho_o f)$ (Wiafe and Nyadjro, 2015)

where, ρ_o is the water density (1024 kg m^{-3})

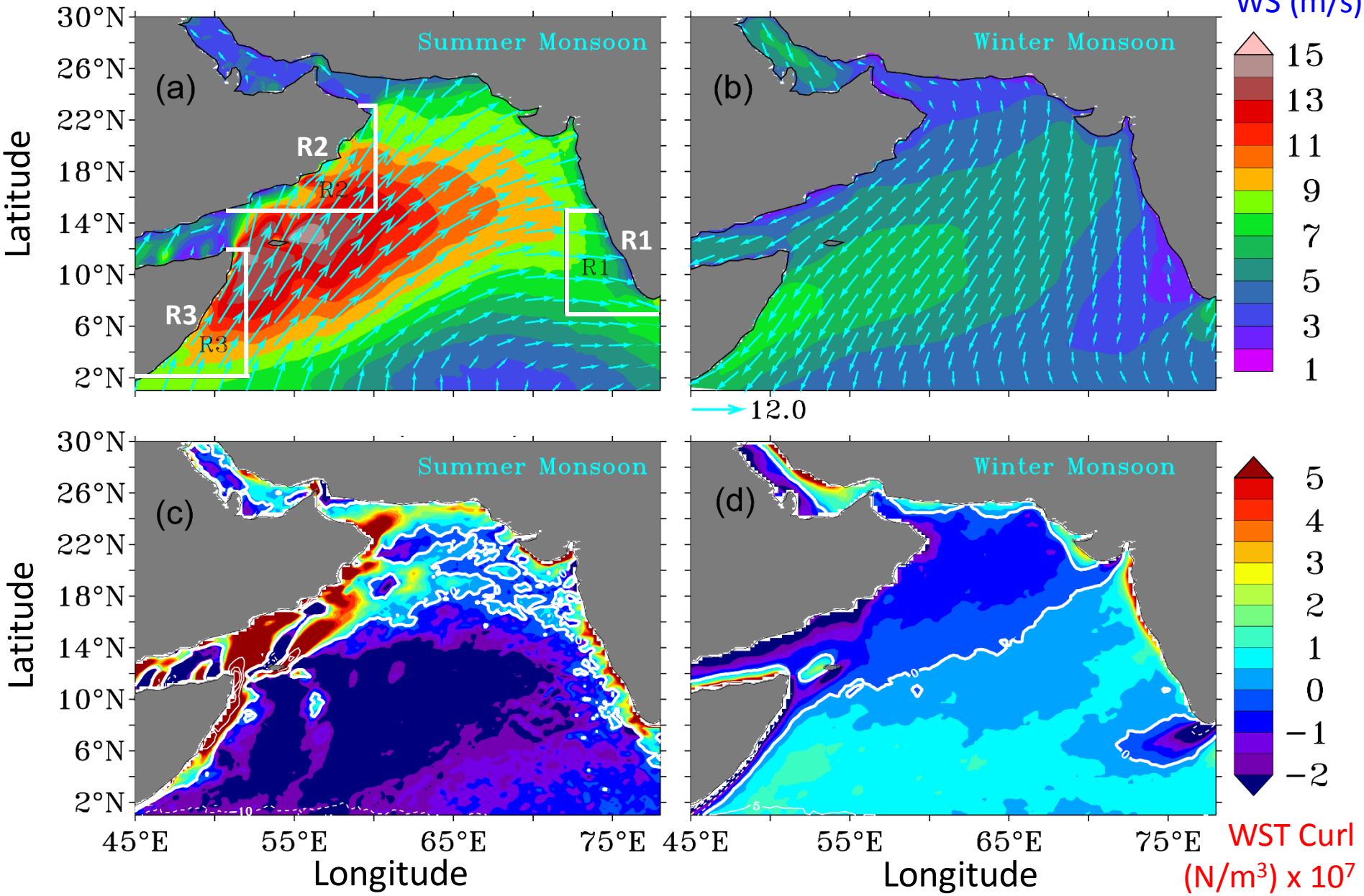
f is the Coriolis parameter ($2\Omega \sin \phi$)

Ω is the angular velocity of the Earth

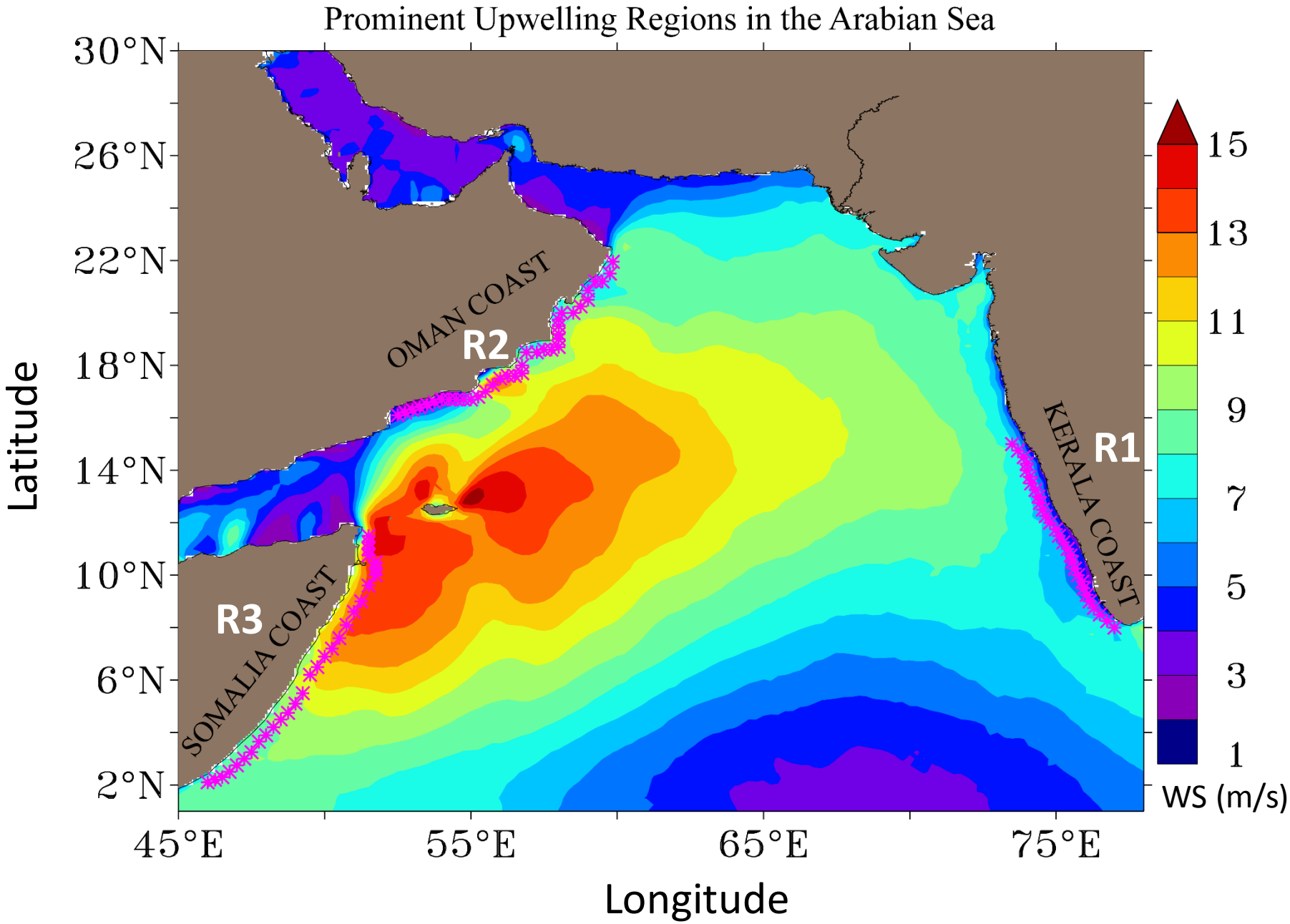
ϕ is the latitude

SCATSAT – 1, L4 25 km Analysed Winds & Wind Stress Curl

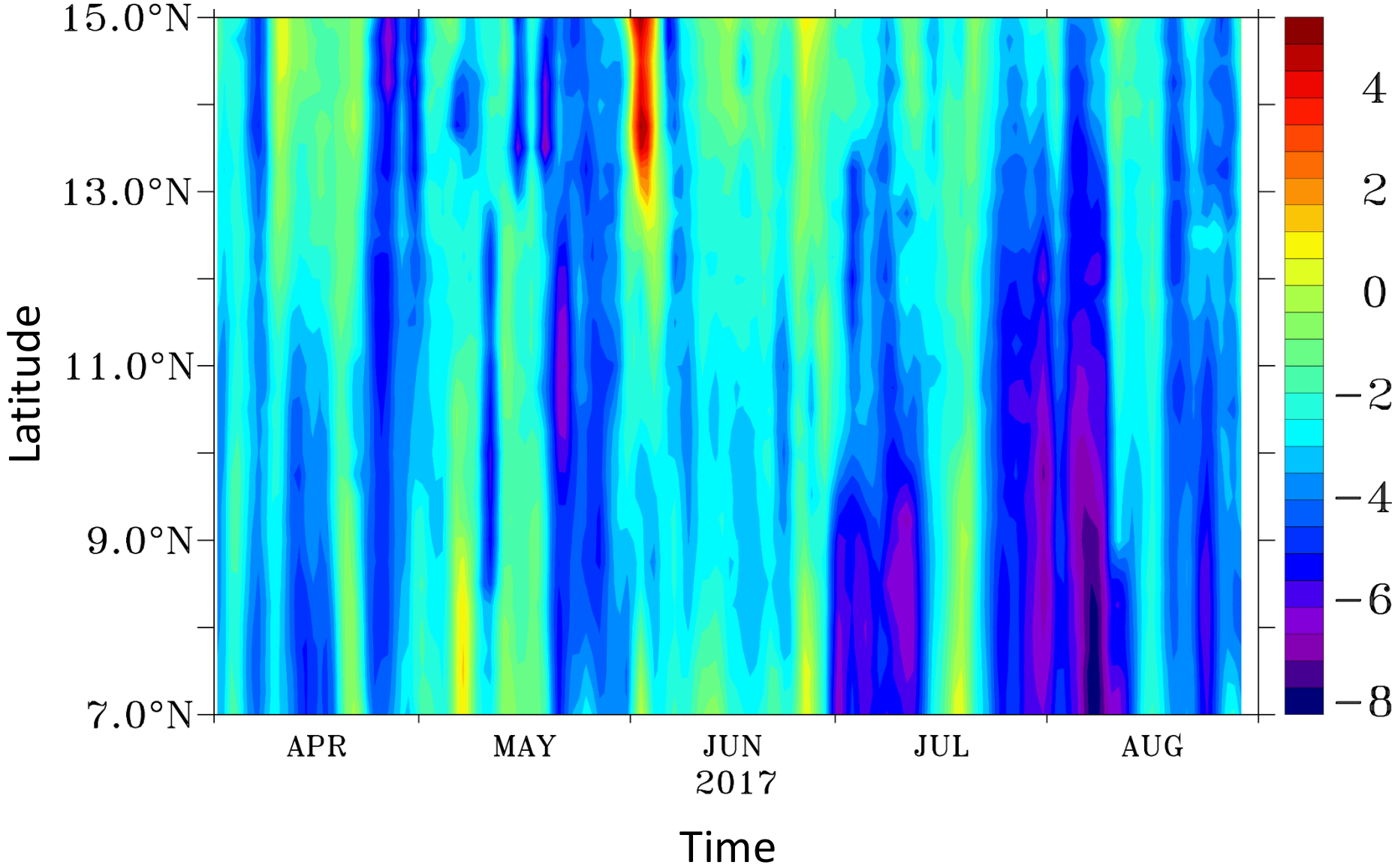
(a) & (c) Jun-Aug 2017; (b) & (d) Nov-16-Feb 2017



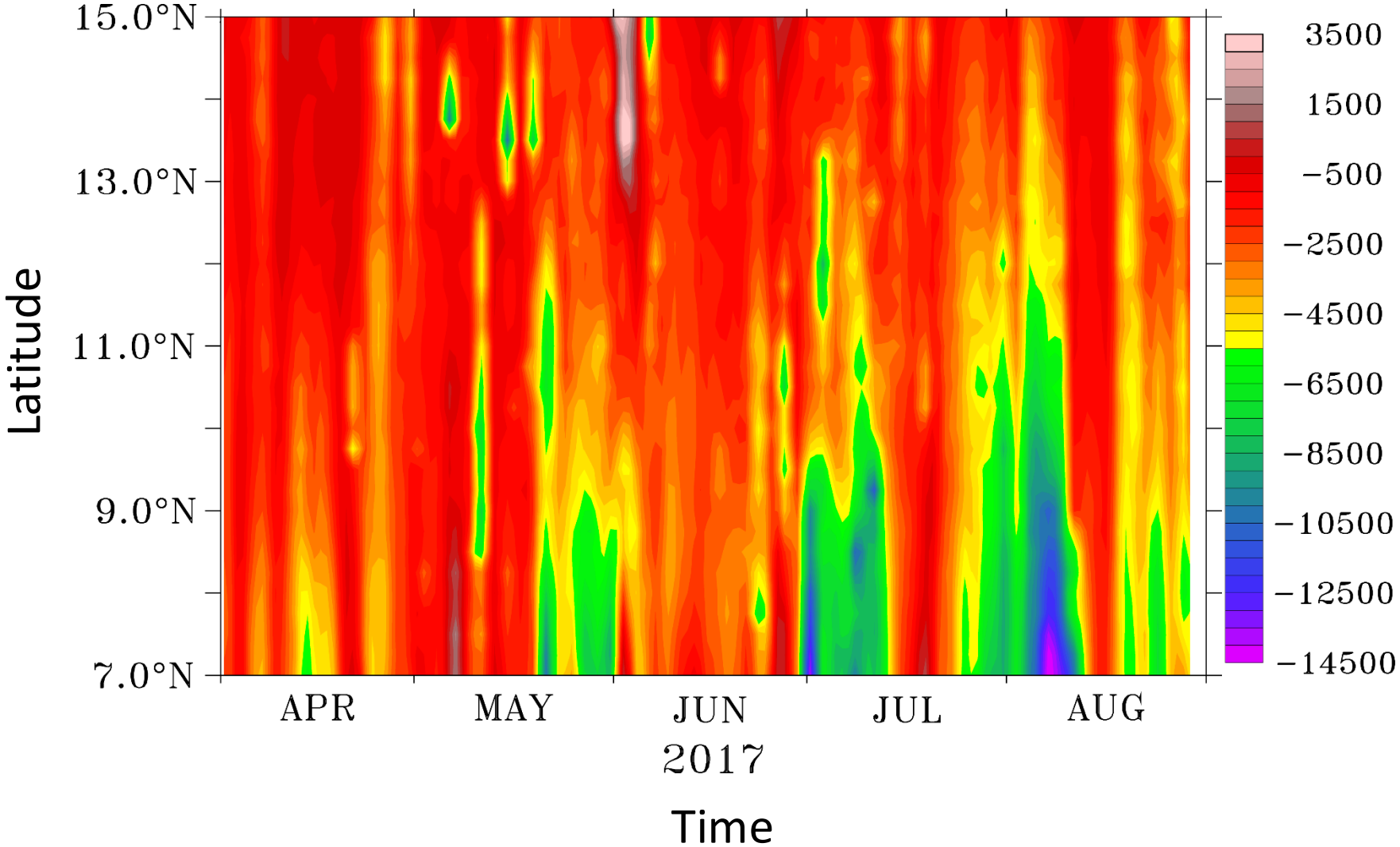
SCATSAT– 1 Winds (Summer Monsoon)



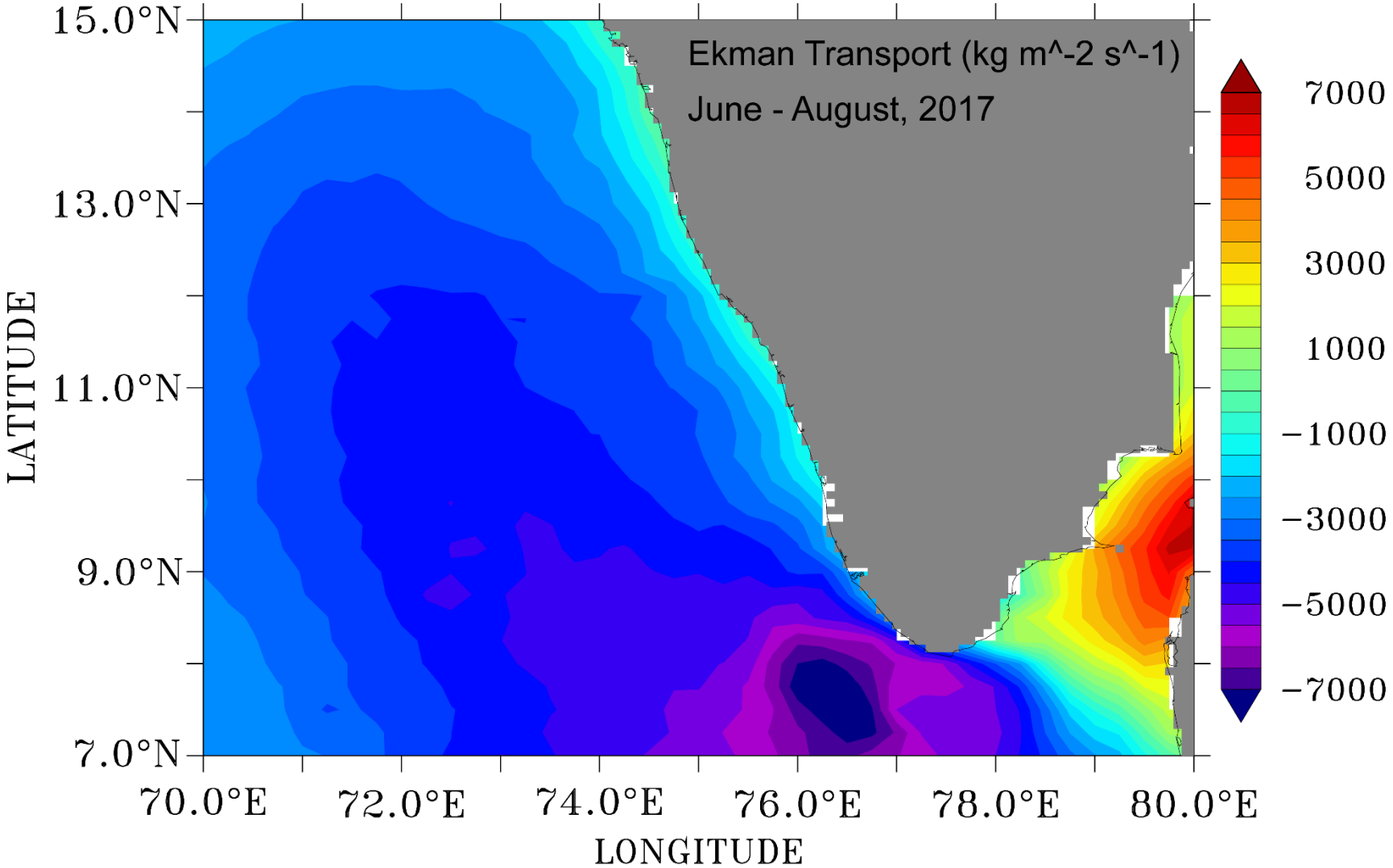
Along-Shore Wind Speed (m/s) in R1: SEAS



Ekman Transport (kg/m^2/s) in R1: SEAS



Ekman Transport (kg/m^2/s) in R1: SEAS



Ocean Surface Currents

Surface Geostrophic Currents (from Altimeter)

(computed as the gradient of SSH from absolute SSH)

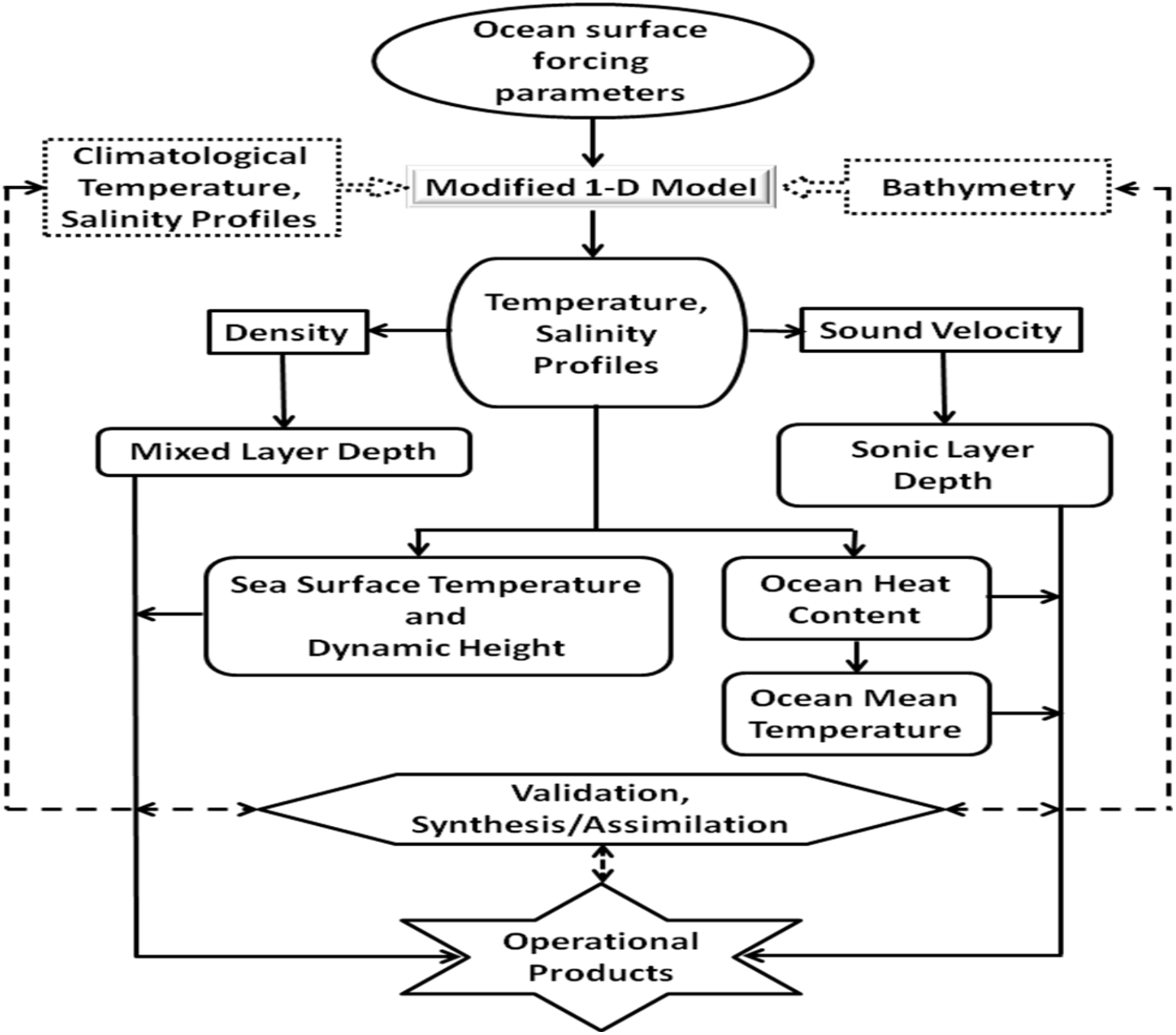
$$u_s = -\frac{g}{f}\frac{\partial \zeta}{\partial y}; \qquad v_s = \frac{g}{f}\frac{\partial \zeta}{\partial x}$$

where, g is the acceleration due to gravity, f is the Coriolis parameter ($f = 2\ \Omega \sin \varphi$), ζ is the height of the sea surface above a level surface (elevation), φ is the latitude and Ω is the angular velocity of the earth's rotation (= 0.729×10^{-4}).

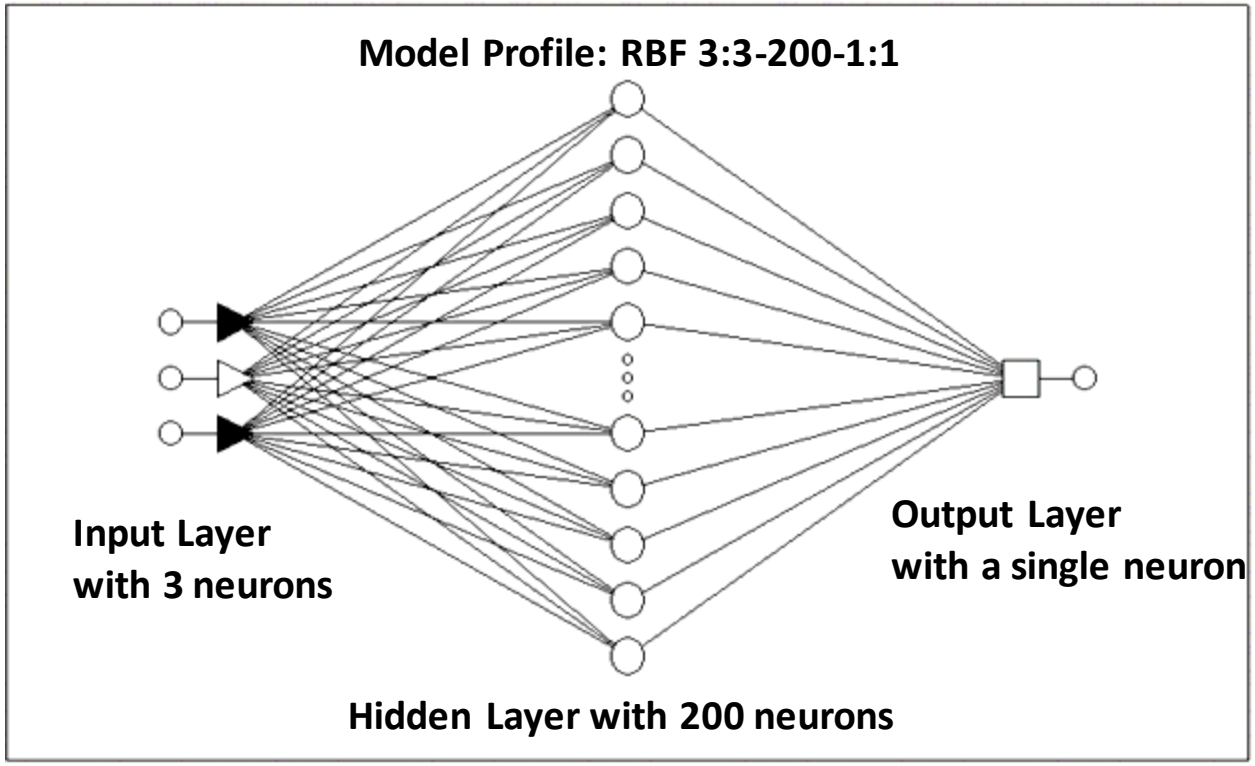
+ Wind Driven Ekman Currents (from Scatterometer)

$$[u, v] = \mathbf{V}_0 \exp(-z/D)\ [\cos(\pi/4 - z/D), \sin(\pi/4 - z/D)]$$

where, wind stress is assumed northward is the surface amplitude; D is the e-folding scale depth; z is depth taken positive downward; and ρ is the density of seawater that can be assumed constant.


Ocean surface forcing parameters
Climatological Temperature, Salinity Profiles
Modified 1-D Model
Bathymetry
Temperature, Salinity Profiles
Density
Sound Velocity
Mixed Layer Depth
Sonic Layer Depth
Sea Surface Temperature and Dynamic Height
Ocean Heat Content
Ocean Mean Temperature
Validation, Synthesis/Assimilation
Operational Products

Artificial Neural Network Technique



$$Y_q = A_{q0} + \sum_{j=1}^{k} A_{qj}\Phi(B_{j0} + \sum_{i=1}^{n} B_{ji}X_i),\ q = 1, 2, \ldots, m$$

where, X_i & Y_q are the components of the input and output vectors, respectively

A & B: fitting parameters

Φ: the activation function

n & m: the number of inputs and outputs, respectively

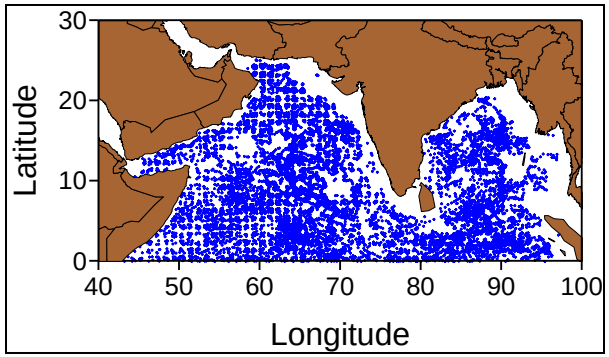
k: the number of neurons in the layer

Artificial Neural Network Approach

Derivation of Ocean Sound Speed Profiles from Remote Sensing Data

In situ Data

- Levitus Monthly climatological T/S profiles at 1^0 X 1^0
- T/S profiles from Argo floats during 2002 – 2006
- T/S profiles and surface parameters from WHOI mooring data
- T/S profiles and surface parameters from ARMEX during 21 Apr – 3 May 2005 at 8 ^{0}N & 73 ^{0}E



Locations of Argo floats during 2002 - 2006

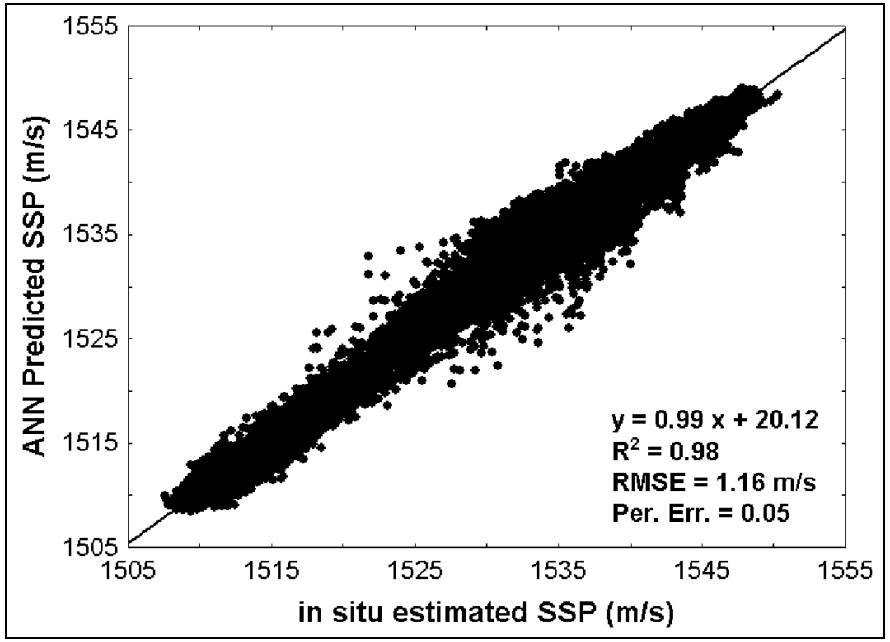
Remote Sensing Data

- Sea surface height anomalies from altimeters [TOPEX, JASON, ERS, ENVISAT, GFO during 2002 – 2006 and during Oct 1994 to Oct 1995]
- Daily sea surface temperature (SST) from NOAA AVHRR during Oct 1994 to Oct 1995, 3 day average SST from TMI during 2002 – 2006
- 3 day average wind speed from TMI during 2002 – 2006

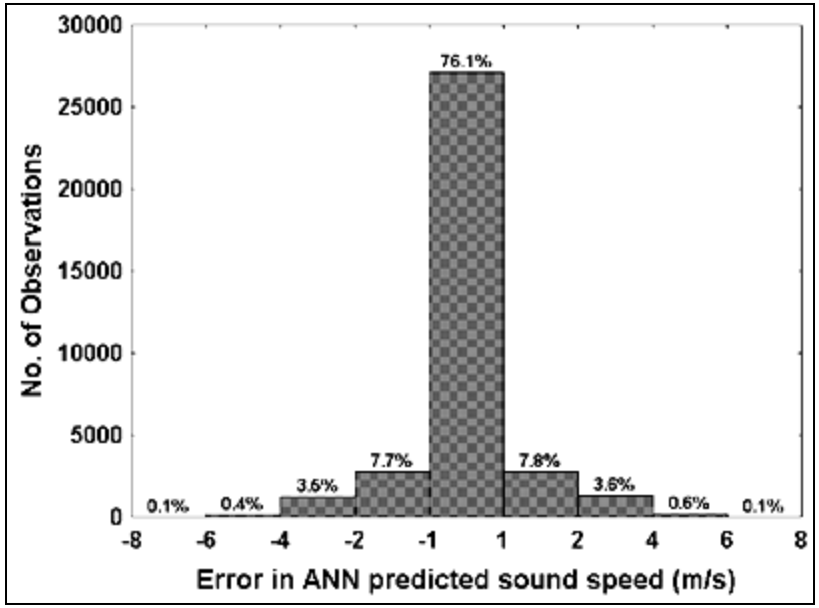
Input parameters: DH, SST, WS, NHF, Radiation

Output parameters: Sound speed at different depths till 100 m (3 hourly profiles at 1 m interval)

Model used: ANN MLP with 3 input neurons, 14 hidden neurons and 18 output neurons



Scatter between observed and predicted SSP



Histogram of the residuals in ANN predicted SSP

Sensitivity Analysis

Rank 1: DH

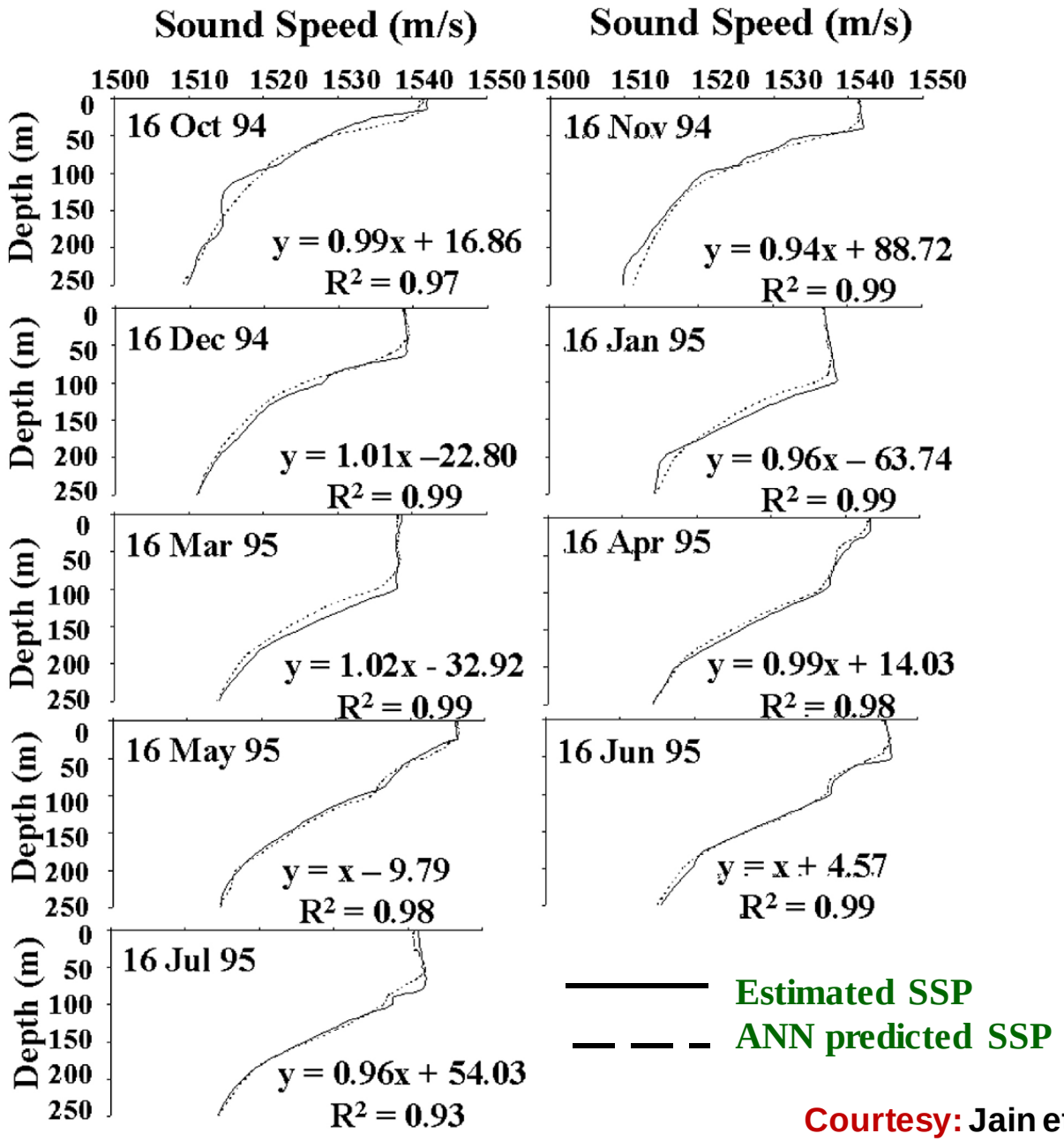
Rank 2: SST

Rank 3: WS

Rank 4: NHF

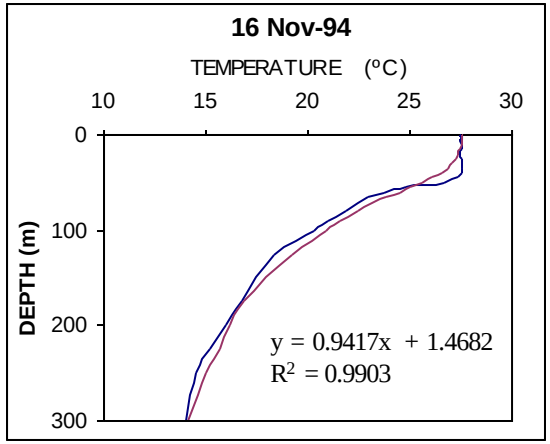
Rank 5: Radiation

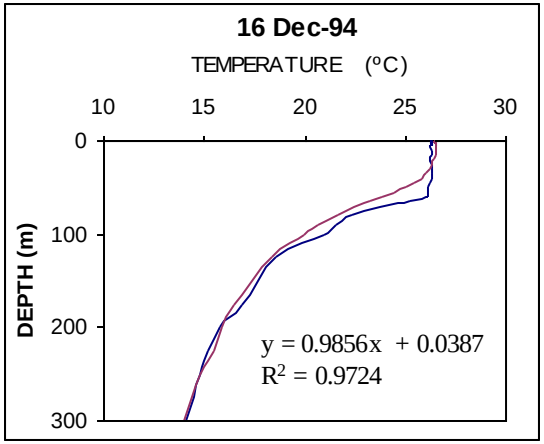
Comparison of in situ estimated and ANN predicted SSP at 27 depths

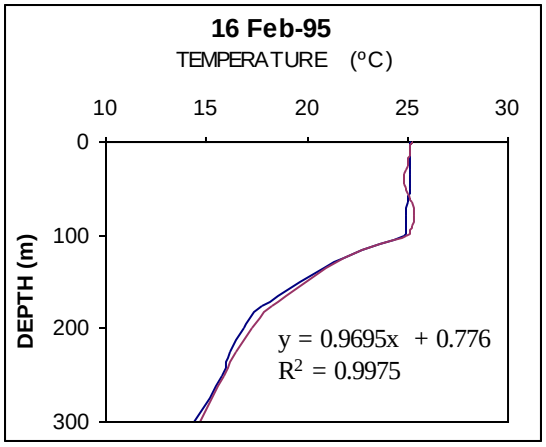


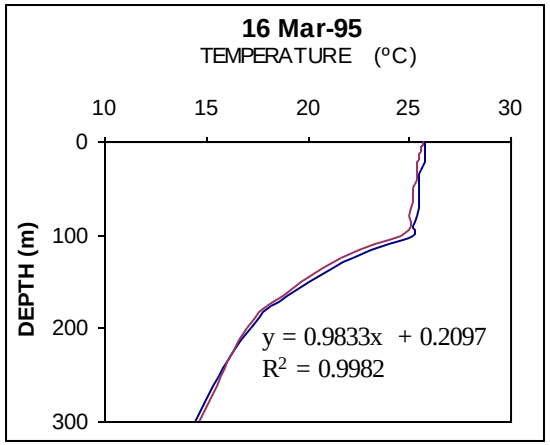
Courtesy: Jain et al., NRSC / ISRO

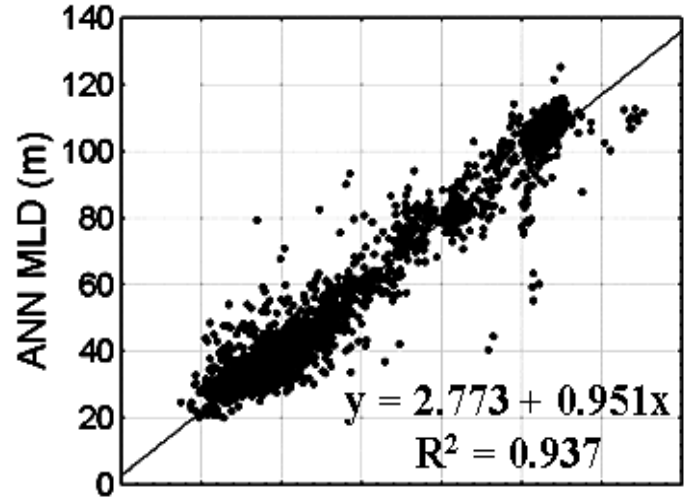
Estimation of Ocean Temperature Profiles & Mixed Layer Depth from Surface Parameters

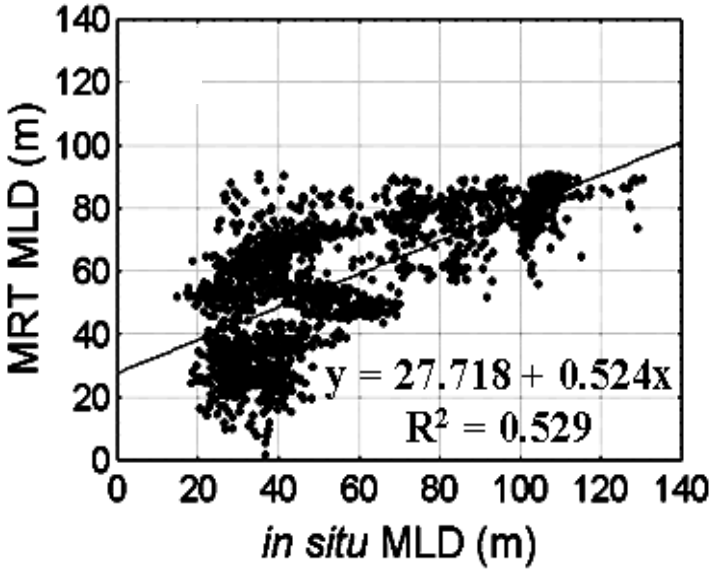












Blue colour : *in situ* observations
Purple colour : ANN Estimations

Source: ***Ali et al. (2004), GRL; Swain et al. (2006), JMR***

Estimation of Bathymetry using GEOSAT/ERS-1 Data

Under Sea Features:

- Seamount, knoll, abyssal plain, hill, trench

Bathymetry Estimation & Feature Classification

Applications:

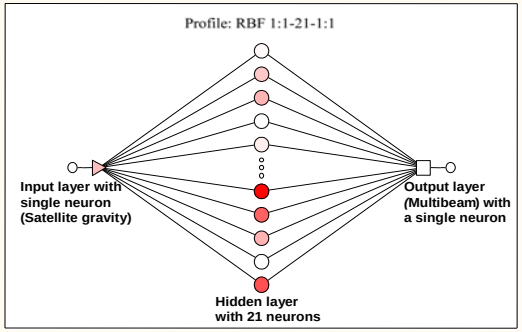
- Navigational safety, exploration and drilling of offshore oil/gas wells, pipeline/cable route planning
- Studies relating to understanding the physical, bio-geo-chemical processes of the ocean

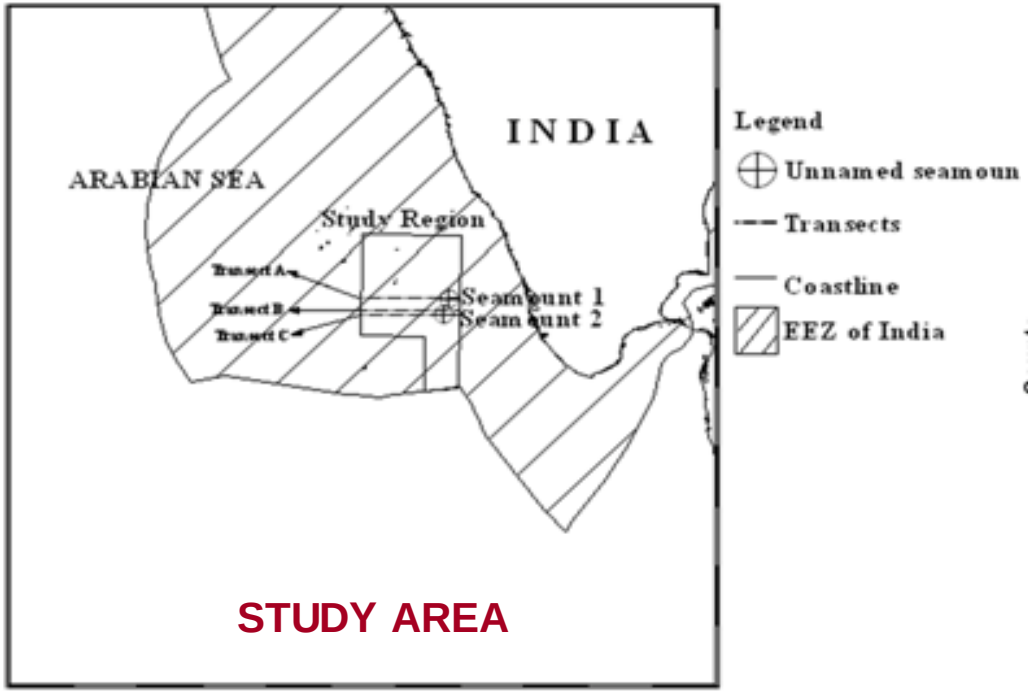
Estimation of bathymetry from gravity:

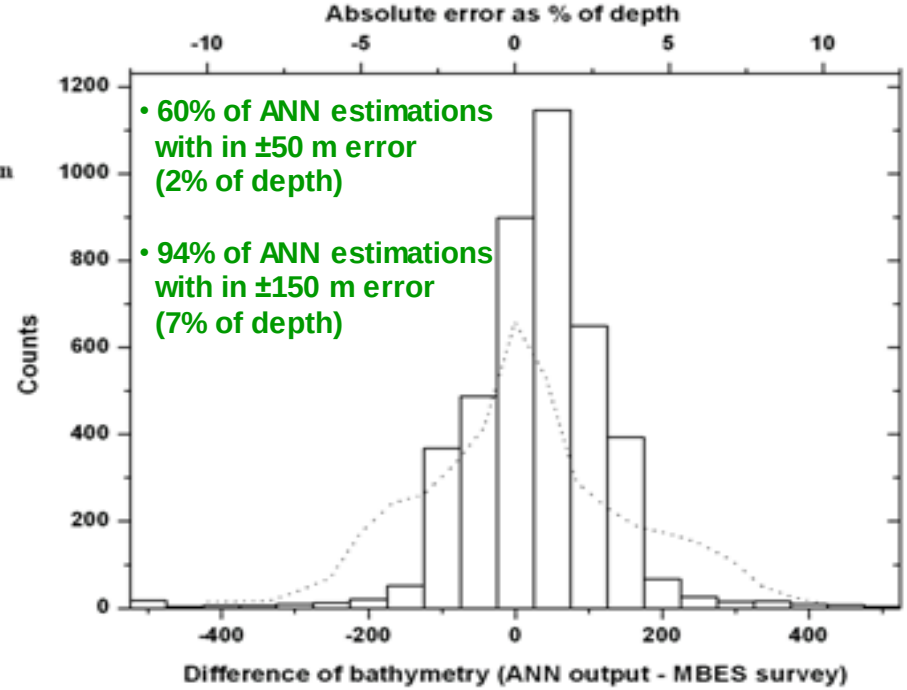
Indirect & a very complex approach (abrupt variations in topography/gravity ratios spatially, owing to factors like changes in sediment thickness and others)

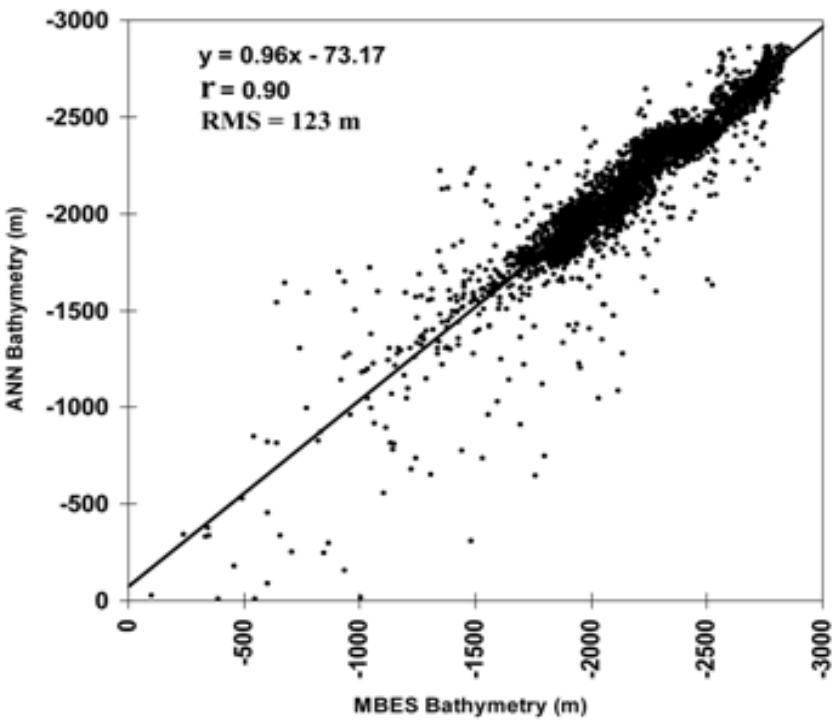
Approach: Artificial Neural Networks

- Input: Geosat/ERS-1 Gravity Anomaly
- Output: Multi-Beam Echo Sounder (MBES) Bathymetry



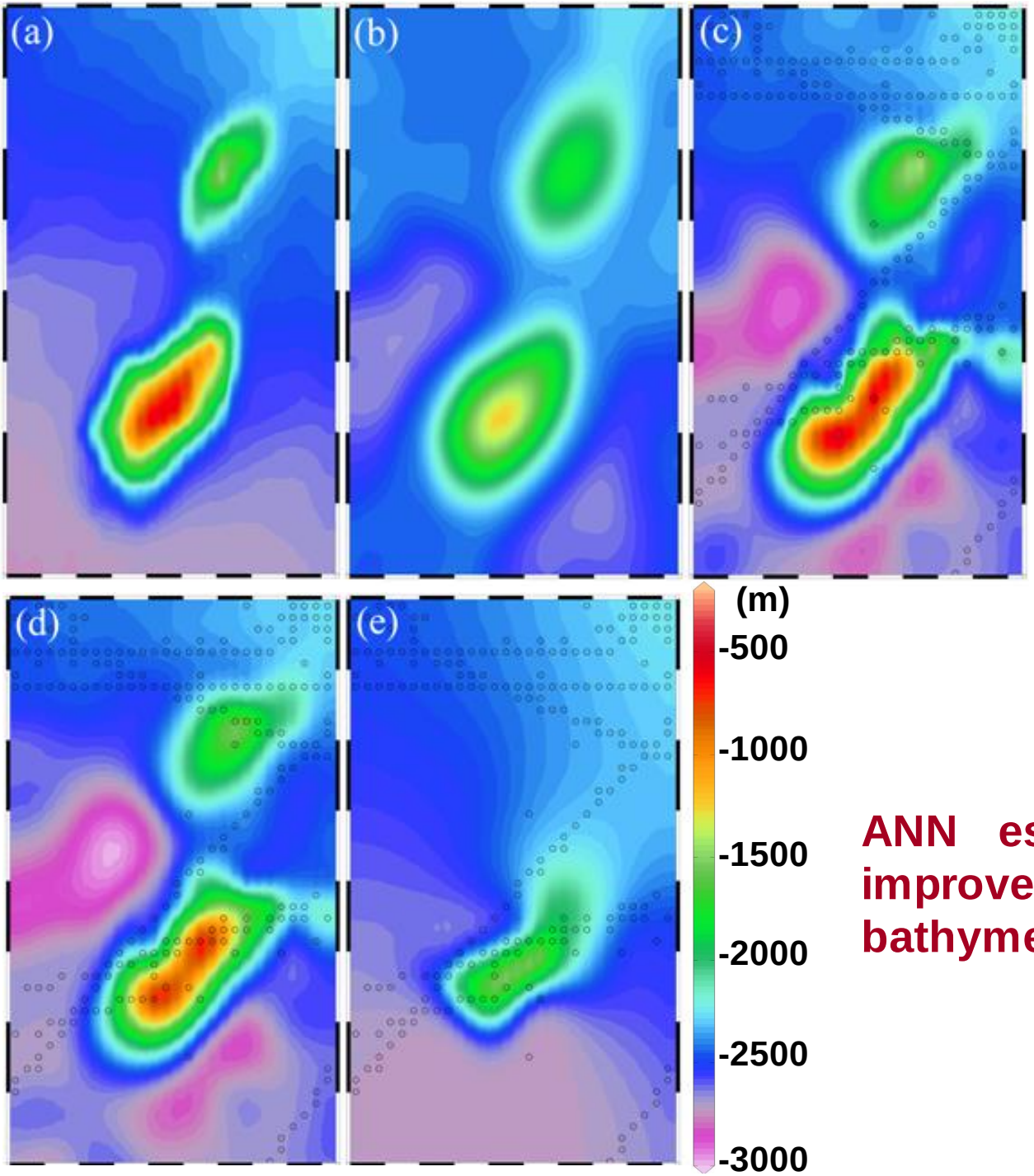






Validation

- MBES Bathymetry
- Model bathymetry products (1' Spatial Resolution):
  - (a) SS V13.1 (Smith and Sandwell, 1997)
  - (b) Earth Topography One Arc-Minute Global Relief Model (ETOPO1, 2009)
  - (c) General Bathymetric Charts of the Oceans (GEBCO V2.0, 2008)



BATHYMETRY IMAGES:

(a) MBES survey
(b) ANN Technique
(c) SS V13.1
(d) ETOPO1
(e) GEBCO V2.0

(circles represent ship tracks of SBES survey)

ANN estimated bathymetry is improved than the global model bathymetry products

Source: Jena et al. (2012), IJAEOG

Retrieval of Atmospheric Temperature profiles from INSAT-3D with improved Vertical Resolution

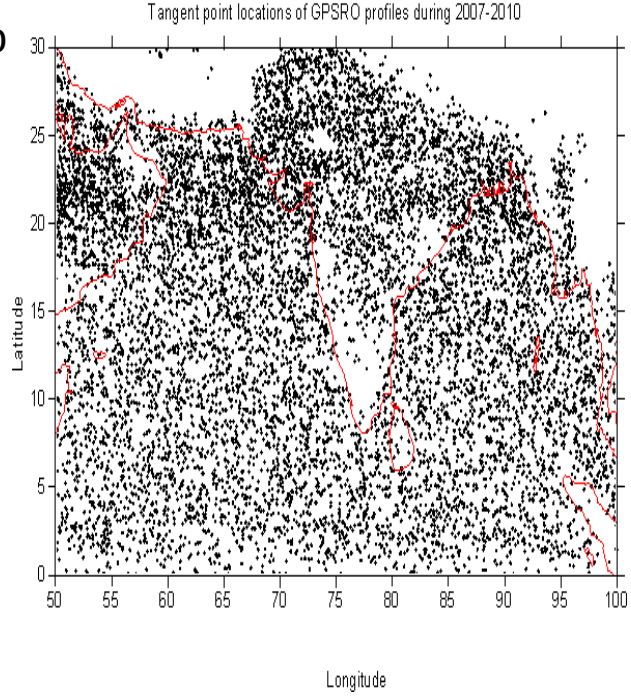
Data: High vertical resolution atmospheric temperature profiles; INSAT-3D IR Sounder observations (coarse vertical resolution, but high temporal and spatial coverage

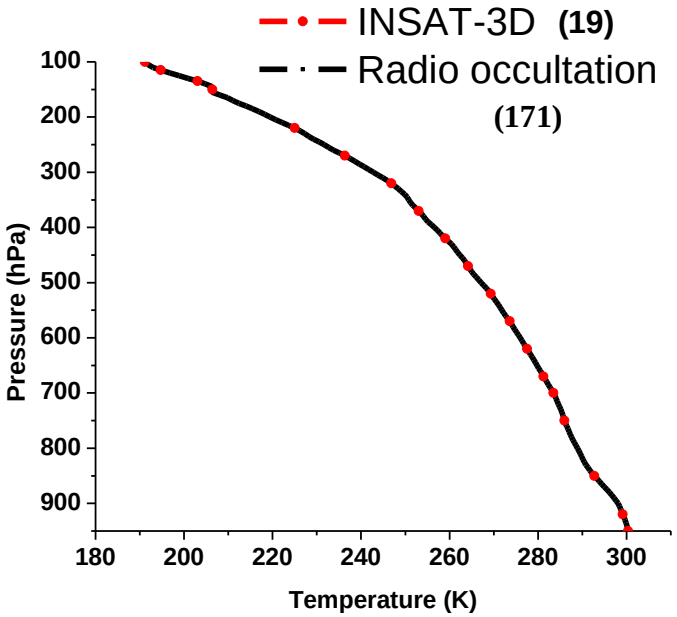
Available techniques:

- Radio Occultation observations: Limited spatial and temporal coverage but high vertical resolution (~200 m)
- Microwave Sounders: Estimate the temperature of thick layer (~10 Km).

Test data: COSMIC Radio occultation data (2007-2009)

Total profiles: 10,485
Training data set: 4112
Testing data set: 3331
Validation data set: 3042

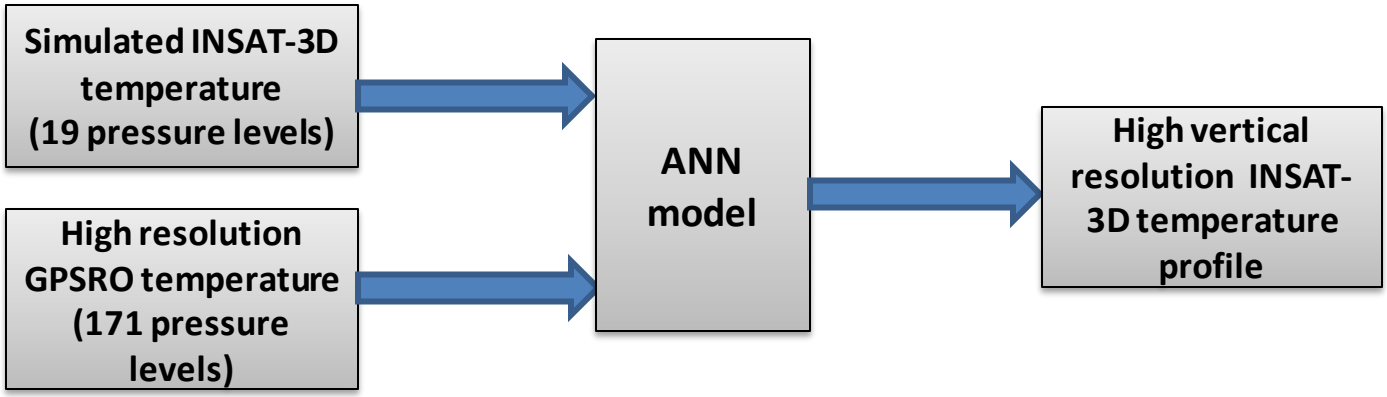




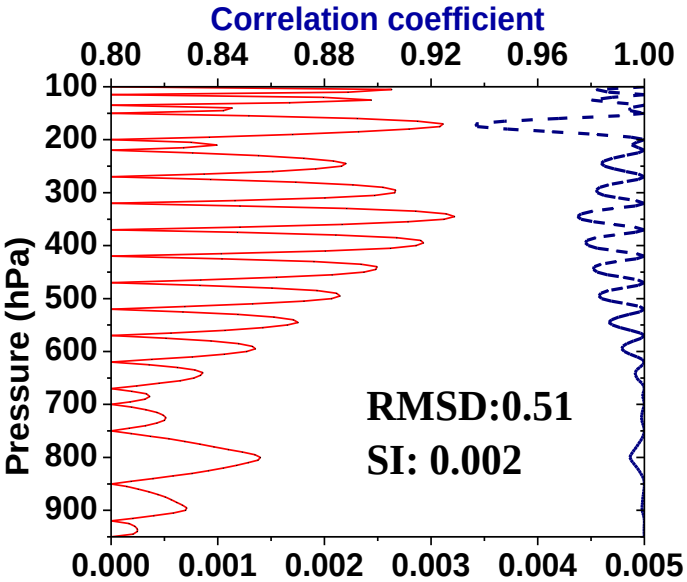
19 pressure levels of INSAT-3D ➡ 171 pressure levels (vertical resolution of 5hPa)

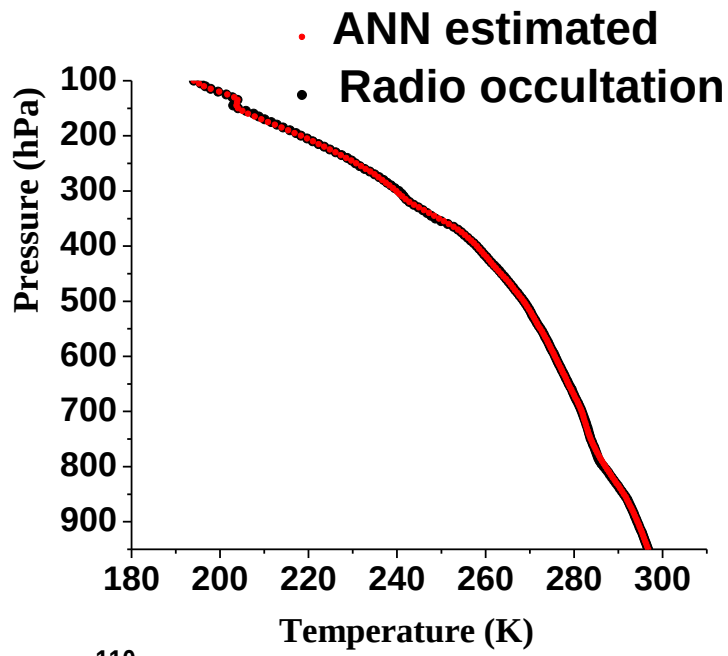
Technique Used: Empirical Approach (Artificial Neural Network)

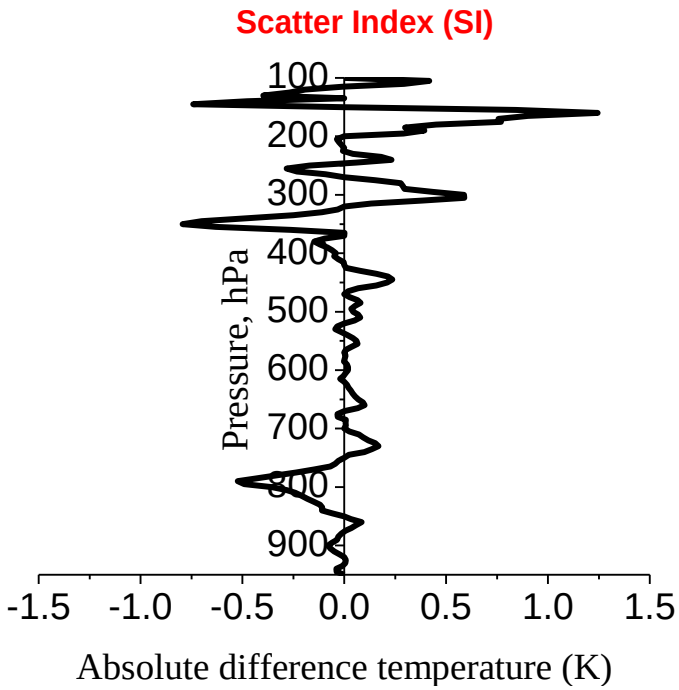
Single model for entire domain, all seasons

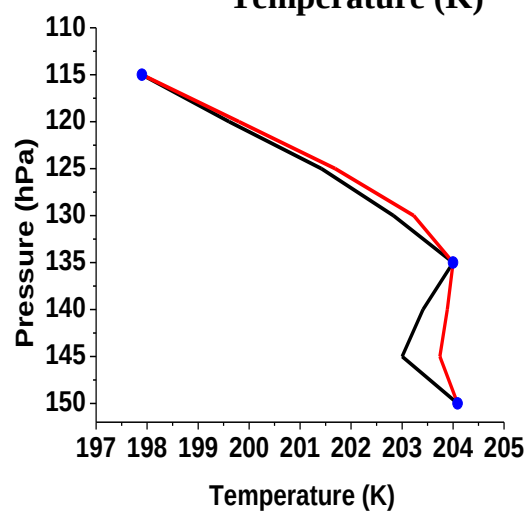


Statistics for validation data set









Courtesy: Sharma et al., NRSC & SAC/ISRO

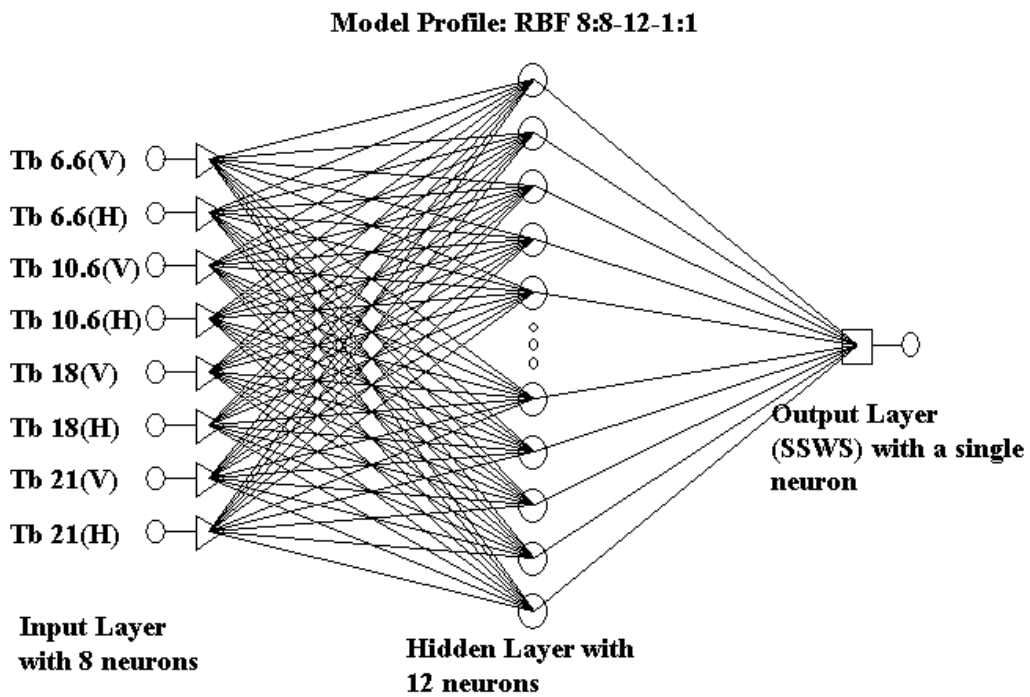
MSMR Wind Speed Retrieval using ANN

Inputs: MSMR brightness-temperature (T_B) in four channels (with dual polarizations)

Output: DS Buoy SSWS

Data Sets: collocated & concurrent observations

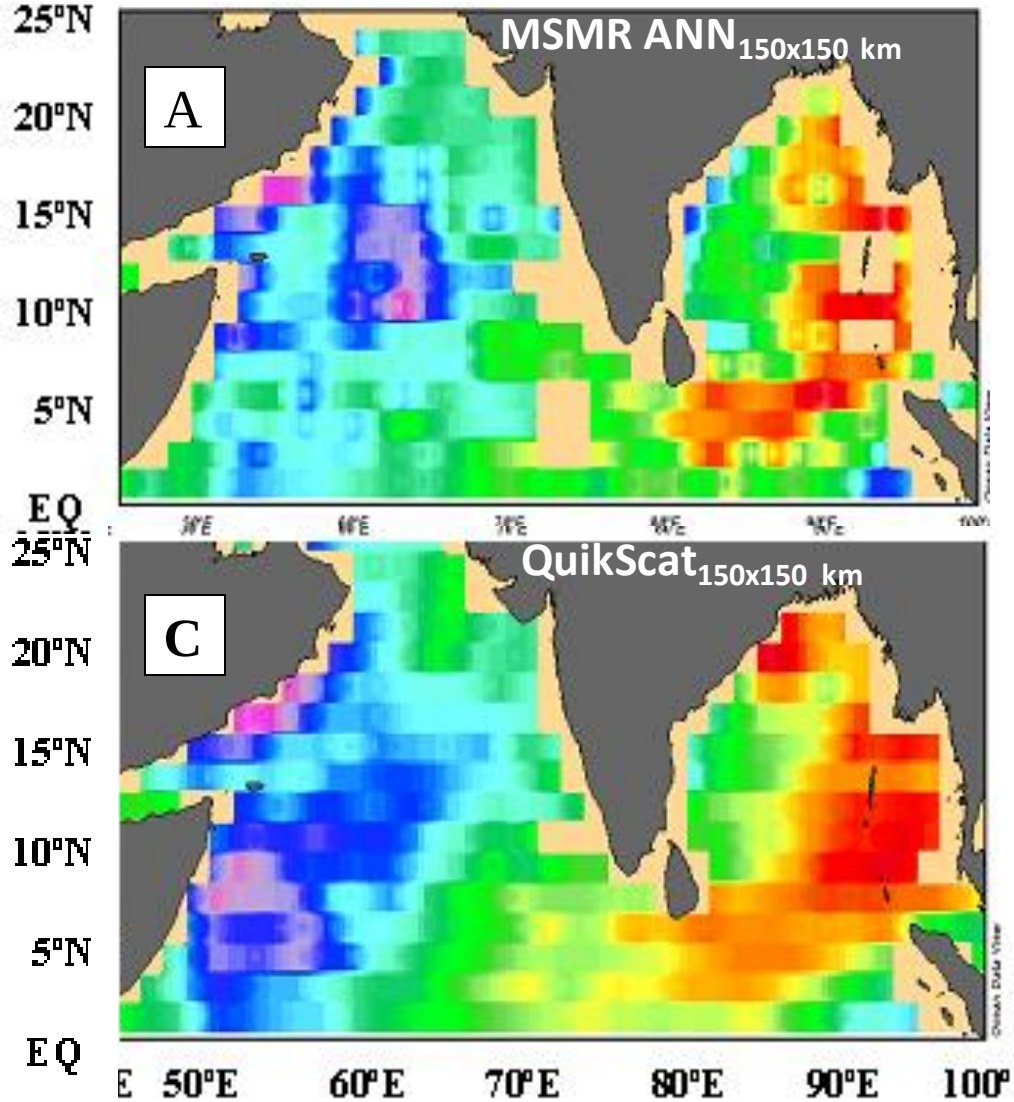
Training : 50%
Verification: 25%
Validation : 25%
(Random Selection)

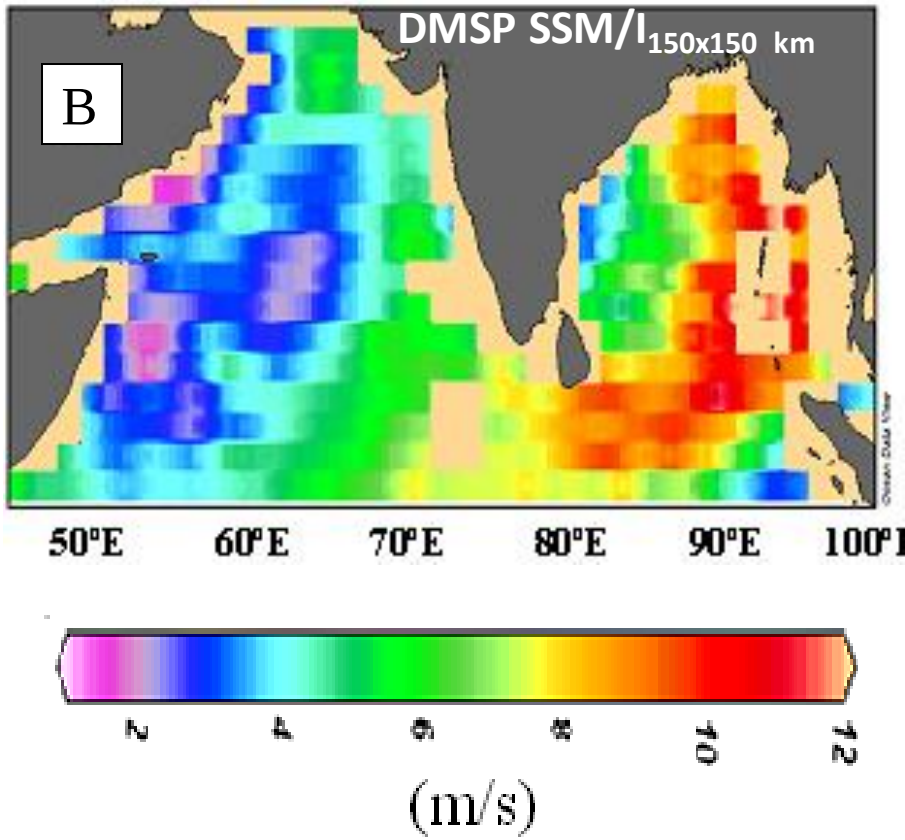


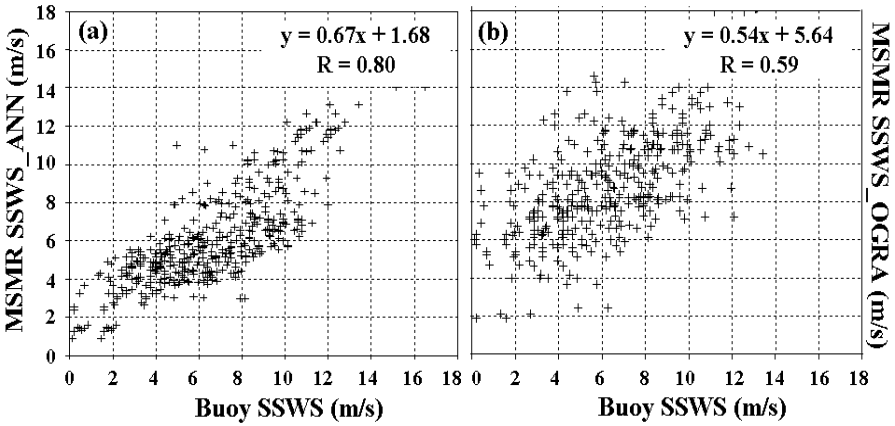
ANN: Radial Basis Function Model

PARA	RMSE	BIAS	±2 m/s	±4 m/s
ANN vs Buoy	1.8 m/s	-0.4 m/s	74%	~100%
OGRA vs Buoy	3.4 m/s	2.5 m/s	38%	73%

Wind Speed Estimation

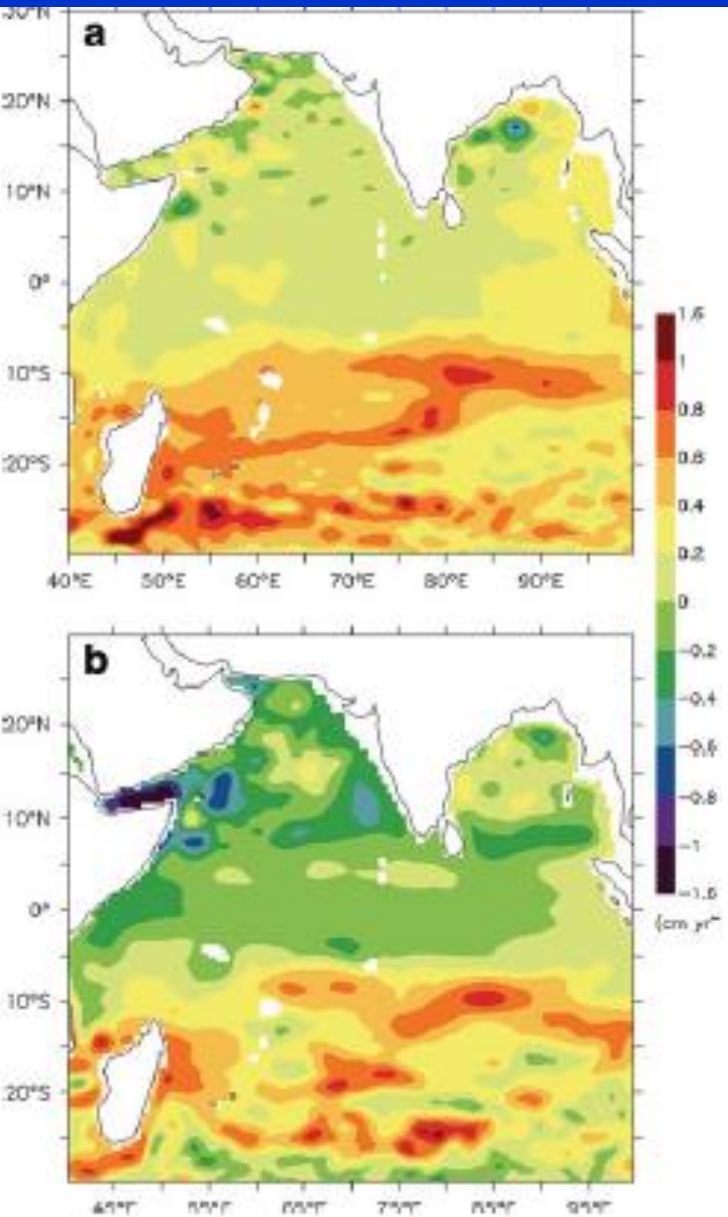




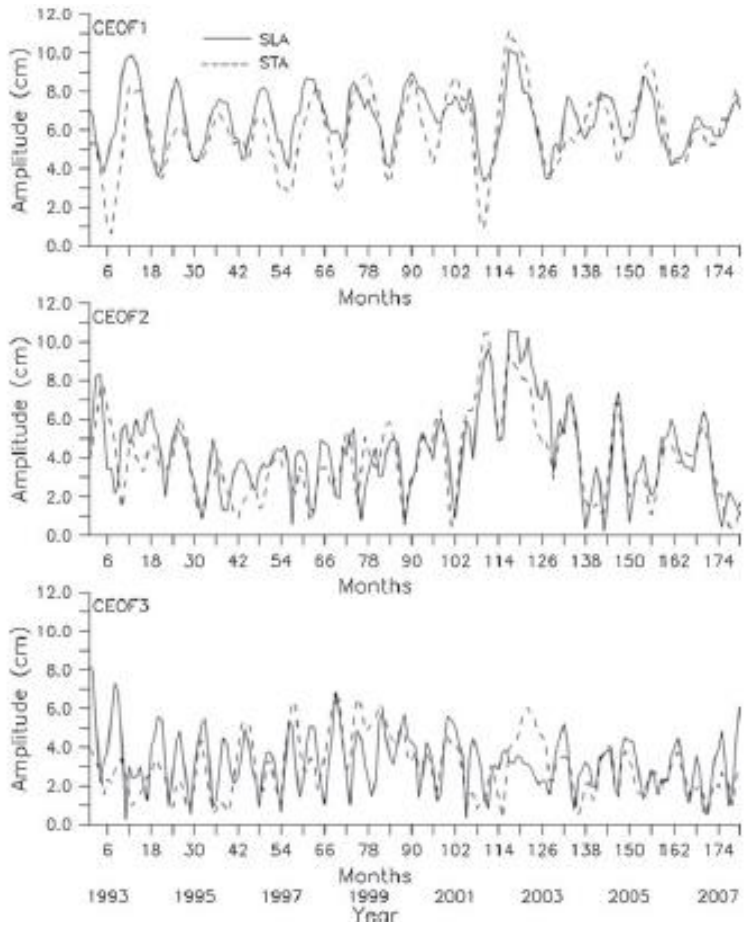


Source: ***Jena et al. (2010), IEEE-GRSL***

SSH Variability in the Tropical Indian Ocean from SODA Climatology using CEOF



Long term linear growth rate of (a) SLA and (b) STA in the Tropical Indian Ocean



First three temporal functions of CEOF modes of SLA and STA

Percentage contributions of the first five Complex-EOF modes of SLA and STA

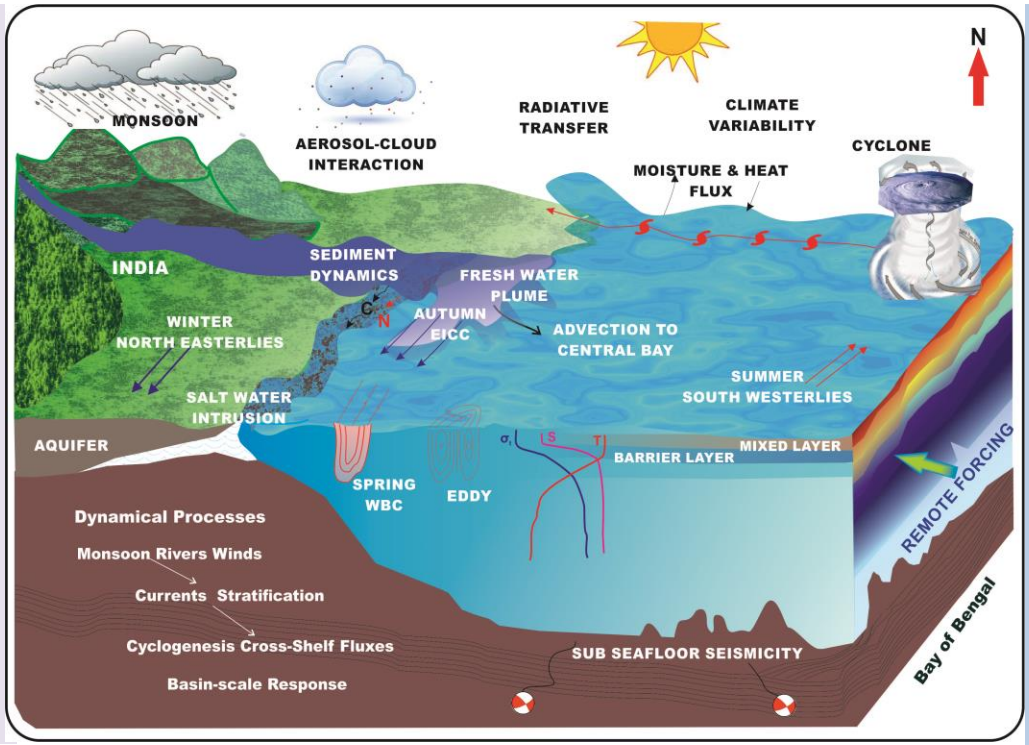
CEOF	SLA (%)	STA (%)
1	49.11	46.69
2	25.48	24.26
3	14.28	13.32
4	6.36	8.75
5	4.78	6.98

Source: Nayak et al. (2012), JISRS

Bay of Bengal Coastal Observatory

NATIONAL

- Indian National Centre for Ocean Information Services (INCOIS), Hyderabad
- National Institute of Ocean Technology (NIOT), Chennai



INTERNATIONAL

- Massachusetts Institute of Technology, Massachusetts (USA)
- University of Massachusetts, Dartmouth (USA)
- The University of Rhode Island (USA)
- Woods Hole Oceanographic Institution, Woods Hole (USA)
- University of Southampton, Southampton (UK)

A Joint Centre of

IIT Bhubaneswar and Ministry of Earth Sciences

Short-term and Long-term Thrust Areas

- Ocean Modeling and Predictions
- Air-Sea Interactions
- Cyclone Research
- Modeling of Seasonal, Sub-seasonal to Inter-annual climate variability
- Climate Change modeling
- Exploration Seismology and Ocean Floor Monitoring
- Storm Surge
- Ocean Biogeochemistry

- Fresh water balance
- Ocean Acidification and Ocean heat content in a changing climate
- Multi hazard Coastal and Social Vulnerability
- Hydrothermal Sulfide and Cobalt Crust Programme
- Ocean Engineering and Technology
- Deep Circulation Studies
- Deep Ocean Carbon Observations
- Geothermal Energy Resources
- Sea Level Rise
- Studies on Benthos

Seasonality of coastal current and its role on heat and salt transport along Odisha Coast

Objective: To obtain the seasonality of the ocean current structure using existing observations.

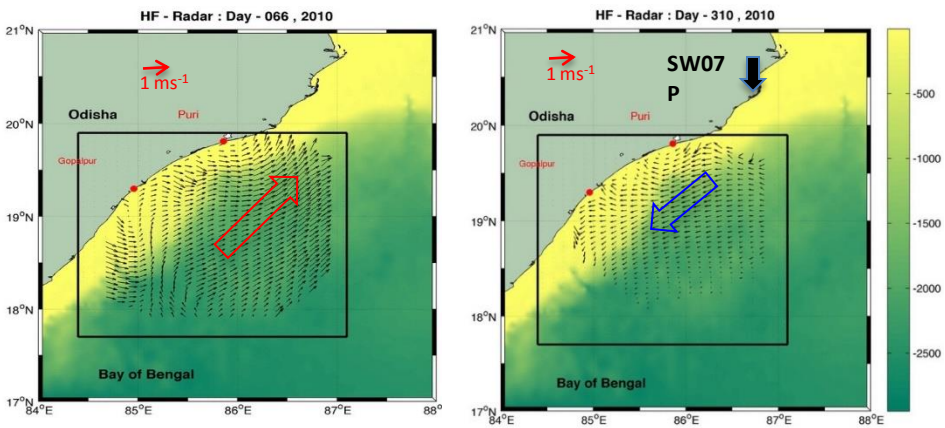


Figure A1: Reversal of Boundary Current from daily field: Northward from daily field is 1.8 m/s during March associated the Western Boundary Current and reverses during November with maximum value 1.2 m/s.

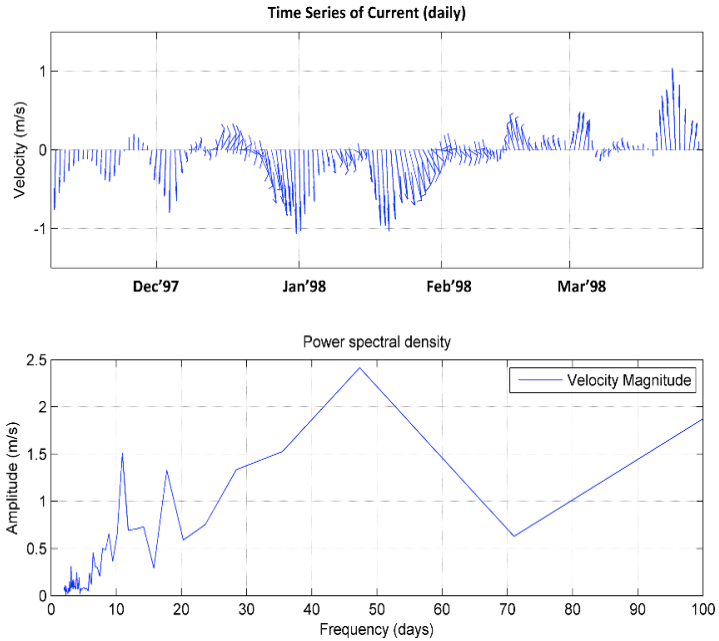


Figure A2: The power spectrum of the current at SW07P (20.192 °N, 86.702°E) near Paradip showed the maximum peak of amplitude close to 2.5 m/s at 48 days with other dominant peaks at 7, 12 and 18 days during November, 1997 to 31st March, 1998 .

Time series data of surface and subsurface current are to be collected near Puri, Odisha. Along with current data, the temperature and salinity will be collected as well to study the heat and salt transport along the Odisha coast associated with boundary currents.

Source: Sil et al.

Investigations of the Biogeochemical Processes in the Bay of Bengal

Objective

Understand the role of thermohaline variations on upper ocean dynamics in the Bay of Bengal (BoB)

Analyses in progress:

(a) Investigations on short-term variability of barrier layer thickness (BLT) in the Bay

Data: Temperature, salinity & depth profiles, met-ocean parameters during October 2013 – Spetmber 2014 (OMNI buoys)

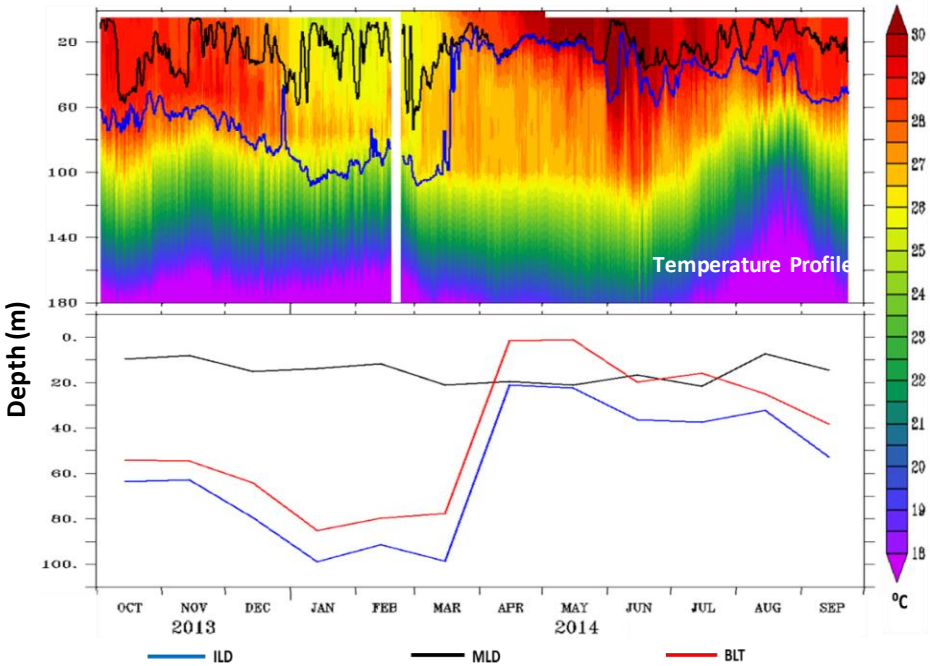


*Figure A: Seasonal Variability of Isothermal Layer Depth, Mixed Layer Depth & Barrier Layer Thickness for **BD09** (BoB)*

Observations:

- BLT maximum during January-2014 and minimum during April-2014.
- Seasonal build-up of warm water in the upper ocean during the summer period (April-May, 2014).
- Barrier Layer formed in summer monsoon continued to exist throughout the post monsoon season as well.

(b) Initiation of marine observations

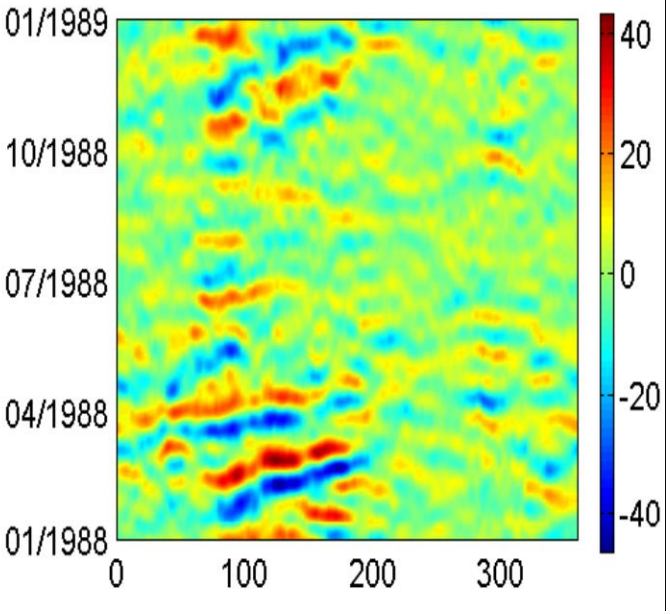
- Observations of temperature and salinity profiles in Lake Chilika.
- Regular observations planned for measurement of water quality as well as other physical parameters

Source: Swain et al.

Impact of air-sea interactions over Bay of Bengal on propagation of equatorial waves and intraseasonal oscillations

Data

- Satellite data : Outgoing longwave radiation
- Reanalysis: NCEP Reanalysis and ERA40
- IMD data: 1degree resolution precipitation and Cyclone intensity and track



Tools

- Two dimensional FFT analysis to identify equatorial waves and intraseasonal oscillations
- Two dimensional wavenumber frequency filtering to quantify different waves over time and longitude

Preliminary Results

- Convectively coupled equatorial waves and intraseasonal oscillations quantified over Bay
- Periods of intense MJO activity over the Bay identified and compared with phase of global MJO phenomena
- Work in progress

Relationship between MJO and cyclone activity over Bay of Bengal being studied

Source: Kiran et al.

Collaborative work between UMassD, MIT, WHOI, INCOIS and IITBBS

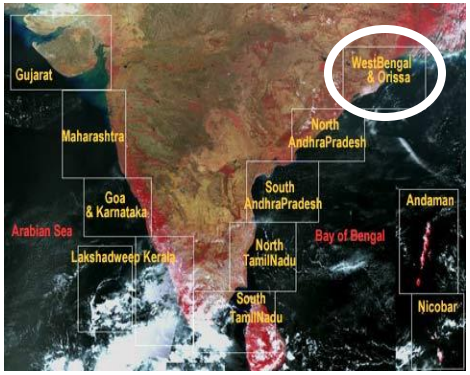
Coastal Ocean Sensing and Forecasting for Fisheries Management: Practical Systems for India

Proposed System

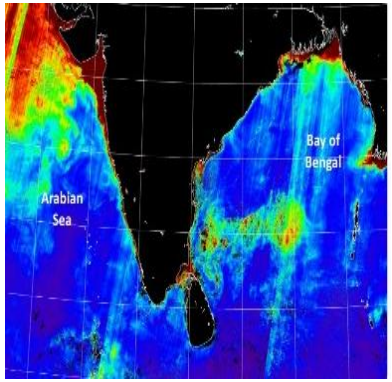
Numerical model with uncertainty quantification (DO-PE)
Dynamically Orthogonal-Primitive equation

Data
Remote sensing, buoys etc. (GMM-DO)
Gaussian Mixture Models –Dynamically Orthogonal

Improved Potential Fishing Zone (PFZ) advisory



The 12 fishing zones in India [Source: INCOIS]



Sample Chlorophyll map from Oceansat-2 [Source: NRSC/ISRO]

Hilsa Fishing

Potential Impacts

- Greater catch per unit effort for fishermen
- Better sustainable fisheries management, monitoring, financial hedging, and re-insurance.
- Reduce poverty and improve the social conditions of disadvantaged workers in the large unorganized fisheries sector in India.

Source: Avijit, UMassD

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- Esteemed Audience (Participants)

Thank You