Coupled data assimilation:

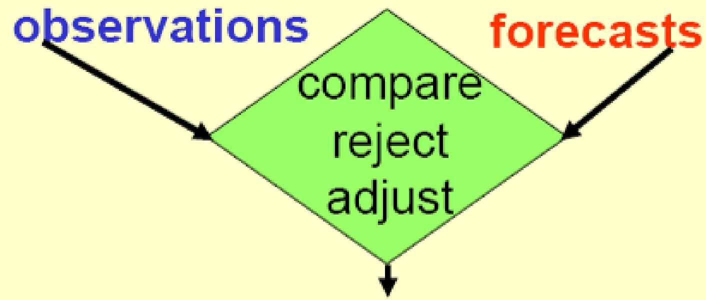
for oceanography work over South Africa’s shelf

Observations are drawn into a coupled model by data assimilation:
ocean, land, atmosphere

- < 10% of observations are in-situ, the rest come from satellite.
- Operational products use past observations, whereas reanalysis products use near-future and late-arriving data.
- Ocean & land assimilation have a generous multi-day time window, but atmospheric assimilation has a narrow cut-off (few hours).
- Observations have ‘influence’ according to the type, accuracy & reliability, eg. in-situ above remote, calibrated above unknown.
- At a model grid-point, the observations affect the interpolated value according to proximity.
- Incoming data are constrained to model physics, climatology, persistence & prior forecast.

Data assimilation is the technique whereby observational data are combined with output from a numerical model to produce an optimal estimate of the evolving state of the system.

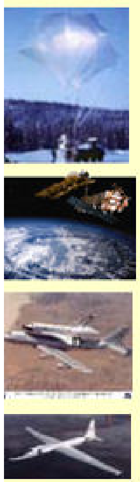
The Data Assimilation Process



estimates of state & parameters

errors in obs. & forecasts

Why We Need Data Assimilation



- range of observations
- range of techniques
- different errors
- data gaps
- quantities not measured
- quantities linked

Methods of Data Assimilation

- Optimal interpolation (or approx. to it)
- 3D variational method (3DVar)
- 4D variational method (4DVar)
- Kalman filter (with approximations)

Types of Data Assimilation

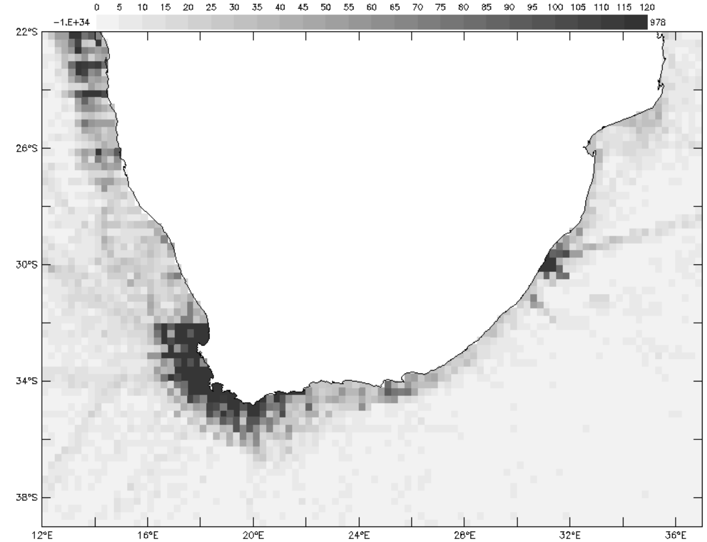
- Intermittent
- Continous

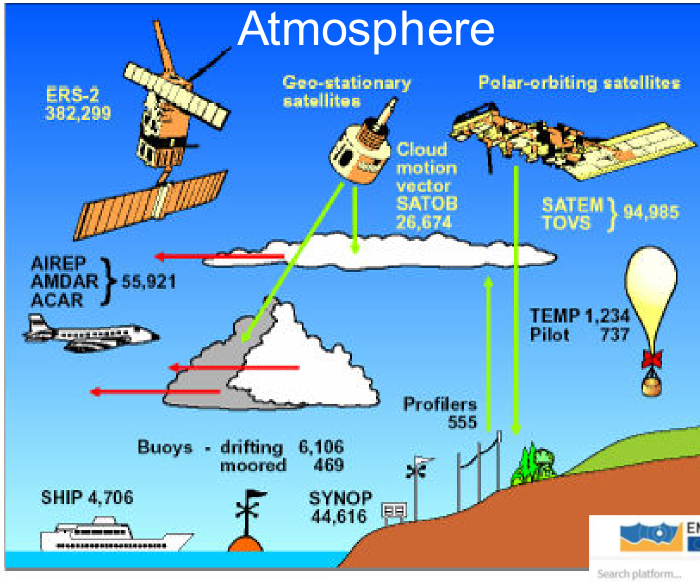
Key data streams

- Surface in-situ measurements: ship, buoy
- Sub-surface observations: float, XBT
- Satellite remote sensing:
  - De-clouded visible & infrared
  - Passive microwave (wide swath)
  - Active microwave (narrow swath)

Model forecast, climatology, persistence
  - Forcing from atmosphere and land models
  - Theoretical calculations by ocean model

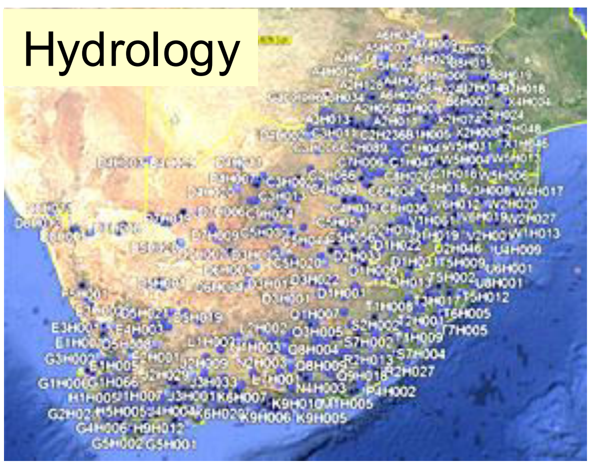
Near-surface temp obs density

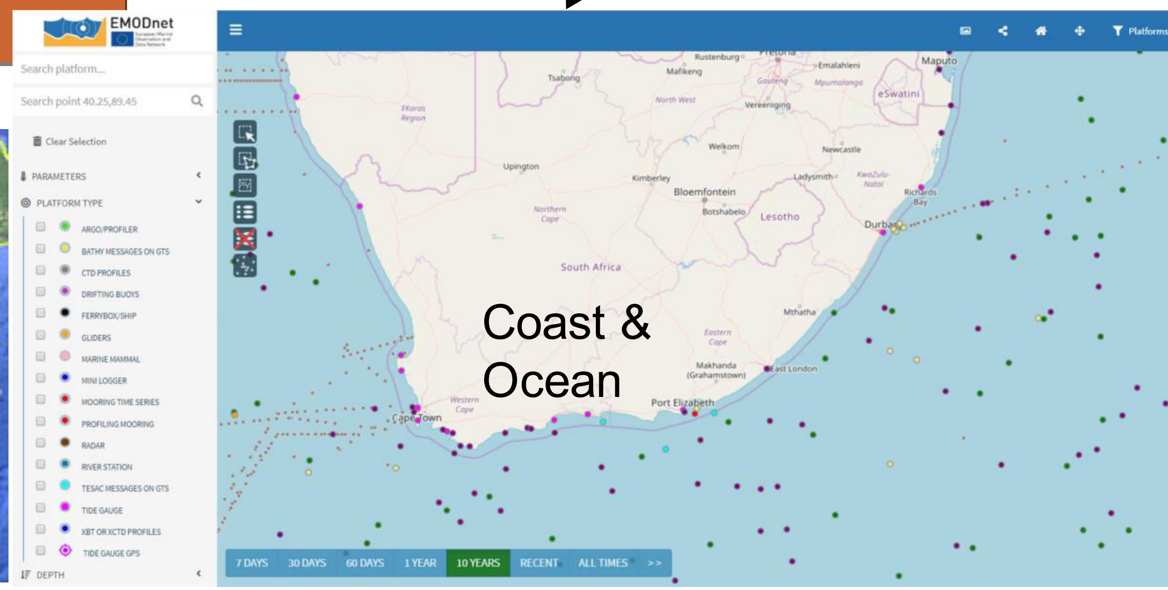




Argo/Profiler : 3830
Gliders : 3
Drift : 1661
Mooring : 998
Ferrybox : 79
Radar : 150
Bathy messages on GTS : 13
CTD profiles : 352
Mini logger : 4
River flows : 173
Profiling mooring : 1
Marine mammal : 90
TESAC : 0
XBT or XCTD profiles : 0
Tide Gauge : 781

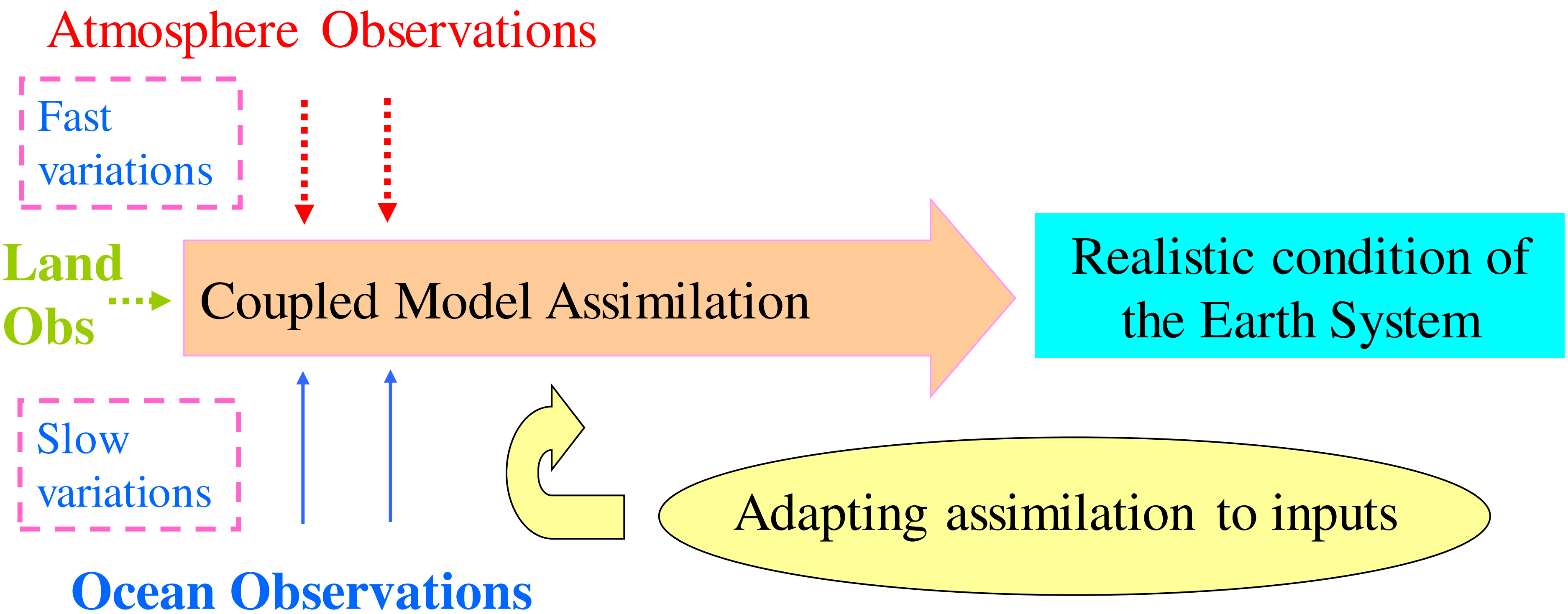
Globally
Locally





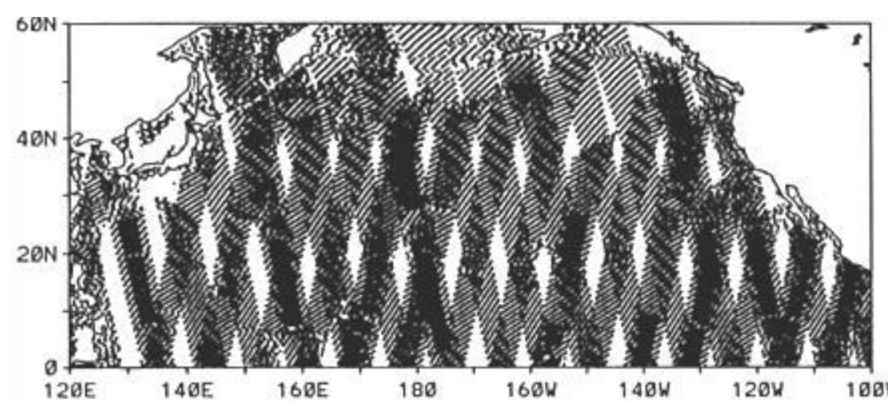
https://www.godae-oceanview.org/science/ocean-forecasting-systems/assimilation-characteristics/
http://www.marineinsitu.eu/dashboard/ http://www.emodnet-physics.eu/Map/
https://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring-observing-system#Ocean

Coupled Data Assimilation

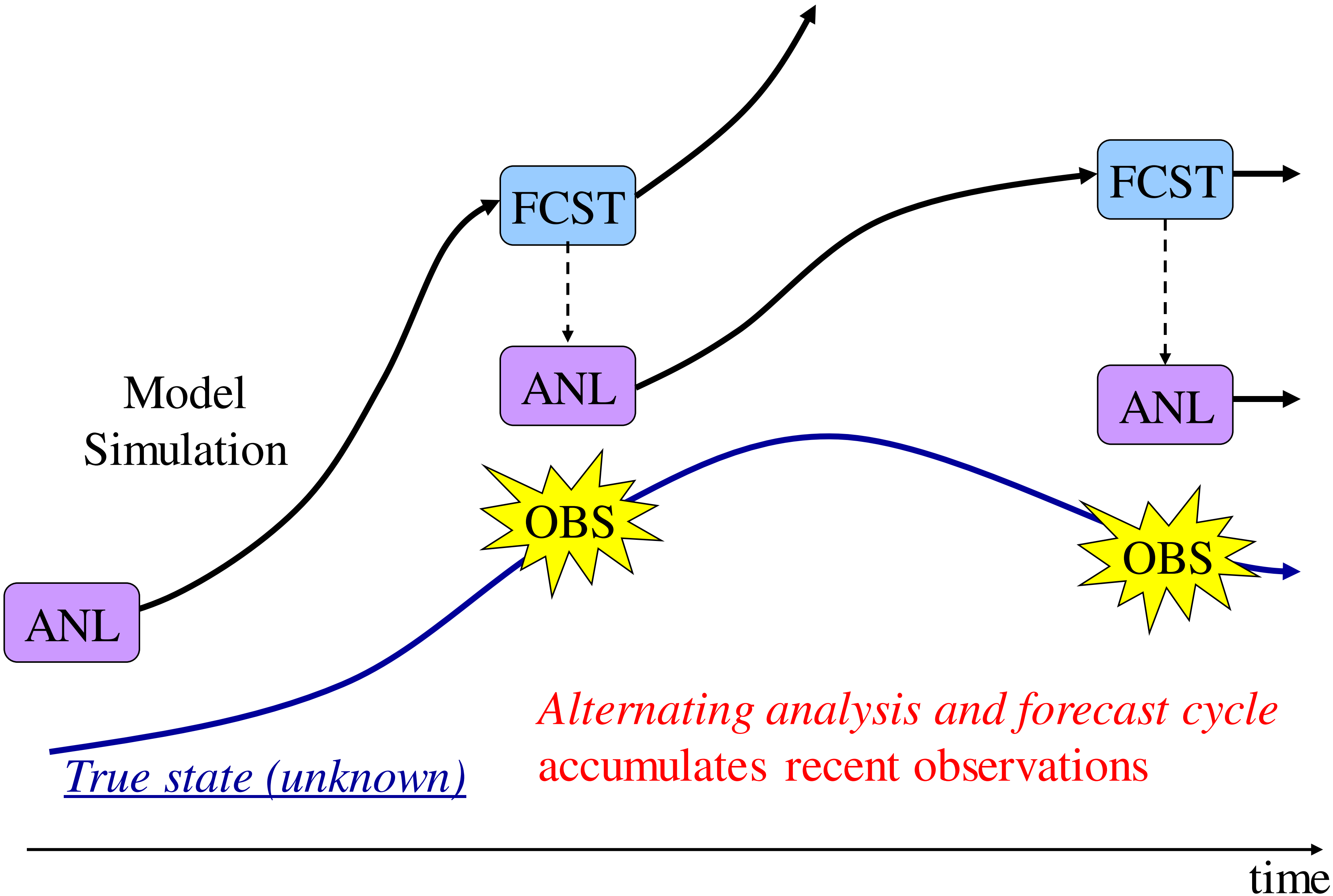


Multi-day coverage by active MW radiometers that provide wind fields for evaporation and Ekman transport

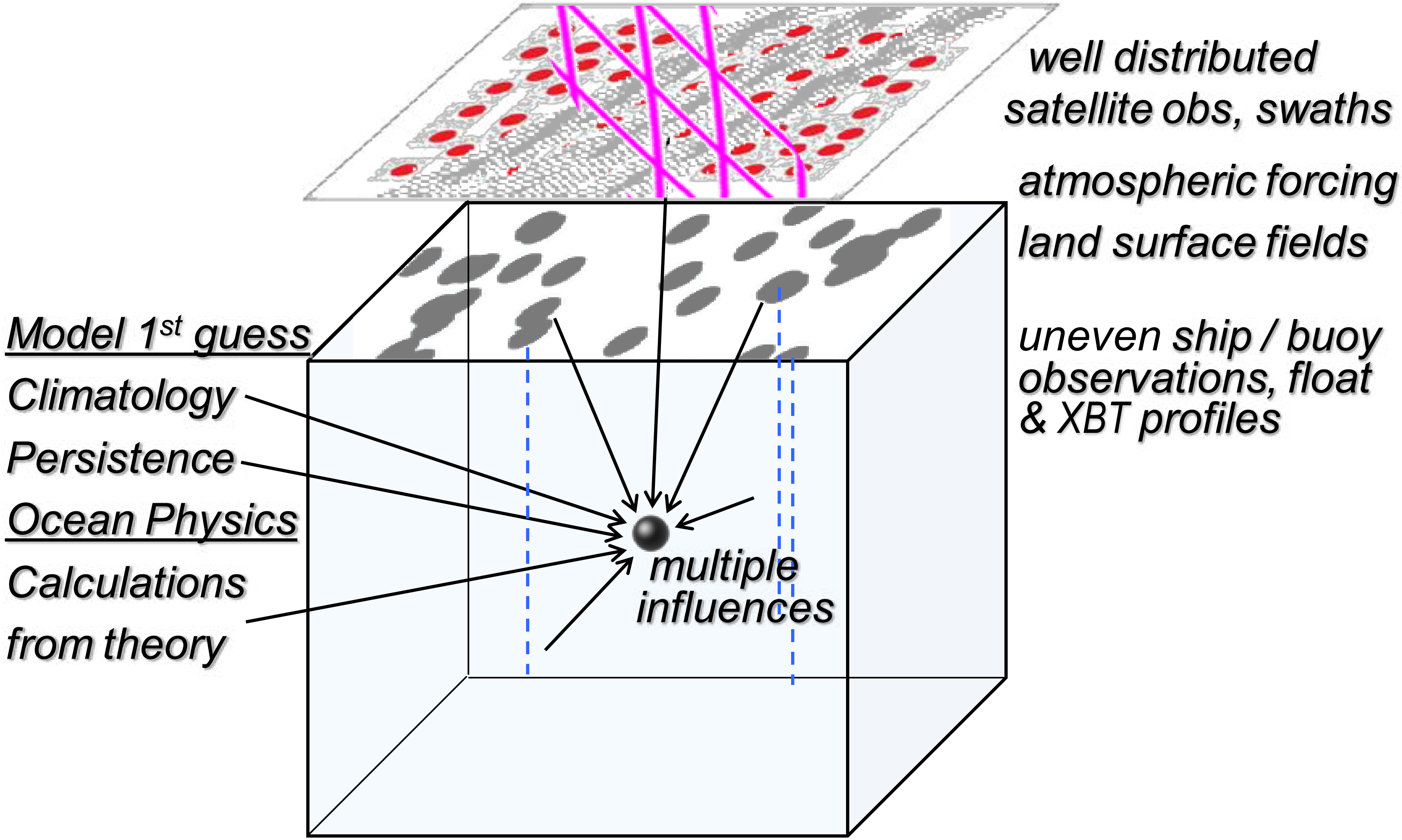
Remember that land-based wind data are <u>not</u> assimilated due to ‘exposure’.



Coupled data assimilation

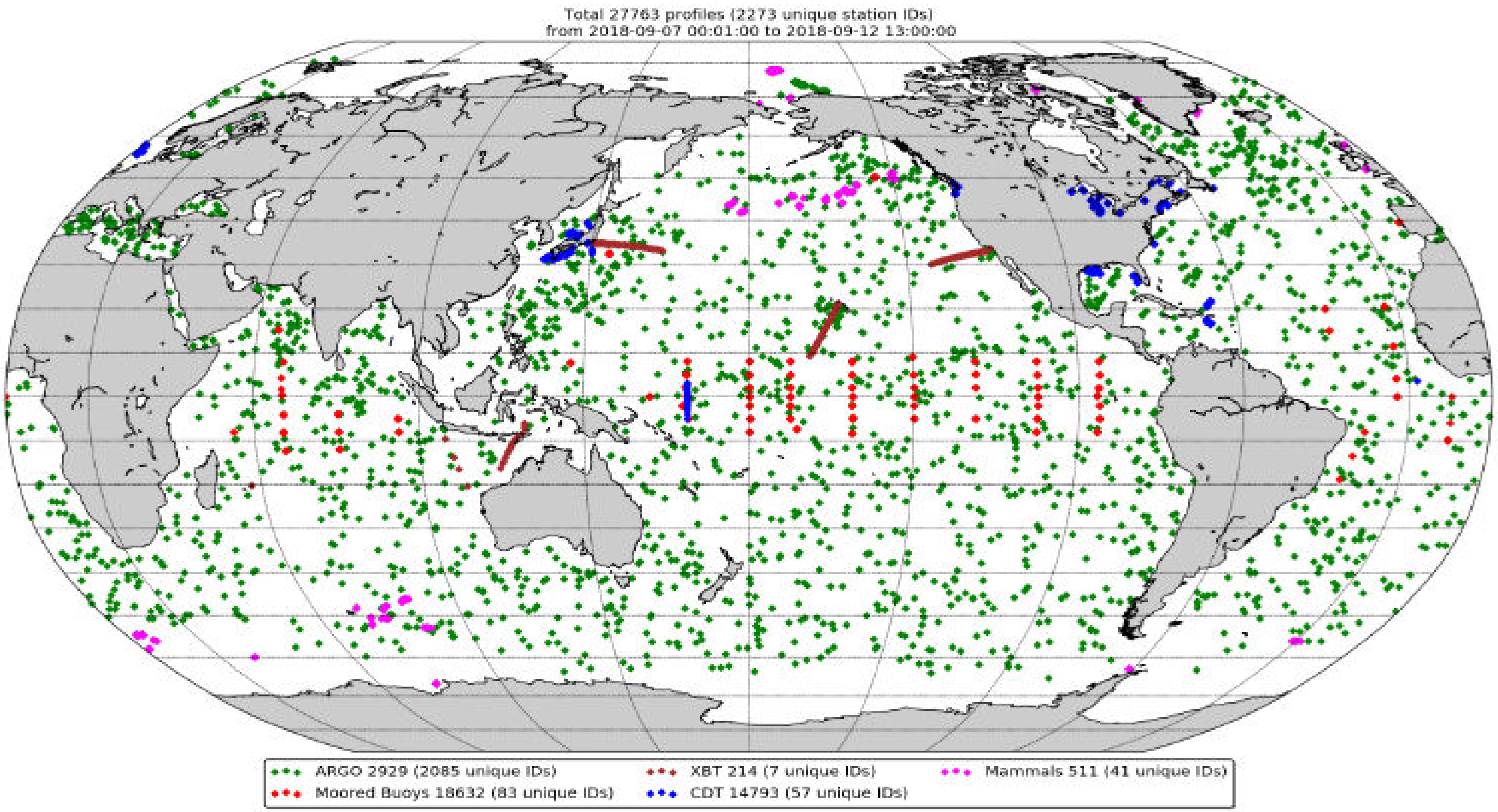


Ocean model data interpolation



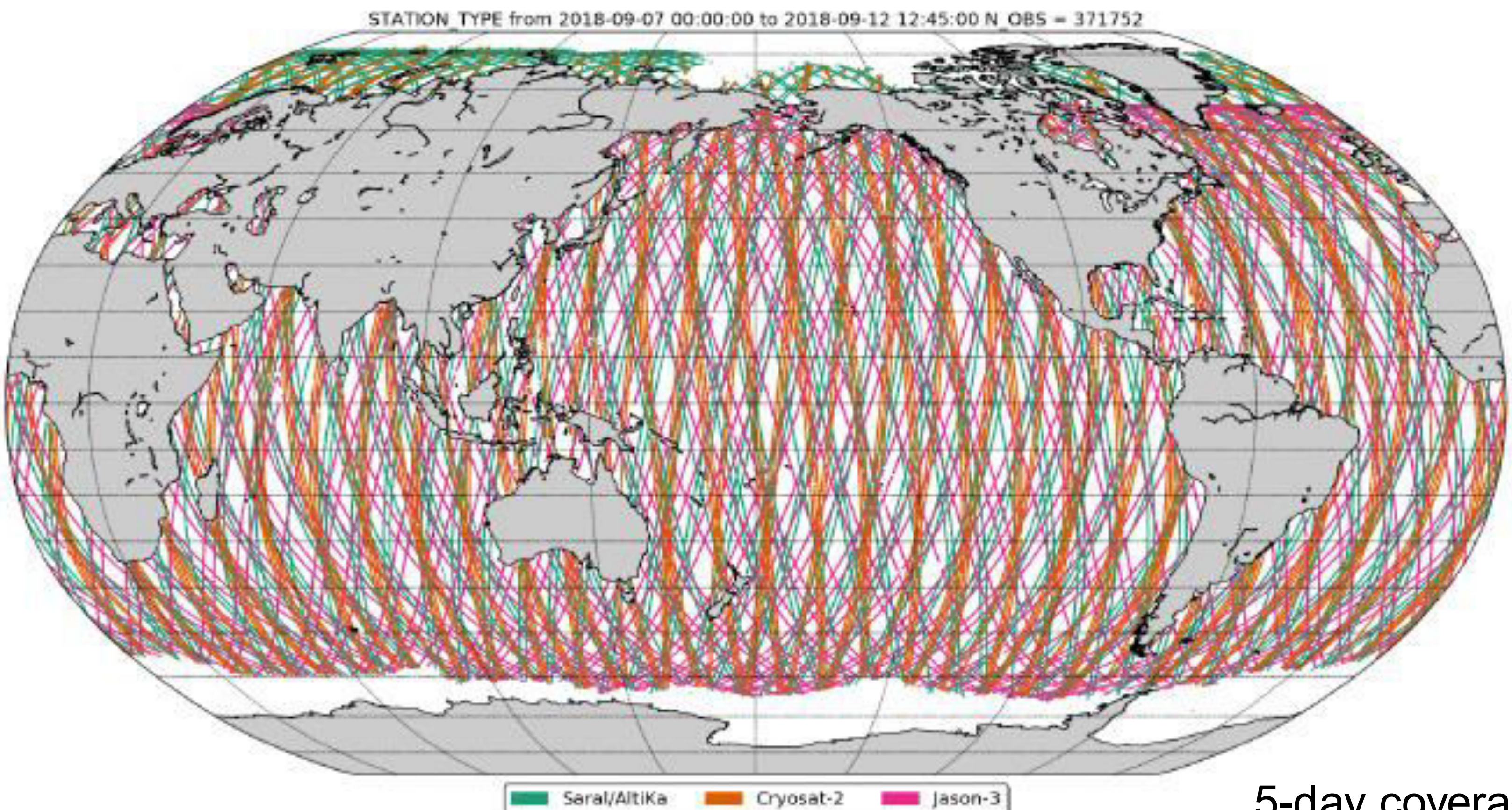
Measurements at earlier (or later) times have less influence than recent

Ocean observing system



Floats, buoys, ships, and other in-situ obs

Satellite altimeter obs of geoid-corrected sea surface height anomaly



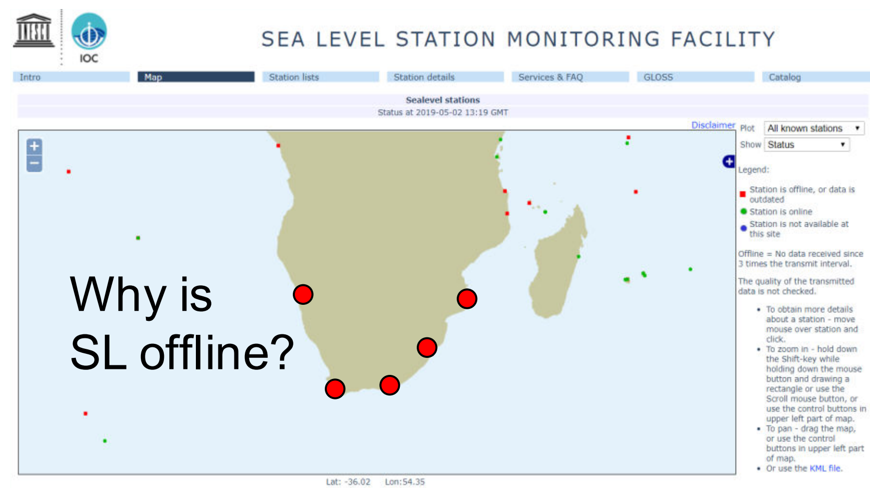
5-day coverage

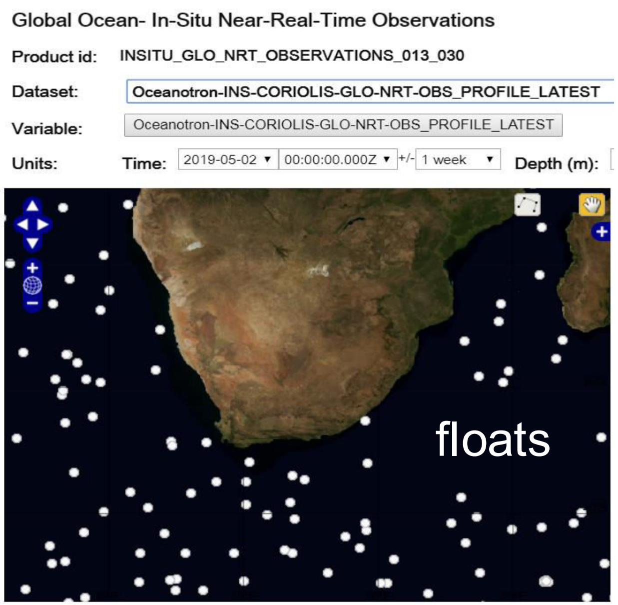
SA involvement in real-time ocean monitoring is limited

- Weather reports from station / ship
- Global profiling by floats and aircraft

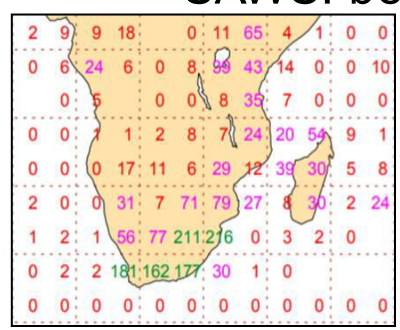
but

- No marine stations (buoys) reporting
- Harbours tide gauges are ‘quiet’

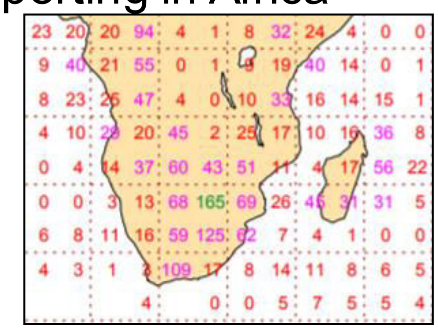




SAWS: best reporting in Africa



surface

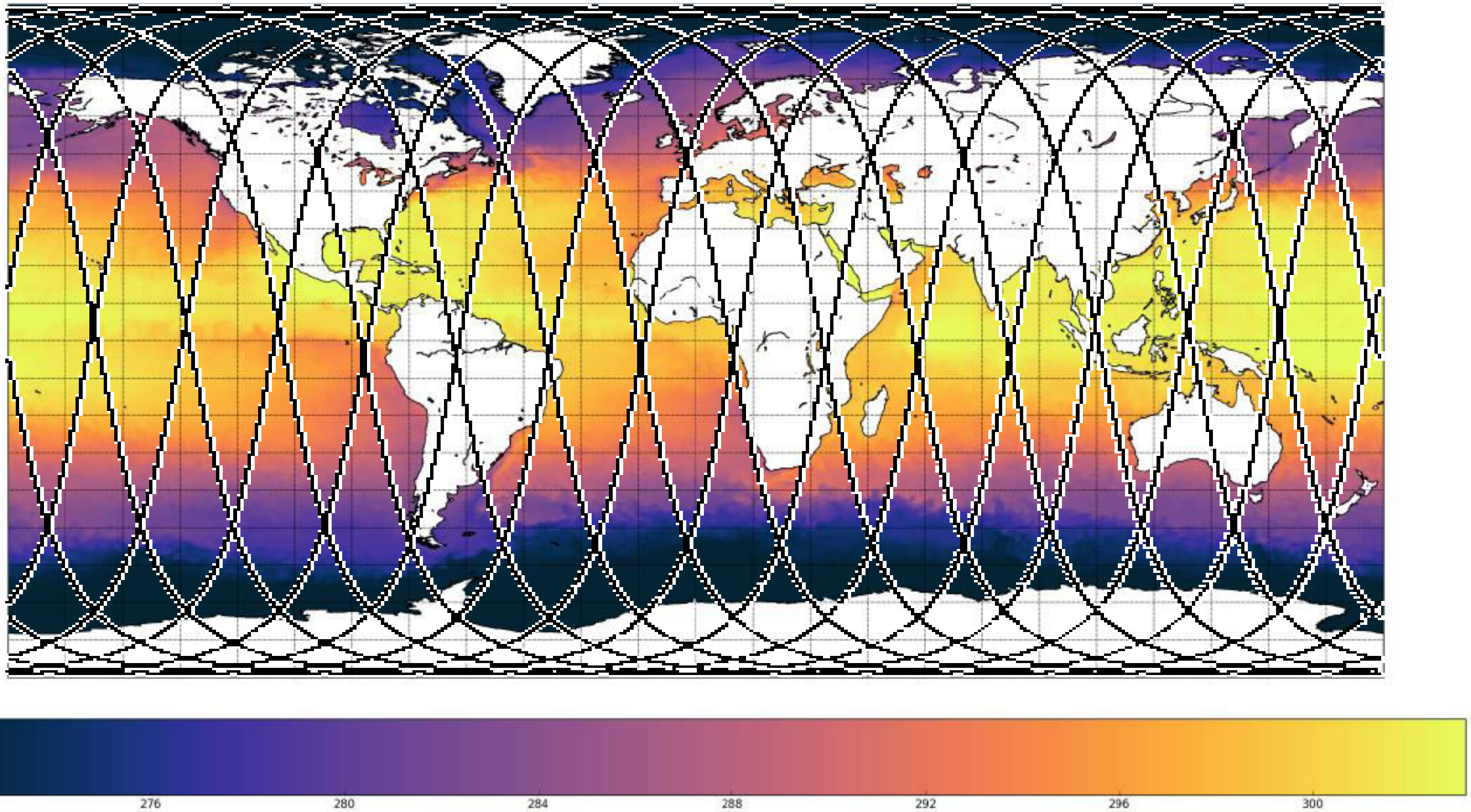


aircraft

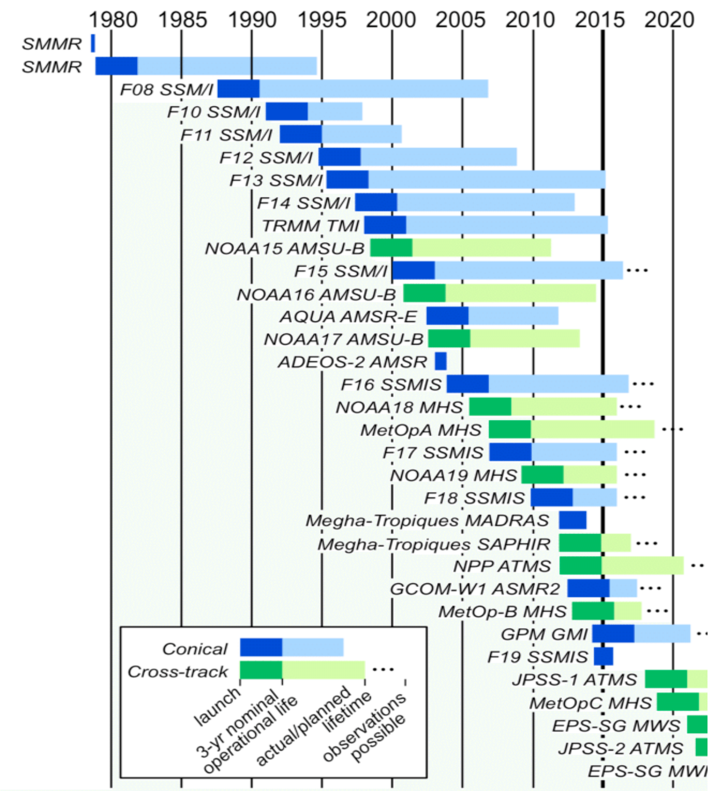
The SA marine science community is skeptical of ocean reanalysis; users do not feel confident in their outcomes, so operational research has limited influence.

SST from IR+MW satellite with insitu-calibration, after de-clouding over multi-day window

Latest L4 sea-surface temperature observations from OSTIA (20180912)

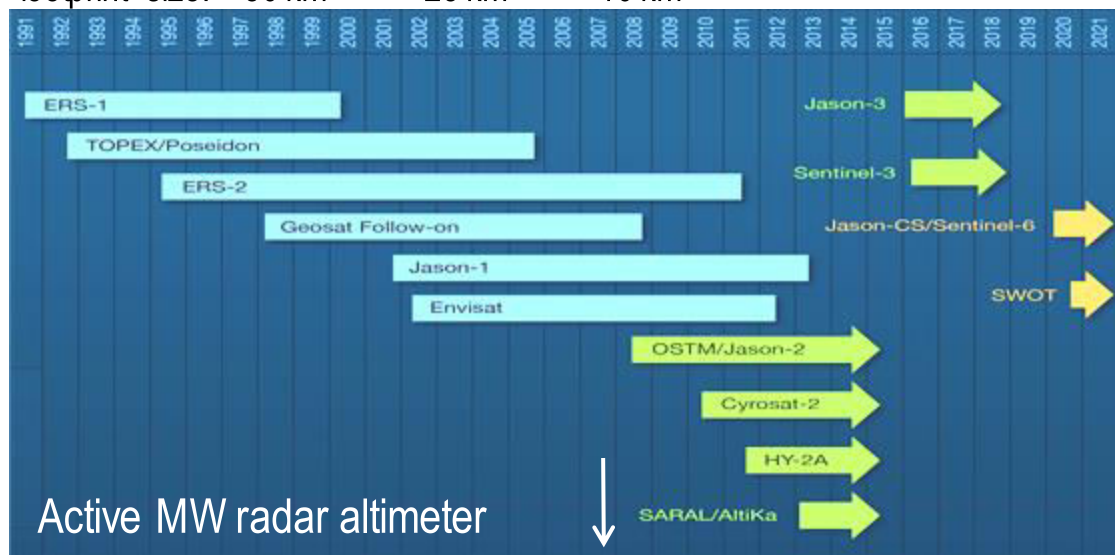


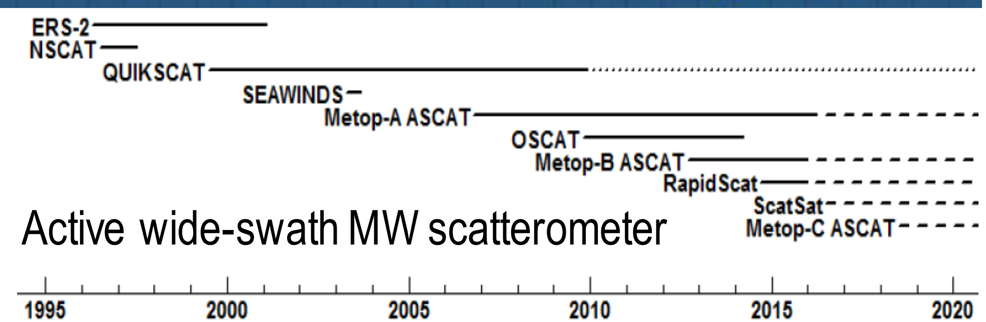
Overlapping satellite missions to collect essential data



Passive wide-swath MW radiometer

'footprint' size: 50 km ⟶ 25 km ⟶ 10 km





Ocean reanalysis products have improving technology, and resolve the coastal gradient after 2008, with the advent of higher resolution radiometers

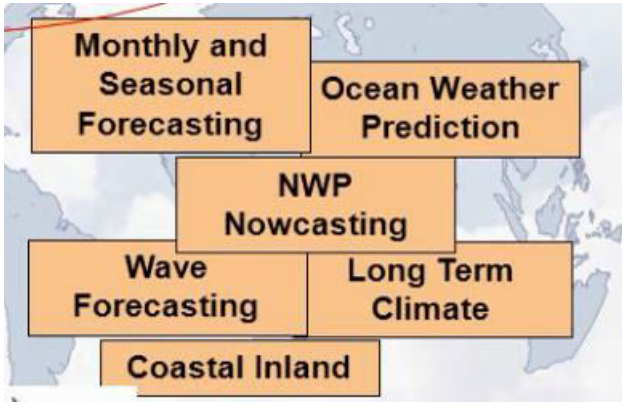
Satellite vs reanalysis

- Individual satellites have orbital limitations and aging radiometers.
- Satellite 'level-3' products are corrected for radiometer drift, atmospheric contamination (reflection, scattering, absorption), coastal contamination by land fraction within radiometer footprint.
- Level-3 products are interpolated to a grid after correction, and usually represent composites of multiple images within a sliding time window.
- SST reanalysis products blend IR and MW products, to reduce contamination: eg. GHR-MUR Level-4 since 2002.
- Ocean reanalysis uses multiple level-3 satellite products from NASA, ESA, etc, in addition to in-situ & ancillary data, model physics & recent meaurements.
- Why use single satellite products?

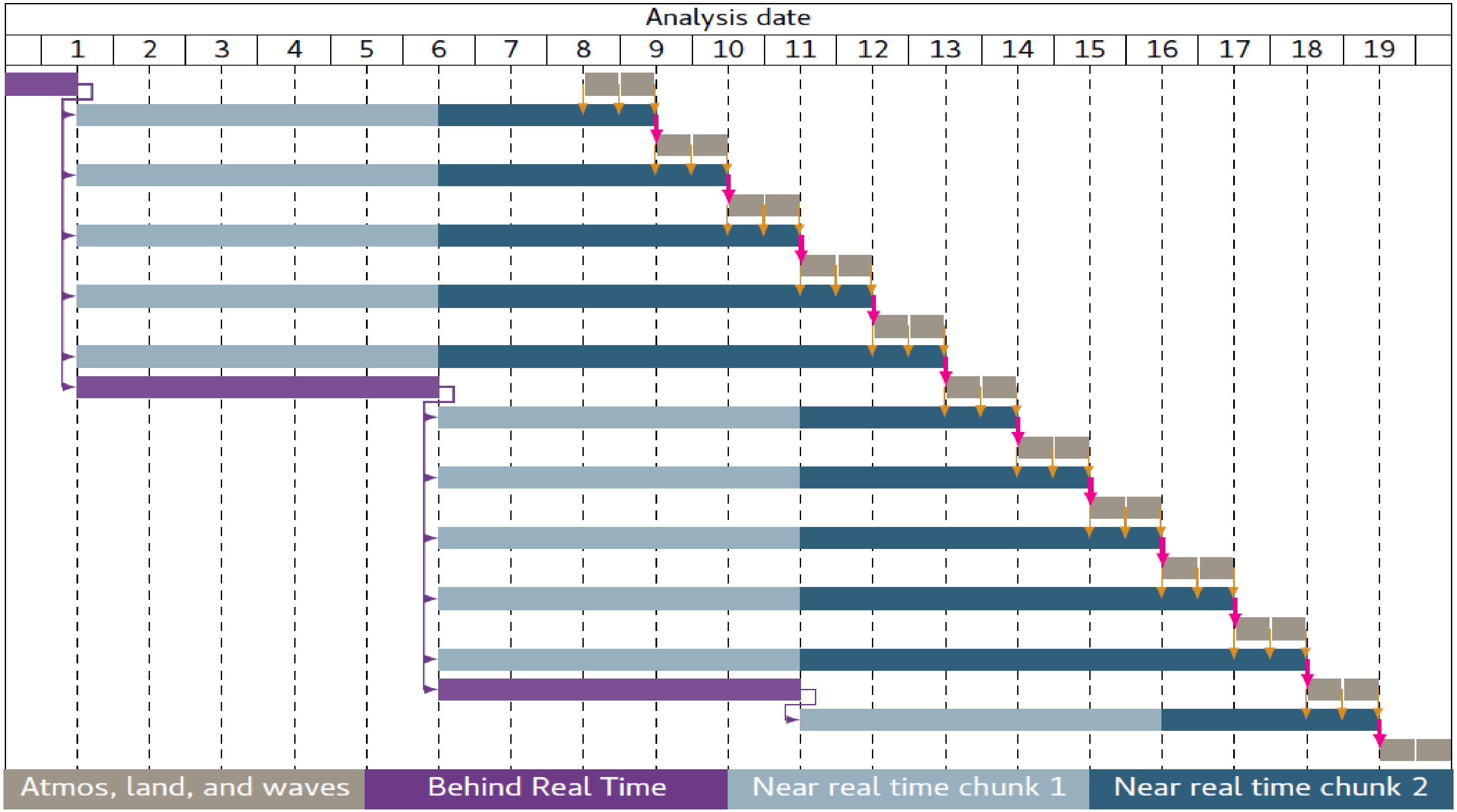
Instrument	Radiometer/Orbit	Resolution	Error	Issues
AVHRR	IR/Polar	1 km	0.6°C	Clouds, aerosols
AATSR	IR/Polar	1 km	0.3°C	Clouds, sparse
MODIS	IR/Polar	1 km	0.5°C	Clouds, aerosols
VIIRS	IR/Polar	1 km	0.4°C	Clouds, aerosols
GOES Imager	IR/Geostationary	6 km	1.0°C	Clouds, aerosols
SEVIRI	IR/Geostationary	6 km	0.7°C	Clouds, aerosols
MT-SAT	IR/Geostationary	6 km	0.7°C	Clouds, aerosols
AVHRR	IR/Polar	9 km	0.4°C	Clouds, aerosols
AMSR-E	MW/Polar	25 km	0.5°C	Land, rain
AMSR2	MW/Polar	25 km	0.5°C	Land, rain
WindSat	MW/Polar	25 km	0.5°C	Land, rain
TMI	MW/Equatorial	25 km	0.5°C	Land, rain
Buoys/ships	*in situ*	variable	$\sim$ 0.5°C	Depth, sparse

DA methodology:
ECMWF ORA5

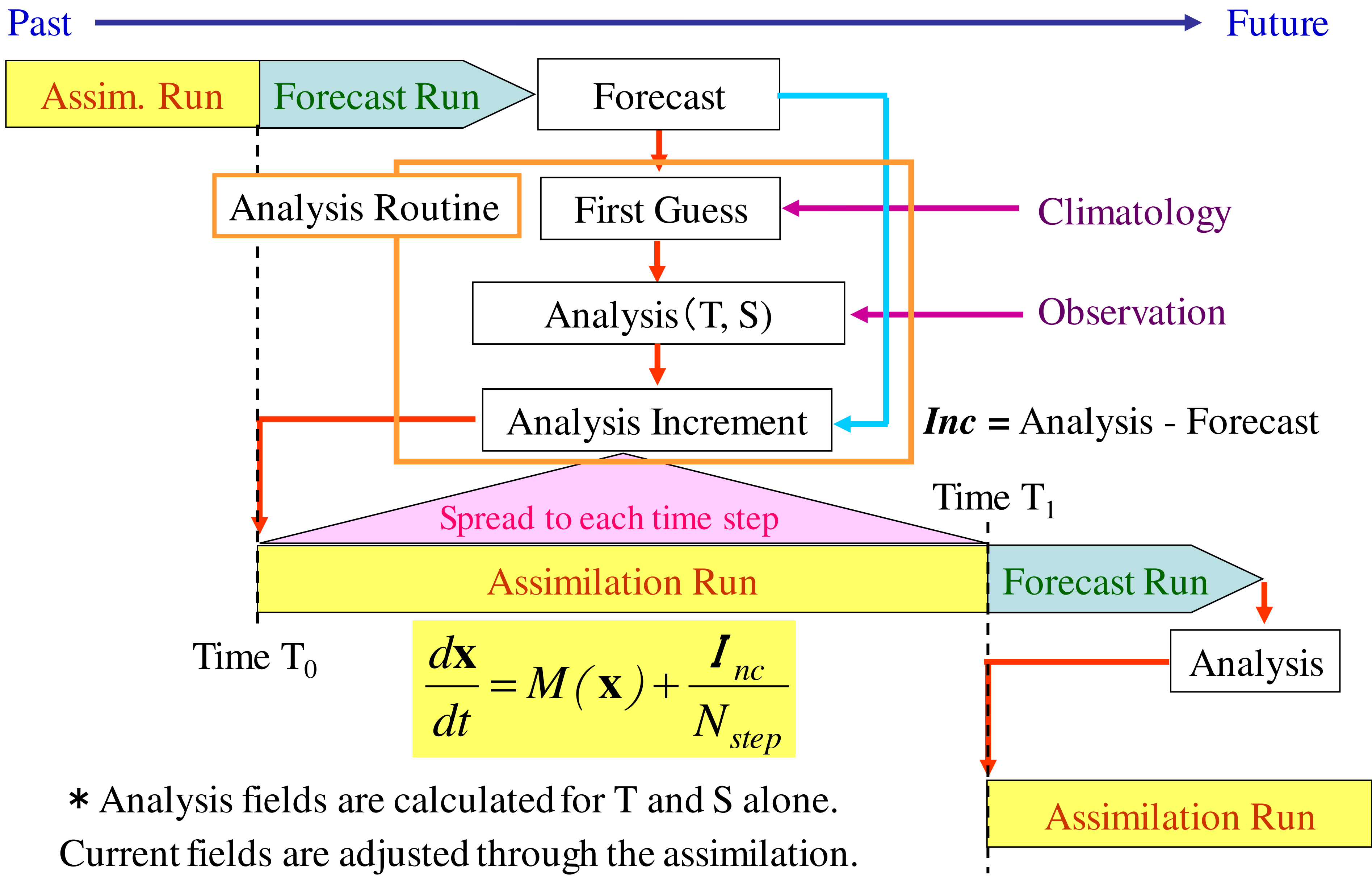
- Methodology is 3D-Var-FGAT
- Assimilation of in situ profiles, SLA, SIC
- Relaxation of SST towards OSTIA
- OCEAN5 is a reanalysis-analysis system with 2 streams - behind real-time and real-time
- Assimilation window varies from 8 days to 12 days and split into two chunks
- Minimisations performed separately for sea ice and ocean components
- Atmospheric forcing comes from the HRES system



A sliding window for incoming data



Incremental Update Cycle



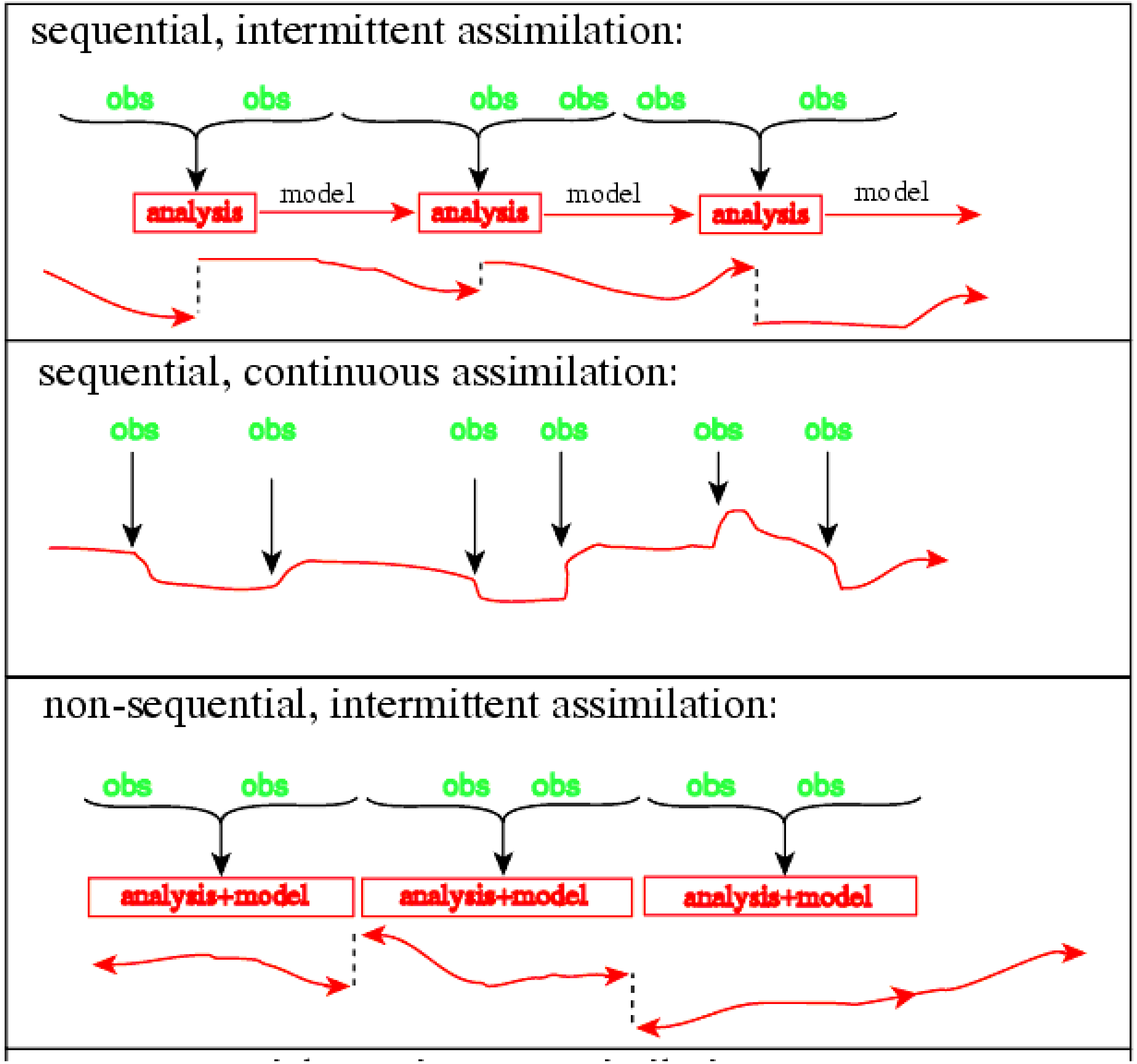
$$\frac{d\mathbf{x}}{dt} = M(\mathbf{x}) + \frac{I_{nc}}{N_{step}}$$

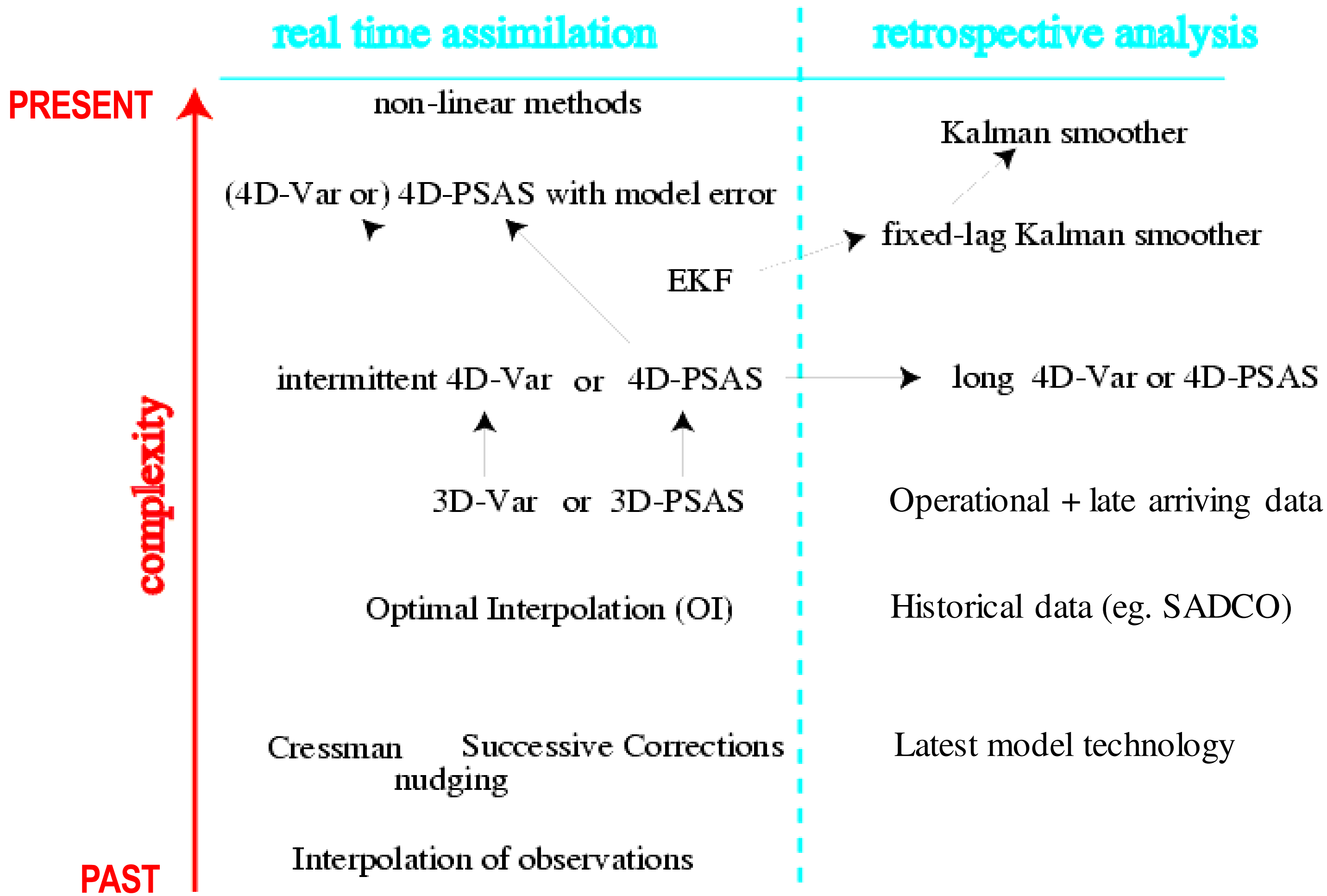
* Analysis fields are calculated for T and S alone.
Current fields are adjusted through the assimilation.

Cold start, has no prior ‘knowledge’

Warm start, uses persistence to ‘nudge’ the result

Block run, uses climatology to ‘nudge’ the result




real time assimilation
retrospective analysis
PRESENT
PAST
complexity
non-linear methods
Kalman smoother
(4D-Var or) 4D-PSAS with model error
fixed-lag Kalman smoother
EKF
intermittent 4D-Var or 4D-PSAS
long 4D-Var or 4D-PSAS
3D-Var or 3D-PSAS
Operational + late arriving data
Optimal Interpolation (OI)
Historical data (eg. SADCO)
Cressman
Successive Corrections
nudging
Latest model technology
Interpolation of observations

Different time-scales for ocean/land and atmospheric (NWP) modelling

- NWP forecasts have to be produced in a timely fashion
- Not all ocean observations are available for current atmospheric cut-off times
- Would like coupled assimilation for:
  - Coupled observation operators
  - Atmospheric bias correction of ocean sensitive satellite observations
  - More balanced initial conditions
- Outer loop coupling with the atmosphere – lots of potential to help with bias correction and screening of ocean sensitive satellite observations
  - Aligning the ocean analysis window to the current atmospheric window would mean missing lots of vital in situ observations
  - Care needs to be taken not to inherit ocean model biases into the atmospheric analysis

Atmospheric Model

- Aerosol processes (Microphysics)
  - Nucleation/condensation
  - Phase changes
- Cloud processes
  - Conden./evap./deposition/sublim.
  - Precipitation
  - Stability (Vertical/Slantwise Ascent)
  - Convection
  - Entrainment
- Radiative transfer
  - UV/visible/near-IR/thermal-IR
  - Scattering/absorption
  - Snow, ice, water albedos
- Meteorological processes
  - Velocity
  - Geopotential
  - Pressure
  - Water vapor
  - Temperature
  - Density
  - Turbulence
- Surface processes
  - Temperatures and water content of
    - Soil Water Snow
    - Sea ice Vegetation Roads
    - Roofs
  - Surface energy/moisture fluxes
  - Ocean-atmosphere exchange
  - Ocean dynamics, chemistry

Five steps in the generation of a numerical model product

Observations

- All models require obs from an area larger than their forecast domain
- Forecasts longer than 2-3 days require global data sets
- Global Telecommunications System (GTS) gathers and disseminates conventional data to nearly all countries

Analysis

- Objective analysis – obs checked for errors and interpolated to grid on which model atmosphere is represented

Initialization

- Adjusts the analyzed data so that the model and data are dynamically consistent
- Ensures no "noise" is generated when forecast begins

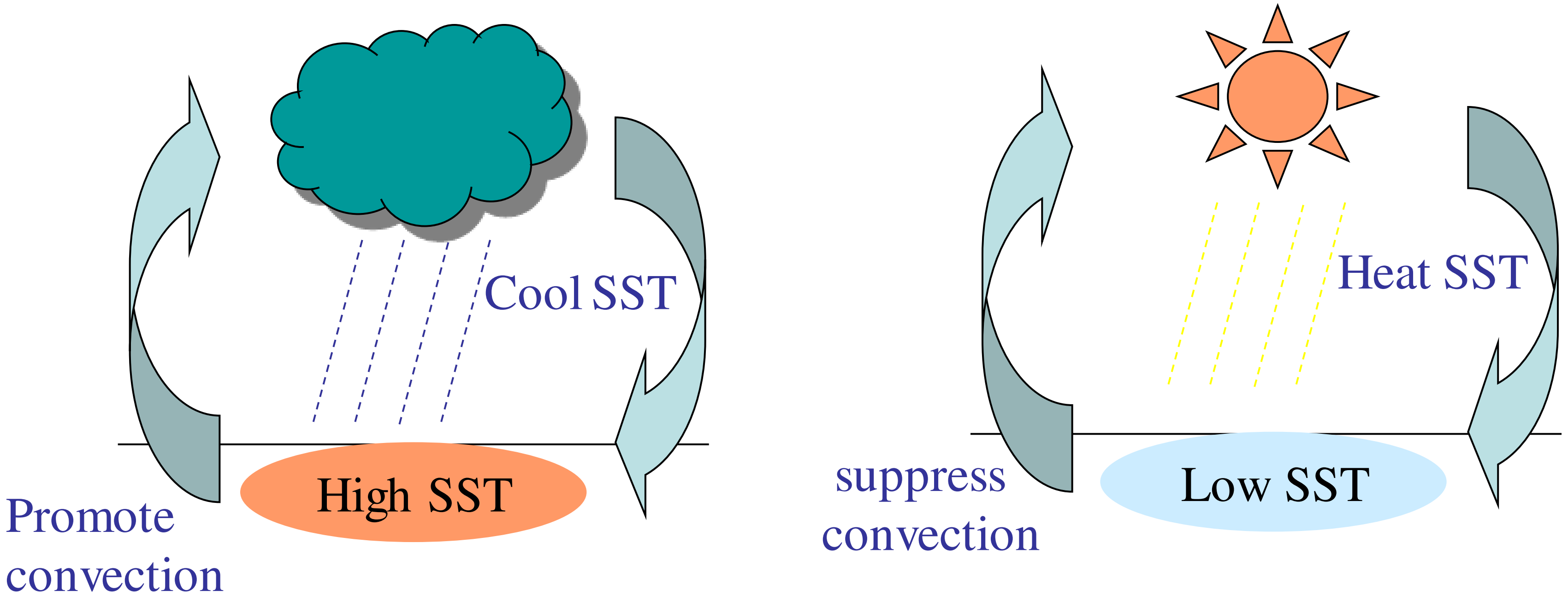
Forecast

- System of forecast eqns marched forward in time until desired forecast length is reached

Output

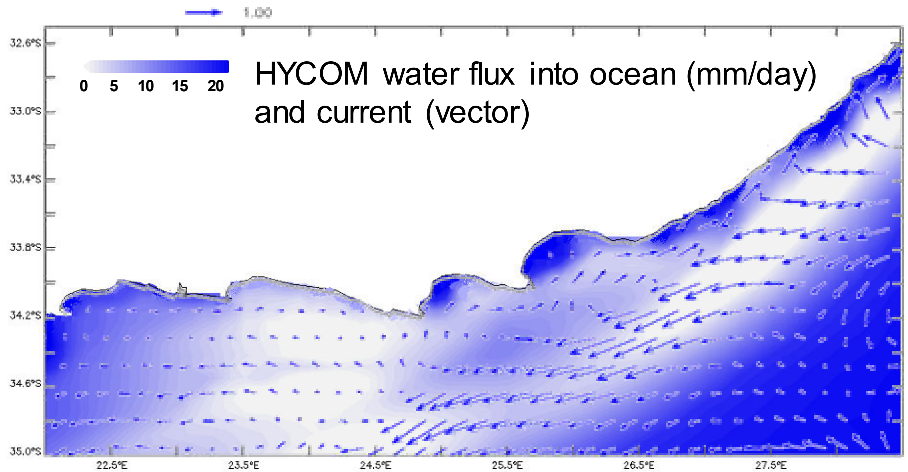
- Forecast maps produced and sent to users, including computations of many quantities not directly forecast by the model
- Forecasts verified to document model errors and biases in order to formulate improvements in the future.

☆ Feedback between SST and rain rate

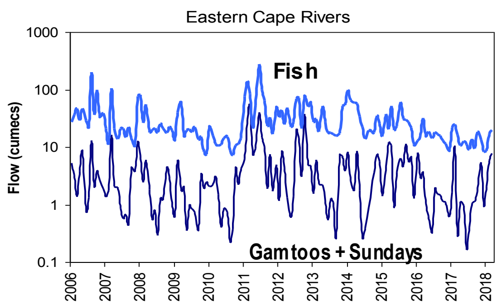


Coupled data assimilation uses constraints to inhibit rainfall over high SST regions, so salinity fields follow observations.

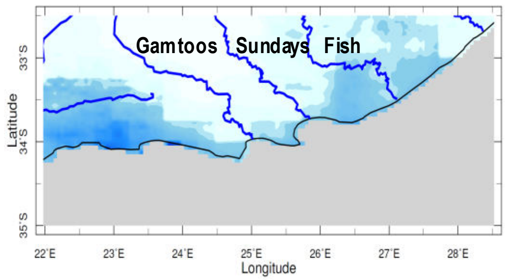
Contribution to ocean data assimilation: atmos / land hydrology → salinity budget



- Atmospheric data assimilation generates rainfall
- Over-land run-off feeds into river catchments, combined with satellite soil moisture
- Coastal river discharge is diffused and advected by winds, waves, turbulence and currents
- Salinity fields incorporate satellite and in-situ measurements, thus effects of upwelling



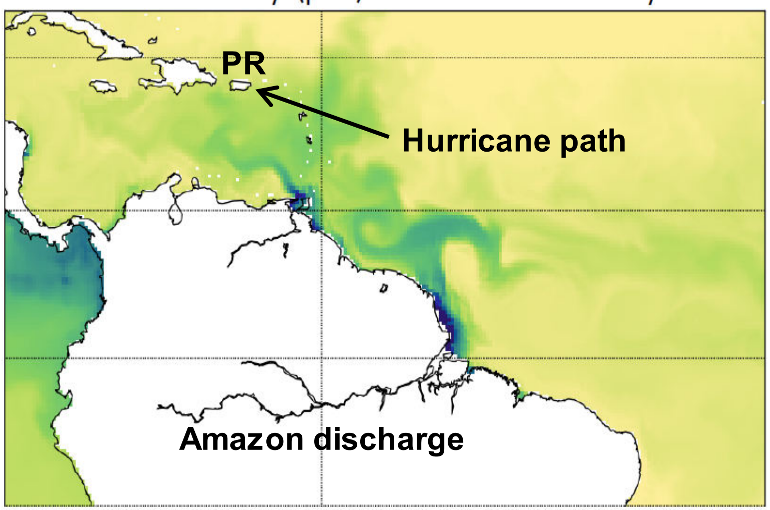
Public DWA hydrology data

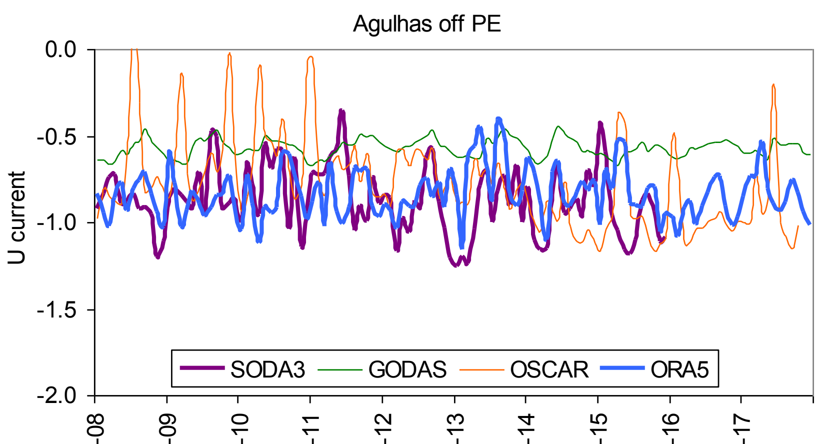


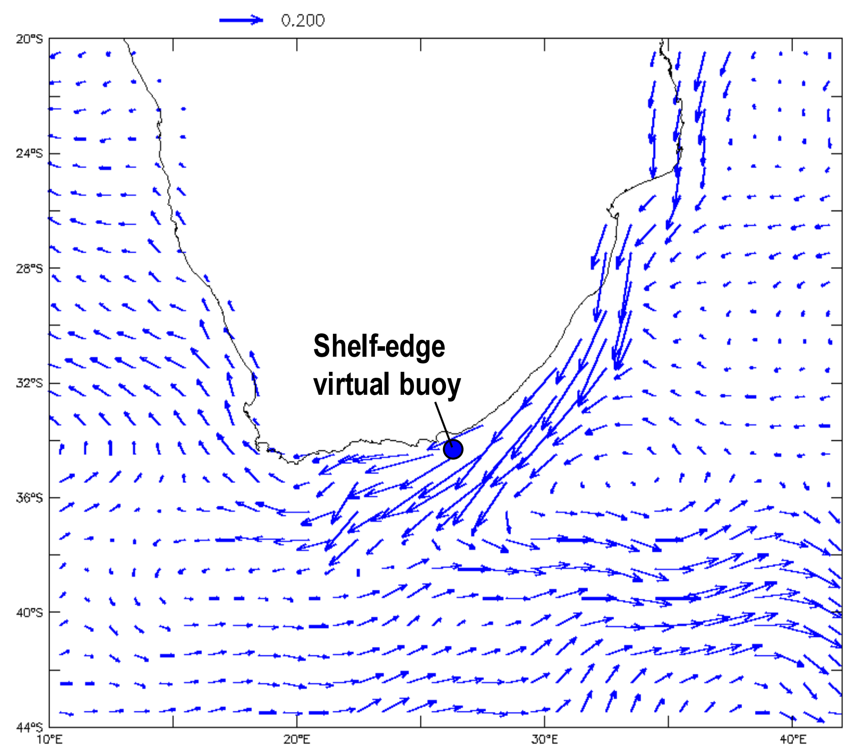
Meteosat-blended gauge data

Soil Moisture and Ocean Salinity Satellite (SMOS)

Examples of Amazon plume and Agulhas Current



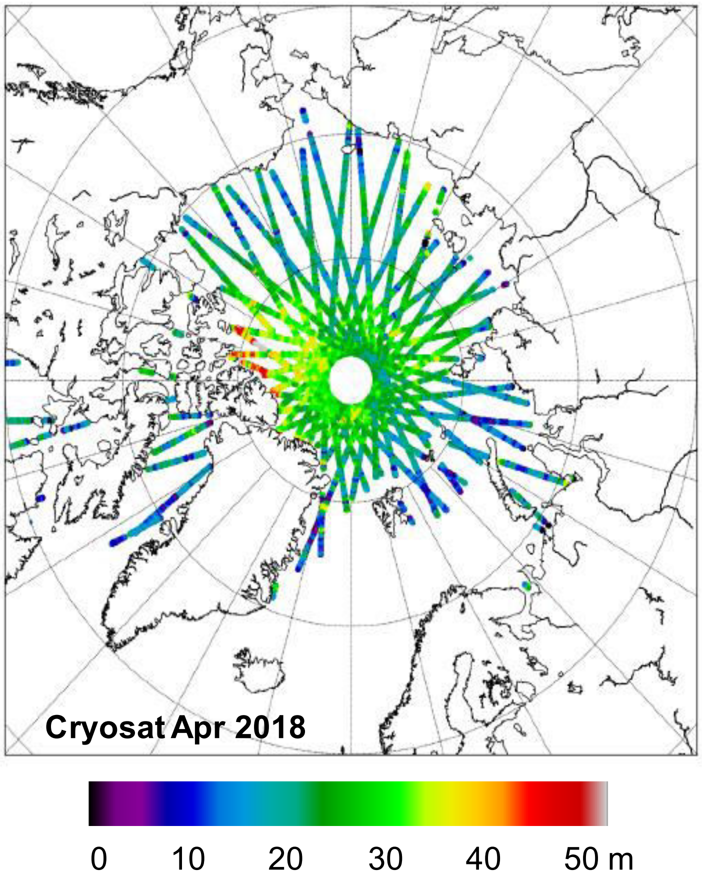


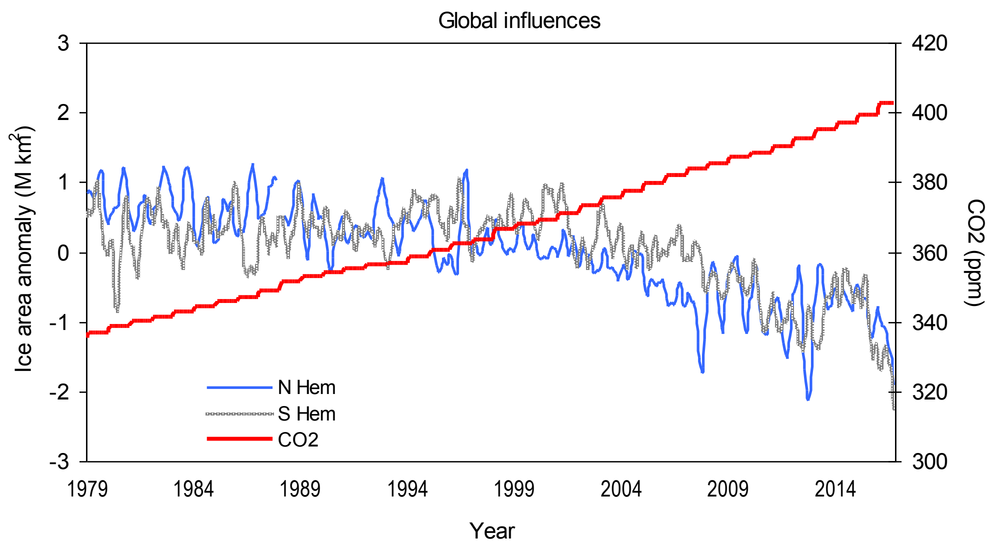


time-series since 2008: agreement for SODA3 & ORA5, but GODAS & OSCAR show weakness & discrepancies

Vanishing sea ice

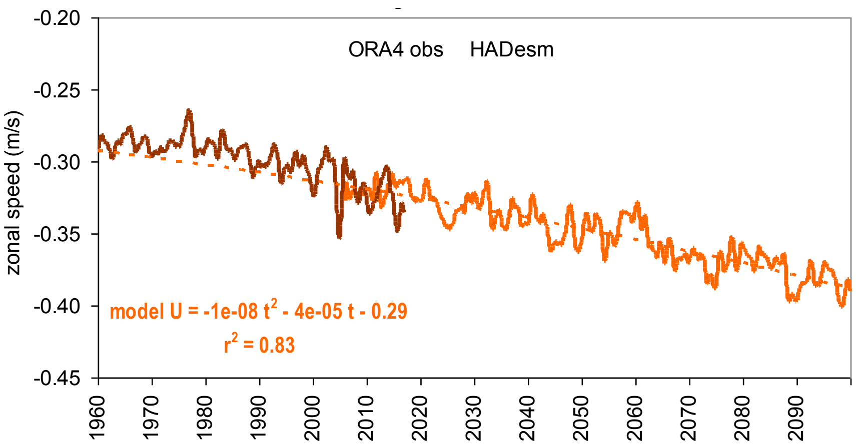
and shrinking beaches?



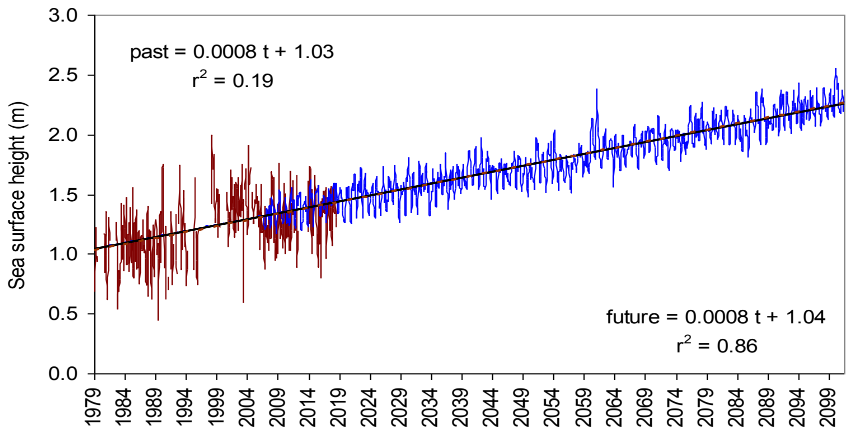


Comparison of past & future:

consistent values and trends?



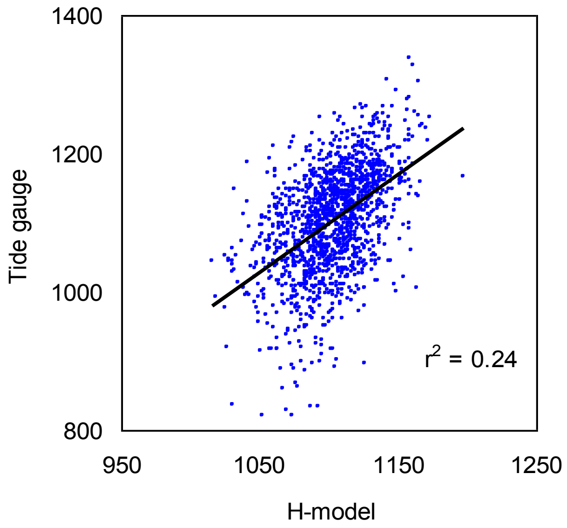
- PE shelf time series of ECMWF-ora4 hindcast and HAD-esm projected 1-50 m zonal current.

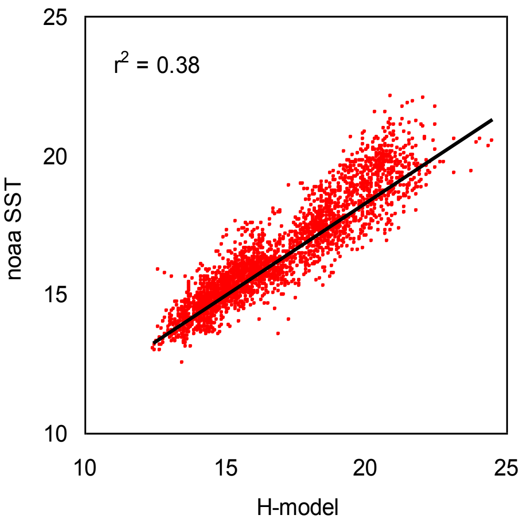


- Gauge measured and HAD-esm projected sea surface height at PE harbour.

For periods of overlap between observed and projected data, confidence can be determined according to means, variance, annual cycle, trends, and other metrics

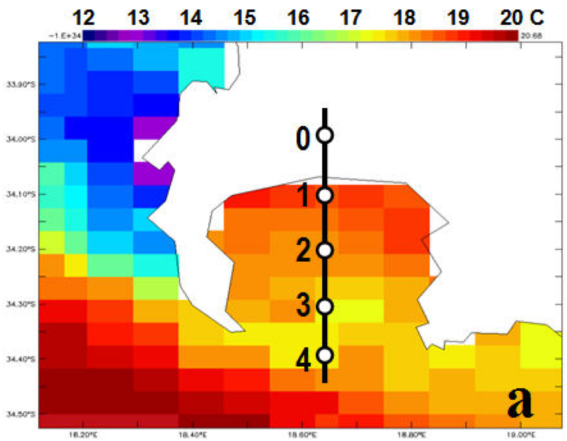
Local validation studies

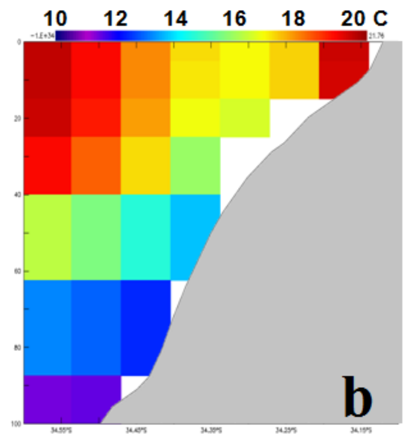


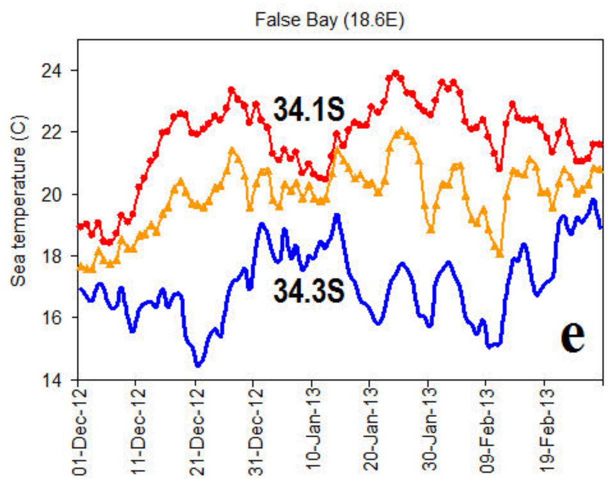


- Comparison of daily HYCOM model at nearest grid-point and: (left) sea surface height from tide gauge in western False Bay and (right) sea surface temperature from NOAA satellite; 2008-2015

HYCOM ability to detect temp gradients within False Bay

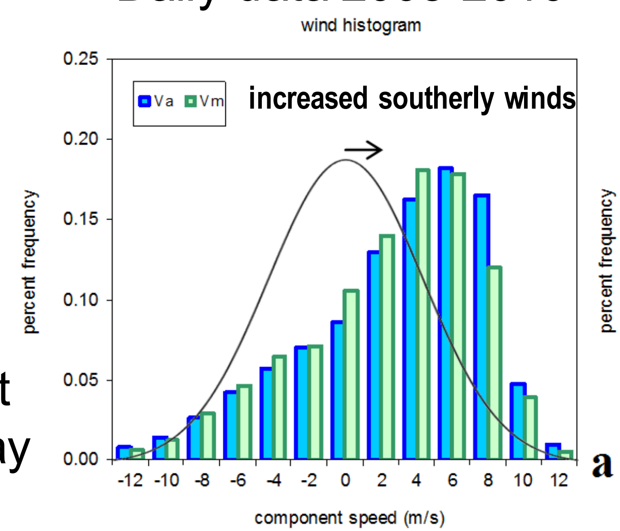






Dec12-Feb13 averages

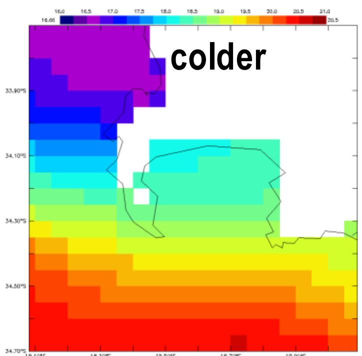
Daily data 2008-2016



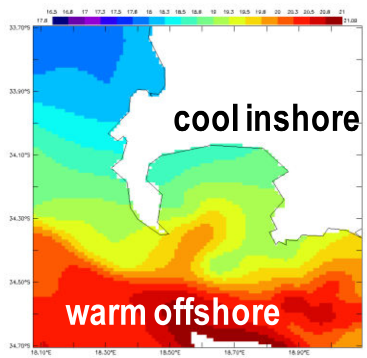
ASCAT ability to detect climate shift in False Bay

Intercomparison of products:

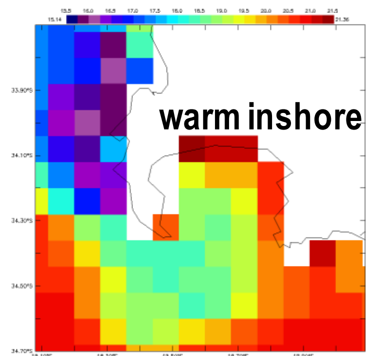
3-day SST ~1 Jan 2013



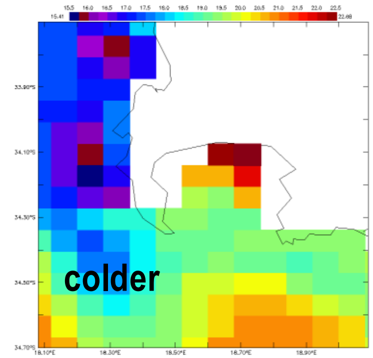
.04 GHR OI SST



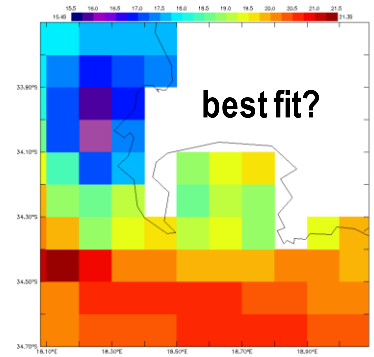
.01 GHR MUR SST



.1 HYCOM rean



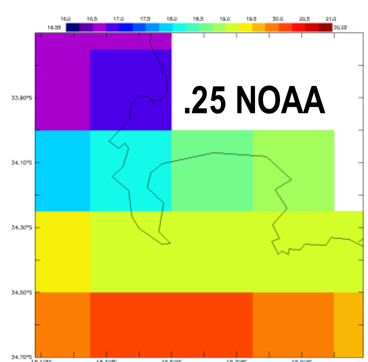
.08 HYCOM oper

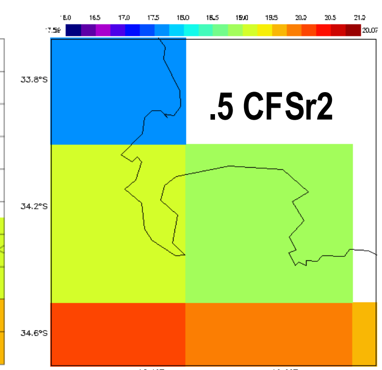


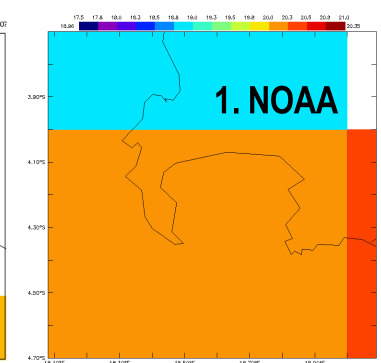
.1 GODAS rean

Hi-res ocean reanalyses should converge over time, as optimal solutions are achieved for radiometer engineering, atmospheric correction, bias removal and coupled DA.

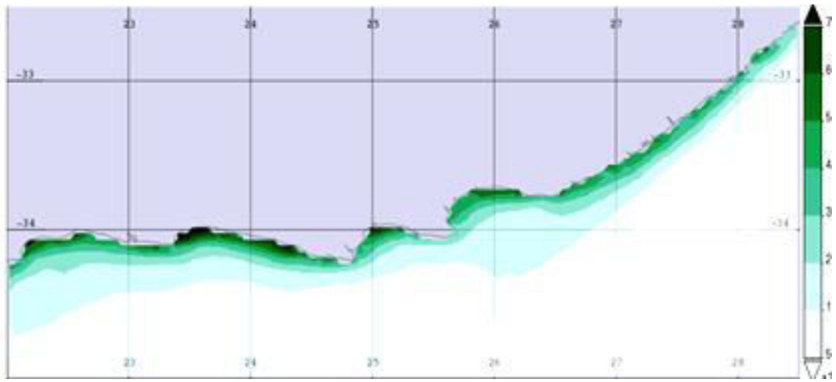
Low-res pattern

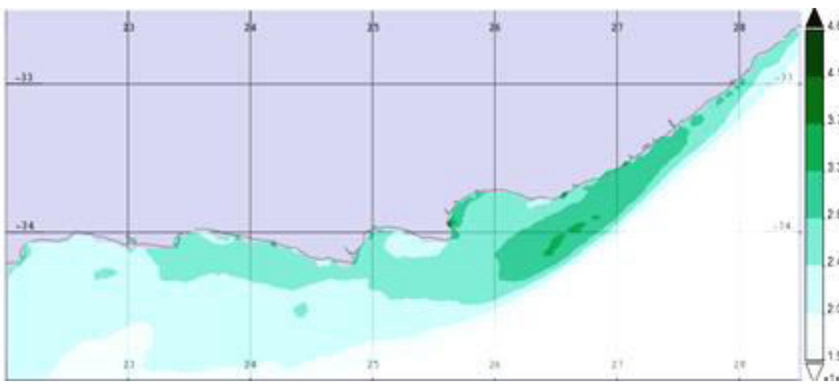


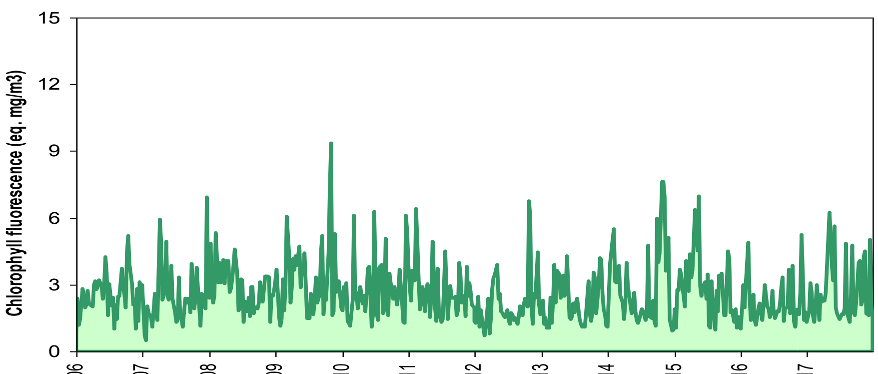




Remote sensing of productivity







What is the appropriate visible band product for marine productivity?

green-band chlorophyll?

Or

red-band fluorescence?

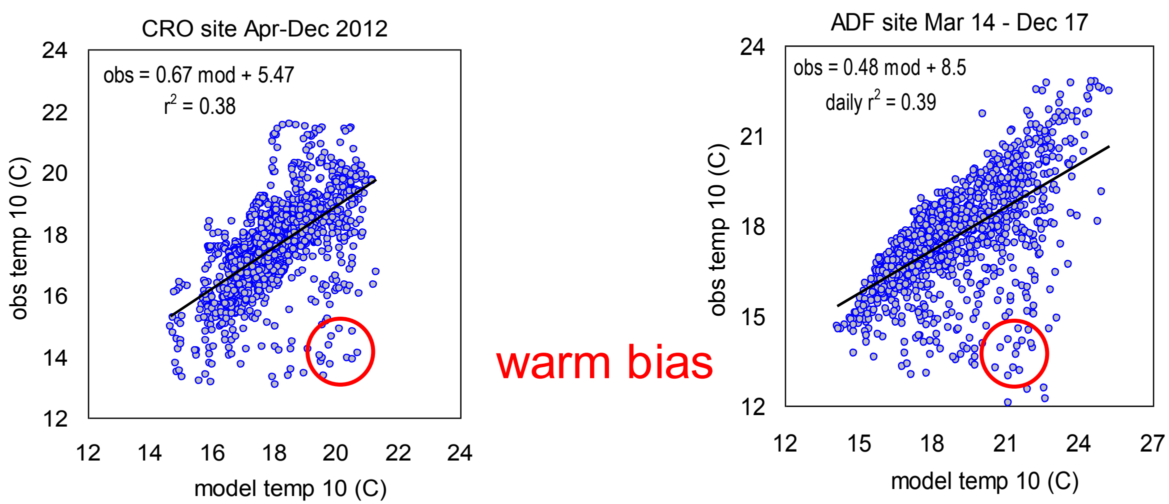
Influence of salinity, turbidity?

Why choose?

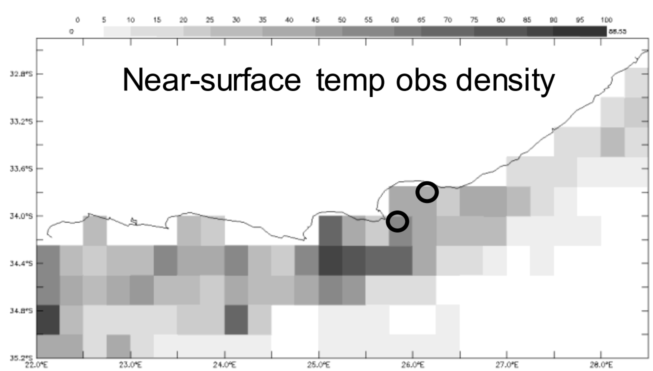
Use the reanalysis concept: all obs have value, so blend.

Retain multi-day time-scale for composite de-clouding.

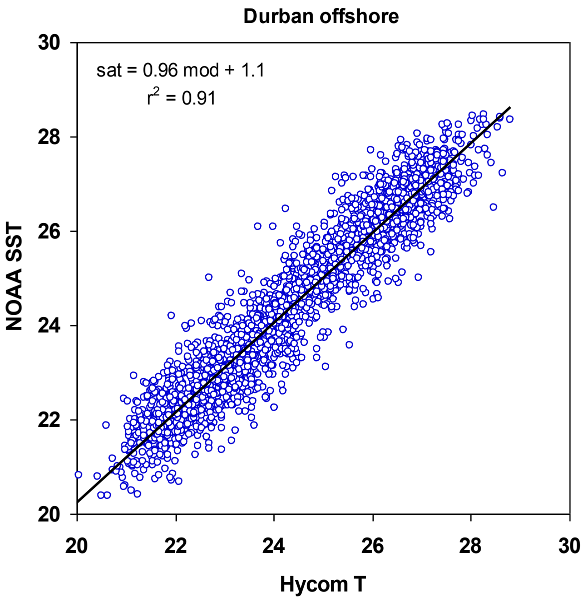
Local validation studies

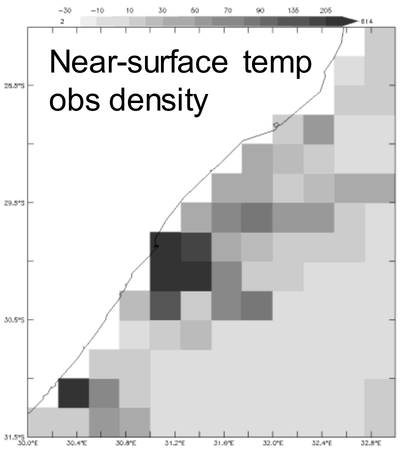


- Inter-comparison of HYCOM model 10 m temperature and UTR data at Algoa buoys (y-axis).



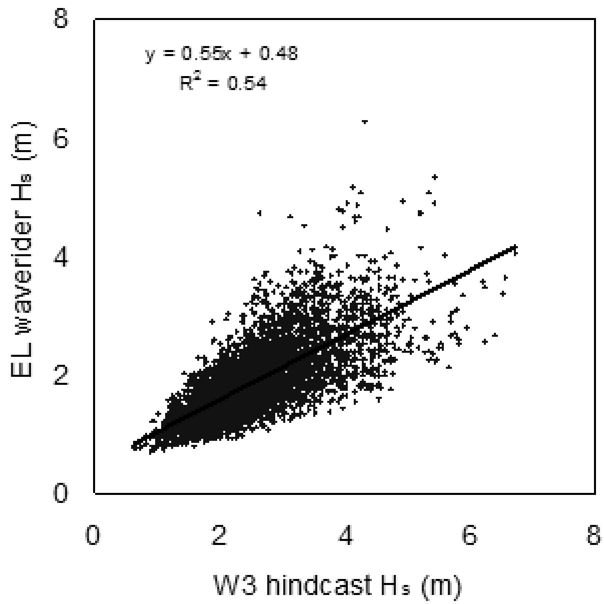
Local validation studies





- Comparison at shelf-edge of Hycom and NOAA sea surface temp 2009-2015 off Durban.

Local validation studies

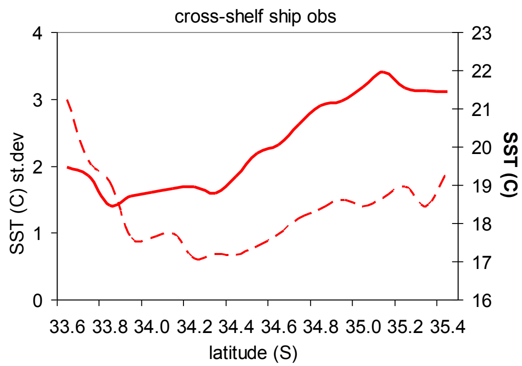


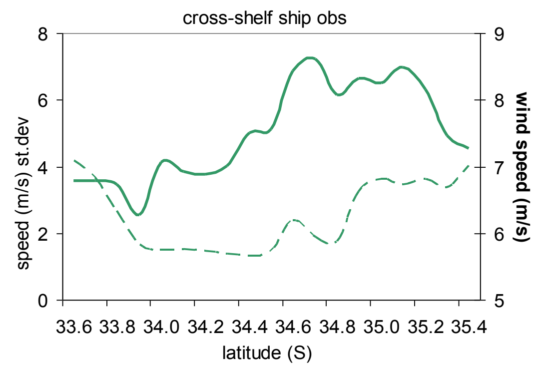
- Comparison of 3-hourly waverider buoy and W3 model significant wave height (2011-2013) near East London.

Local intercomparisons

Over the shelf, west of PE

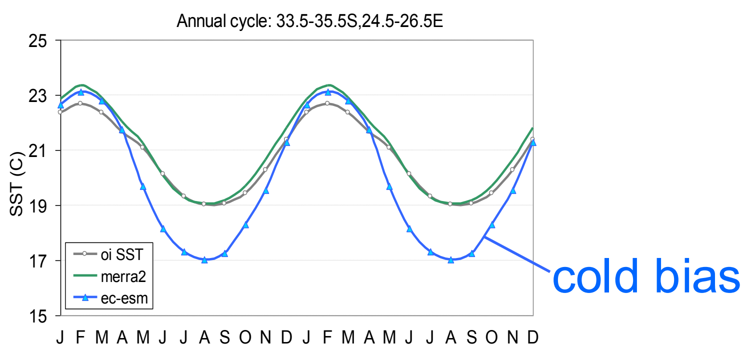
Coastal gradient in SADCO ships data

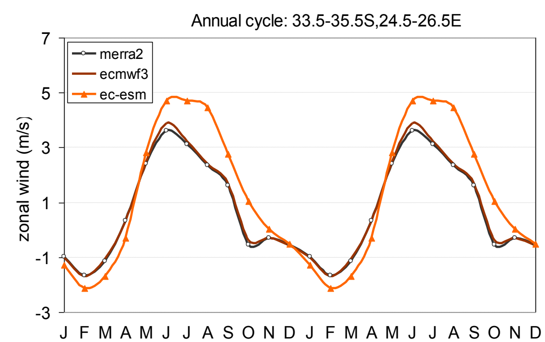




SST

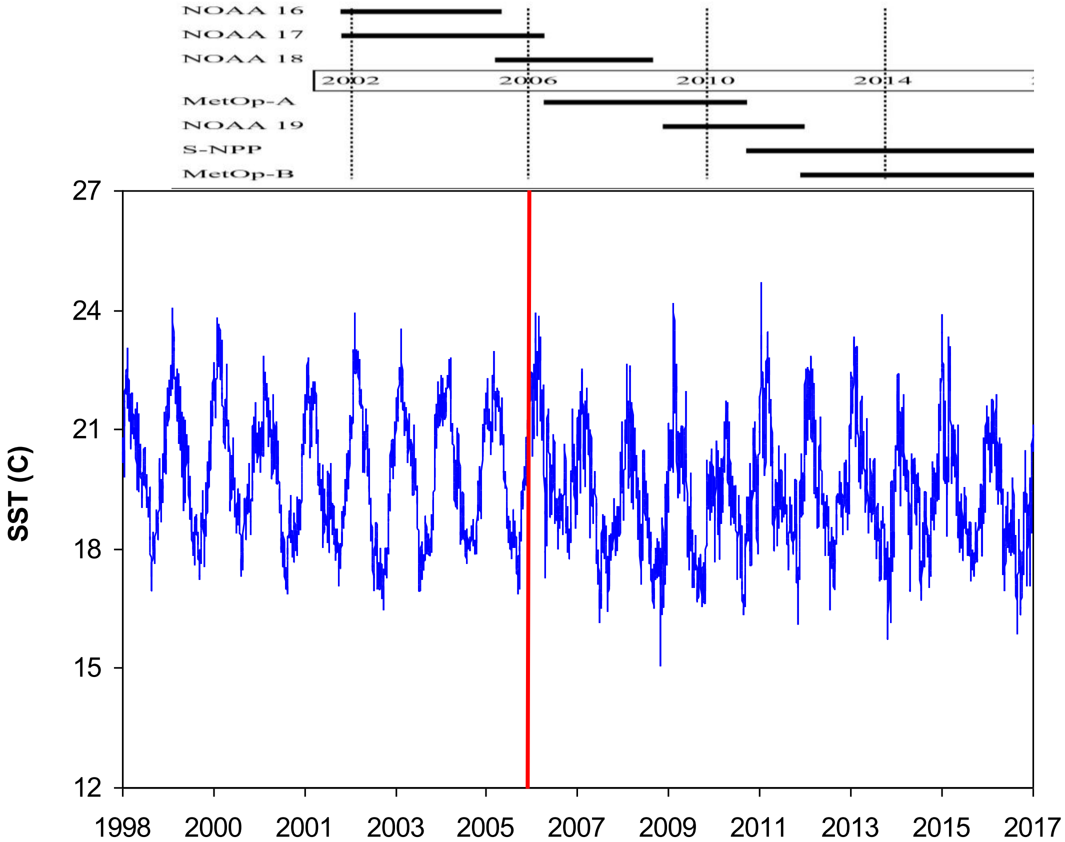
Zonal wind





Seasonal cycle in satellite, reanalysis and coupled model

Changes in variance over time



Daily SST over the shelf west of PE:
Temporal variability dominated by seasonal cycle pre-2006.
Event scale fluctuations much greater thereafter.
Increased ‘noise’ from inshore upwelling, finally resolved.

Globally available resources:

most starting in the satellite era

LABEL	DEFINITION	RESOLUTION	SOURCE
CCMP	Cross-calibrated multi-platform marine wind reanalysis	25 km	Univ Hawaii APDRC
CFSr2	Coupled Forecast System reanalysis v2 (ocean)	30-50 km	Univ Hawaii APDRC
ECMWF5	European Centre Medium-range Weather Forecasts	30 km	Climate Explorer
GODAS	Global ocean data assimilation system (NOAA)	50 km	IRI Clim. Library
HYCOM	Hybrid Coordinate Ocean Model	10 km	Univ Hawaii APDRC
IPCC	Coupled model projections (HAD3esm, etc)	100+ km	Climate Explorer
MERRA2	Modern Era Reanalysis for Research and Applications	50 km	NASA-giovanni
MODIS	Moderate-imaging Infrared Spectrometer	1-4 km	IRI Clim. Library
NASA	National Aeronautics and Space Administration	25-100 km (satellite)	NASA-giovanni
NCEPr2	National Centers for Environmental Prediction	180 km (reanalysis)	IRI Clim. Library
NOAA	National Oceanic and Atmospheric Administration	50 km	IRI Clim. Library
ORA5	Ocean Reanalysis v5 from ECMWF	25 km	Univ Hawaii APDRC
SODA	Simple Ocean Data Assimilation (UMD, Carton)	50 km	IRI Clim. Library
W3	Wavewatch v3 ocean swell reanalysis	50 km	Univ Hawaii PacIOOS
WHOI	Woods Hole Ocean Inst (surface fluxes)	50 km	Univ Hawaii APDRC

See also: https://reanalyses.org/ocean/overview-current-reanalyses

Value of higher resolution and operational reporting

- Products of monthly time-scale and spatial resolution > 0.5° can not resolve the shelf environment and its fluctuations
- HYCOM 0.1° resolves the coastal gradient, and shelf-edge eddies and rings at daily time scale
- CFSr2 and MERRA2 hourly reanalysis resolve diurnal variability at 0.5° resolution, ECMWF5 available at 0.3° resolution
- Confidence in these products is diminished by the scarcity of in-situ marine reports over the South African shelf
- Global ocean data assimilation will proceed with or without us
- More emphasis is needed on real-time measurement and reporting
- So satellite and model products are calibrated toward reality,
- And able to be trusted for use, not only in research, but in strategic decision-making

What is the solution?

exchange of emails

- **From: Mark R Jury 1 Feb 2019 To: T.Morris <weathersa.co.za> [SAWS Marine Coordinator]**
- **QUESTION - I ask how SAWS interacts with SA marine scientists to pass on real-time ocean data collected in our EEZ, for operational and coupled model [assimilation and prediction]?**
- **ANSWER - …the team are planning to address these [non-reporting] issues, [possibly with parallel monitoring systems that duplicate those ‘missing’, such as harbour buoys and tide gauges].**
- **REPLY - …the IOC website shows that all SA marine platforms are off-line. Could you make it part of your group's responsibility to get the data back online?**

- **3 Feb 2019 To: C.Rautenbach <weathersa.co.za> [SAWS Marine Dept]**
- **QUESTION - …path to operational oceanography. I was wondering what existing [marine] data could be [fed] to ocean models used in coupled forecasts? SAEON has quite a few buoys, and could report through SAWS GTS? Same for any data [reaching] SADCO…**
- **ANSWER - …we are having negotiations to add a variety of marine data to our regular GTS reports**

- **21 Feb 2019 To: K.Wilmer-Becker <metoffice.gov.uk> [GODAE Programme Coordinator]**
- **QUESTION – I want to know how much of South Africa's marine observations are reaching the global ocean DA system on an operational basis?**
- **26 Feb 2019 ANSWER - CMEMS Service Desk <mercator-ocean.eu>**

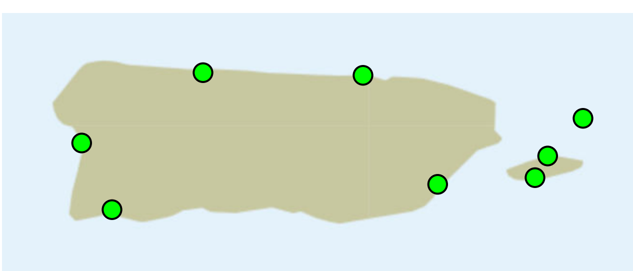
  [According to the] Copernicus insitu expert team …we don't have [any] platforms identified as coming from South Africa [over the most recent DA cycle]: 7 ships, 2 drifting buoys, 4 argo floats, 12 tagged fish. All of them are moving platforms [of external origin]…
- **REPLY - …in case of ‘privatized’ data that requires confidentiality… is it possible to ‘flag’ reports, so to assimilate but keep actual data ‘hidden’?**
- **ANSWER - Yes, that is an option many services are using: [ECMWF, UKMET, METEO-FRANCE, etc].**

How we solve the problem in Puerto Rico

- NOAA contracts the university to provide operational data monitoring and real-time reporting (CARICOOS)
- Graduate students engaged to do much of the work under supervision of professors
- Contract is on-going and stipulates 99% data capture, has budget for maintenance, replacement equipment, bursarys / internships.
- All data are required to be publicly available within 1 hour of collection, mirrored on government websites, with data QC and assimilation handled by quasi-government ocean, land & weather services and NOAA subsidiaries (US-Navy, USGS, etc).
- The university does <u>not</u> conduct in-house data assimilation, that is the work of major centers, given the need for blending with vast amounts of NASA satellite measurements. We maintain the observing & reporting system, and evaluate / validate the DA model outputs.

Puerto Rico’s operational system

Caricoos marine monitoring system

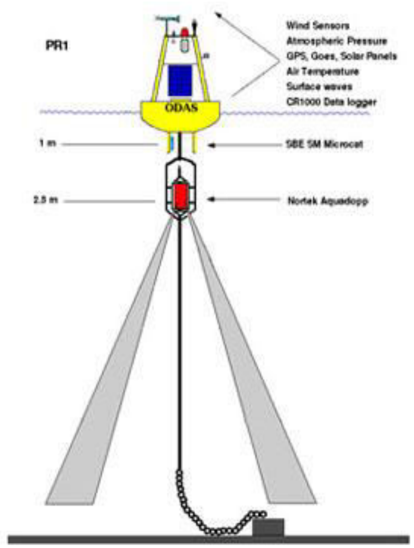


IOC mirror site

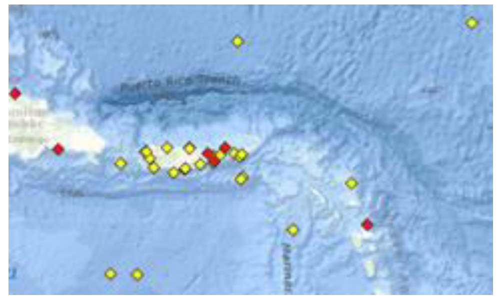
Actual and virtual buoys

Puerto Rico's operational system

PR economy similar to South Africa, except many jobs are automated, all data are publicly available.

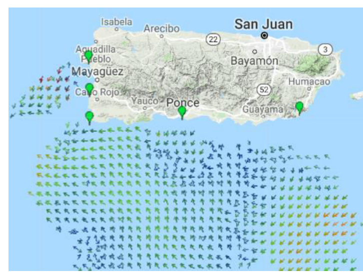


NDBC moored buoy + wx station, with hourly real-time data since 2000+

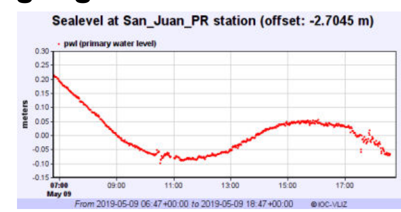


NDBC buoys around Puerto Rico

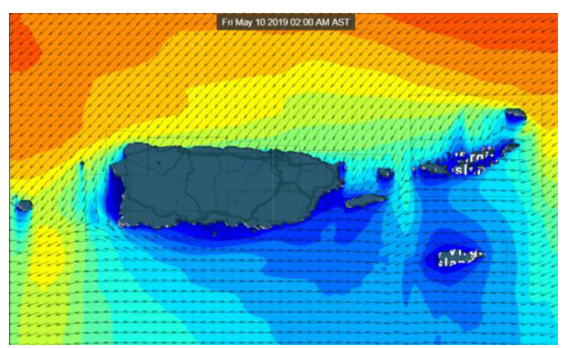
Tide gauge maintained since 1962

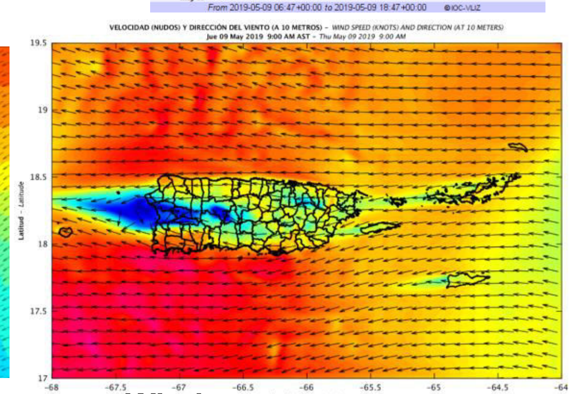


HF radar currents



University researchers assist gov. operations via graduate intern field work, identification of 'bad' obs & systematic DA model errors, applied research theses, publications, outreach.



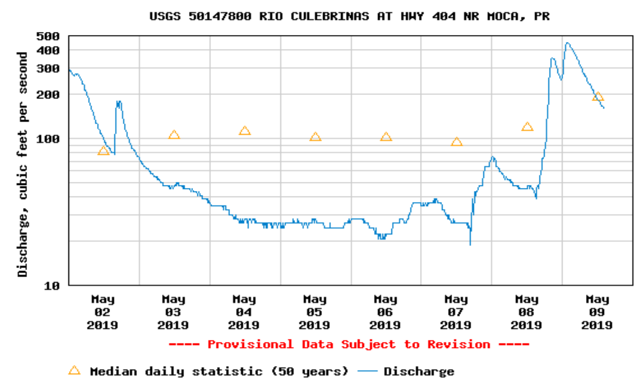


Waves Winds

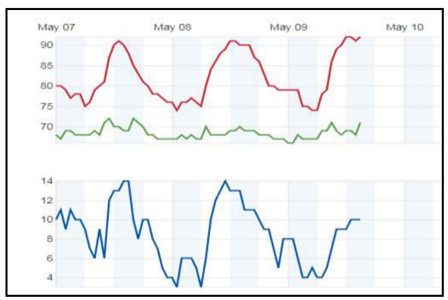
nested model outputs – daily update downscaled from operational products

Puerto Rico's operational system

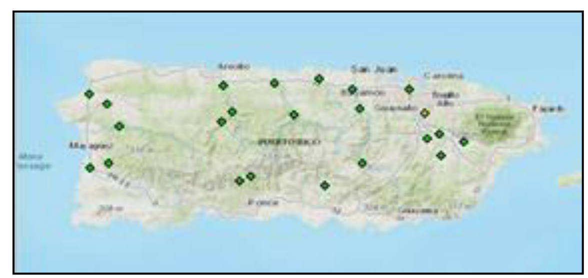
Both ocean and weather services feed to GTS, to ensure real-time reporting to global centers for data assimilation, within atmospheric cut-off window (3 hr)



Real-time reporting weather stations, via Wundermap, with 10 minute update, most derive from quasi-government services



Daily Streamflow Conditions



Cabo Rojo Puerto Rico May 2019

Day of Month	Day of Year	Total Solar Rad. ly.	Wind Ave. mph	V. Dir. Deg	Max. mph	Air Temperature Mean Deg. Fahrenheit	Max	Min	Humidity Mean Percent	Max	Min	Dew Point Deg. Fahrenheit	Wet Bulb	Total Precip. inches	Total Penman ET. inches
1	121	594	14.5	103	37.0	82	89	76	67	79	50	69	72	0.00	0.29
2	122	460	13.7	103	32.0	81	87	77	68	81	56	69	72	0.00	0.23
3	123	514	13.0	96	30.0	80	86	73	64	78	49	67	70	0.00	0.25
4	124	513	12.8	106	27.0	80	86	75	64	74	50	67	70	0.00	0.26
5	125	573	16.3	105	35.0	81	87	76	67	75	54	69	72	0.00	0.28
6	126	573	15.2	108	30.0	81	86	76	70	76	57	70	73	0.00	0.27
7	127	590	15.0	106	33.0	81	85	76	68	76	57	69	72	0.03	0.27

Real-time reporting streamflow gauges, with 10 minute update: the flash-flood warning system linked to wx radar

Value of coupled forecasts

- We used to think that coupled modelling was needed only for long-range predictions (> 2 month lead time) driven by alternating ENSO phase and accumulating greenhouse gases.
- With the advent of hourly-fluctuating, eddy-resolving ocean and land products, it is evident that short-range predictions (> 2 day lead time) out-perform uncoupled forecasts.
- Coupled models better simulate the diurnal cycle of rainfall and wind speed*, changes in tropical cyclone intensity, etc.
- There is a single assimilation system for environmental data; and converging model technology for land, ocean, atmosphere (both physical and chemical).
- Long-range predictions for South Africa summer climate show increasing skill, via ENSO influence on slow undulations of the ocean thermocline that modulate atmospheric convection and circulation.
- But model-simulated fields, mainly derived from satellite estimation, need local calibration (error-constraints) for operational use.