Argo in Weather and Climate Forecasting Systems

M.A. Balmaseda, ECMWF

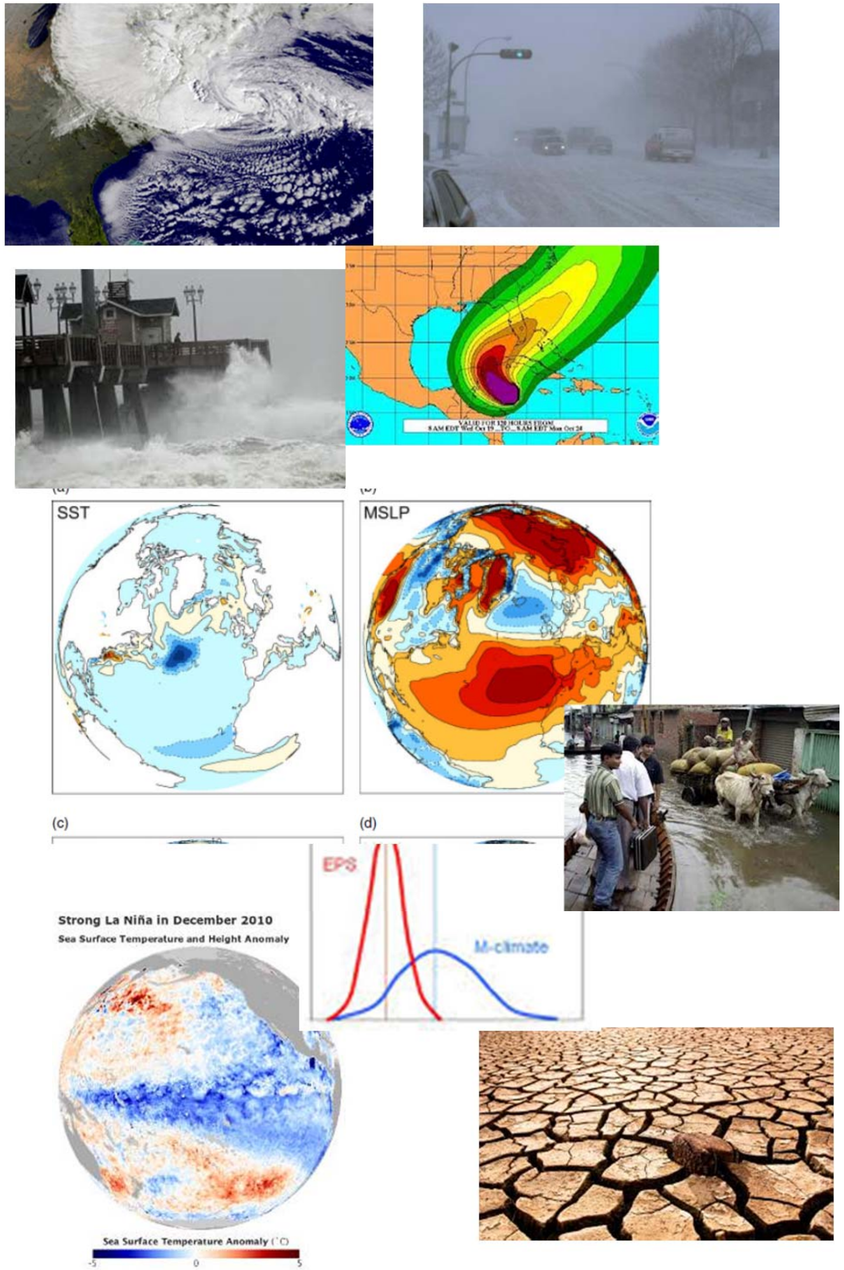
- **Seamless forecasting systems**

  Days, weeks, seasons - Coupled Earth System Models

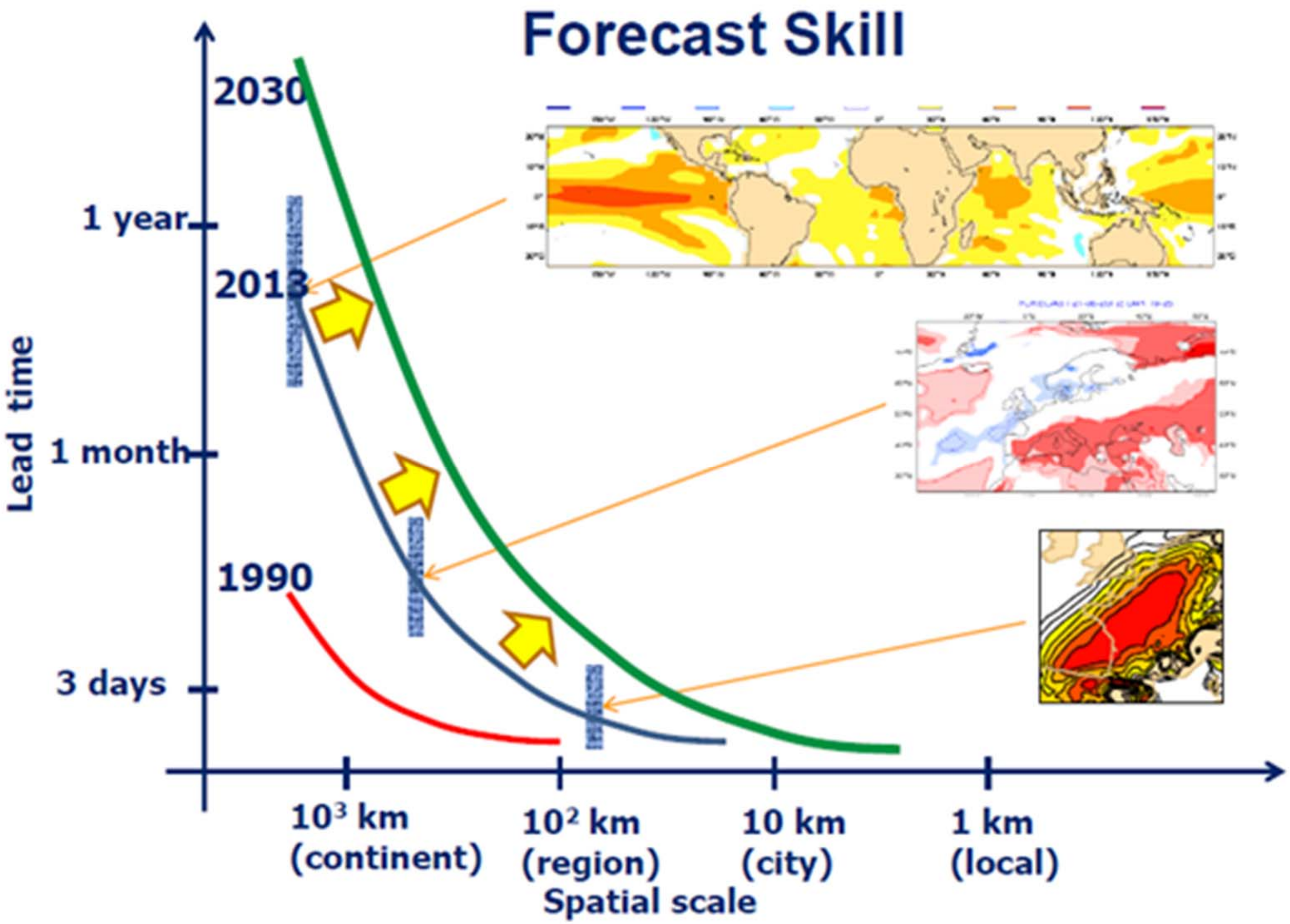
  Integrated Reanalysis-Forecasting Systems

  Coupled Data Assimilation

- **Multifarious value of observations.**
  - Initialization, Model development, Calibration, Verification
  - Or cautionary notes on observing system experiments
- **Ongoing developments using Argo information**
- **Summary**



Seamless: Need for reliable forecasts of meteorology at different time scales



Ready

Seasonal

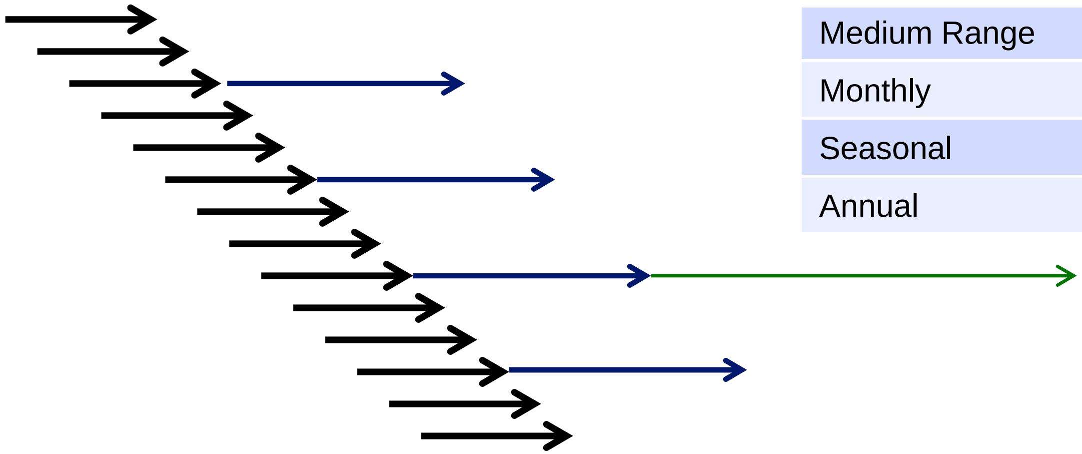
Get Set

Monthly

Go

Short-Range

Seamless Prediction



System	Lead Time	Prod Frequency
Medium Range	15 days	twice daily
Monthly	45 days	twice weekly
Seasonal	7 months	once monthly
Annual	12 months	twice yearly

- Same model, same initial conditions used for the forecast at different lead times.
- Resolution changes as a function of lead time.
- Main advantage: simplicity and cost

Implication: Ocean and Sea-Ice model components are integral part of the weather forecasting systems

Ocean playing a role at all time scales

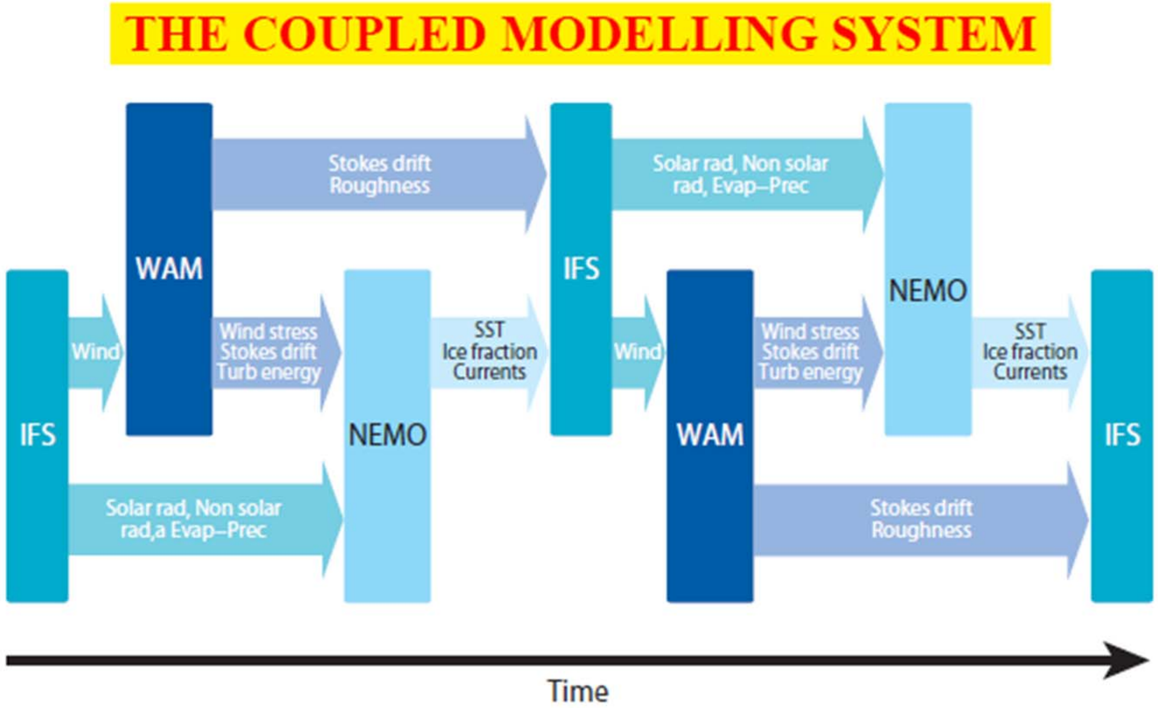


Figure 1: Flow Chart of the coupled model, here two time steps are shown.

Ocean playing a role at all time scales

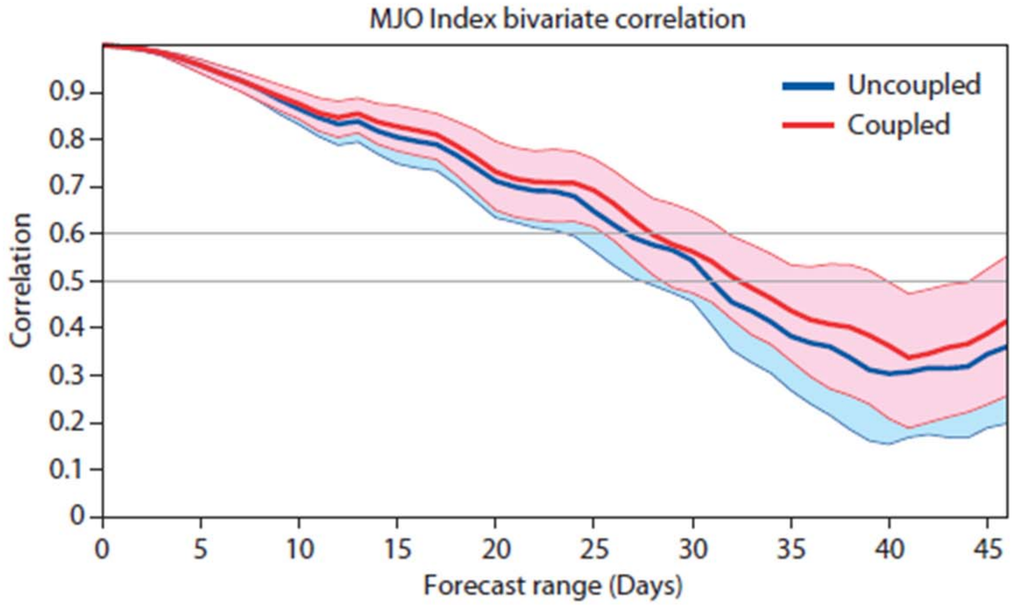


Figure 15: MJO Bivariate correlation for the control runs (legA uncoupled, blue curve) and coupled from day 0 integrations (leg A coupled, red curve). The shaded areas represent the 5% level of confidence using a 10,000 re-sampling bootstrap procedure.

Tropical Scores

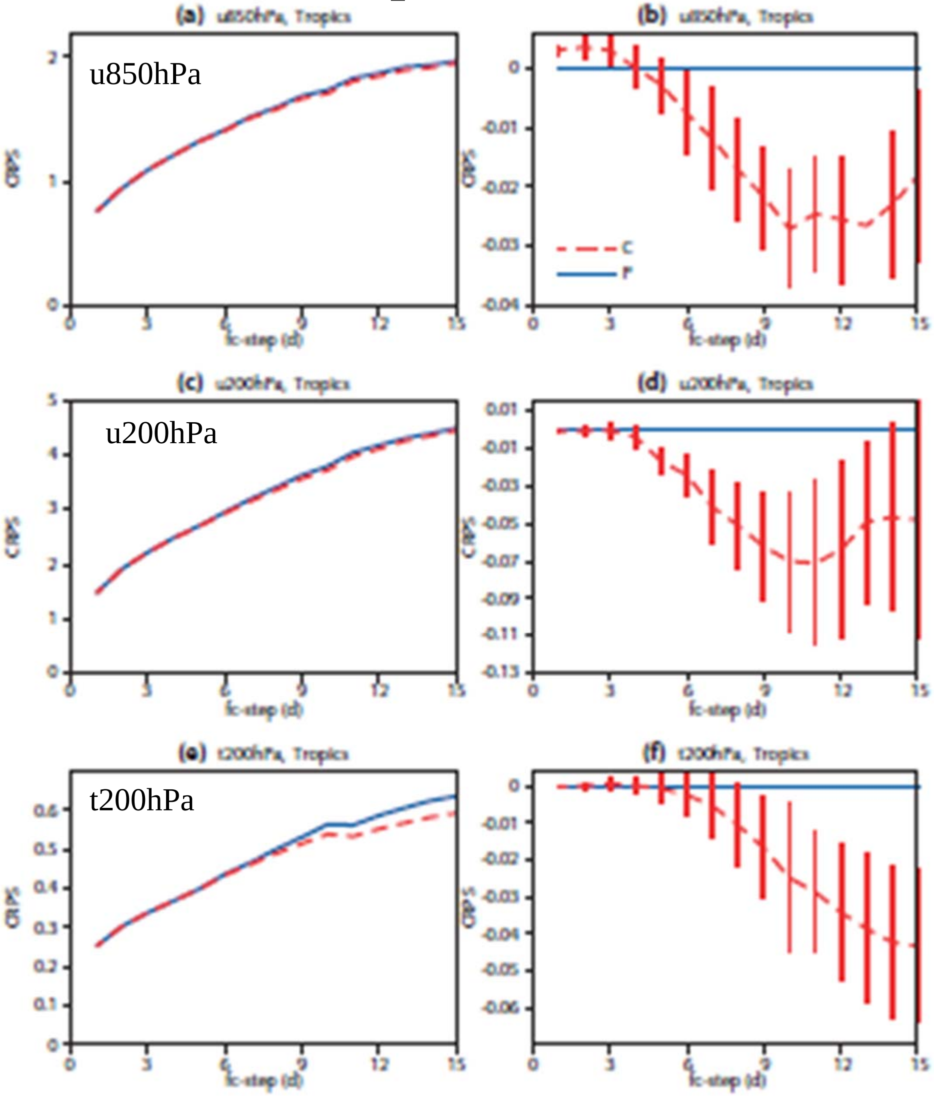


Figure 16: Impact of coupling on CRPS for tropics: (a,b) zonal wind at 850 hPa, (c,d) zonal wind at 200 hPa and (e,f) temperature at 200 hPa.

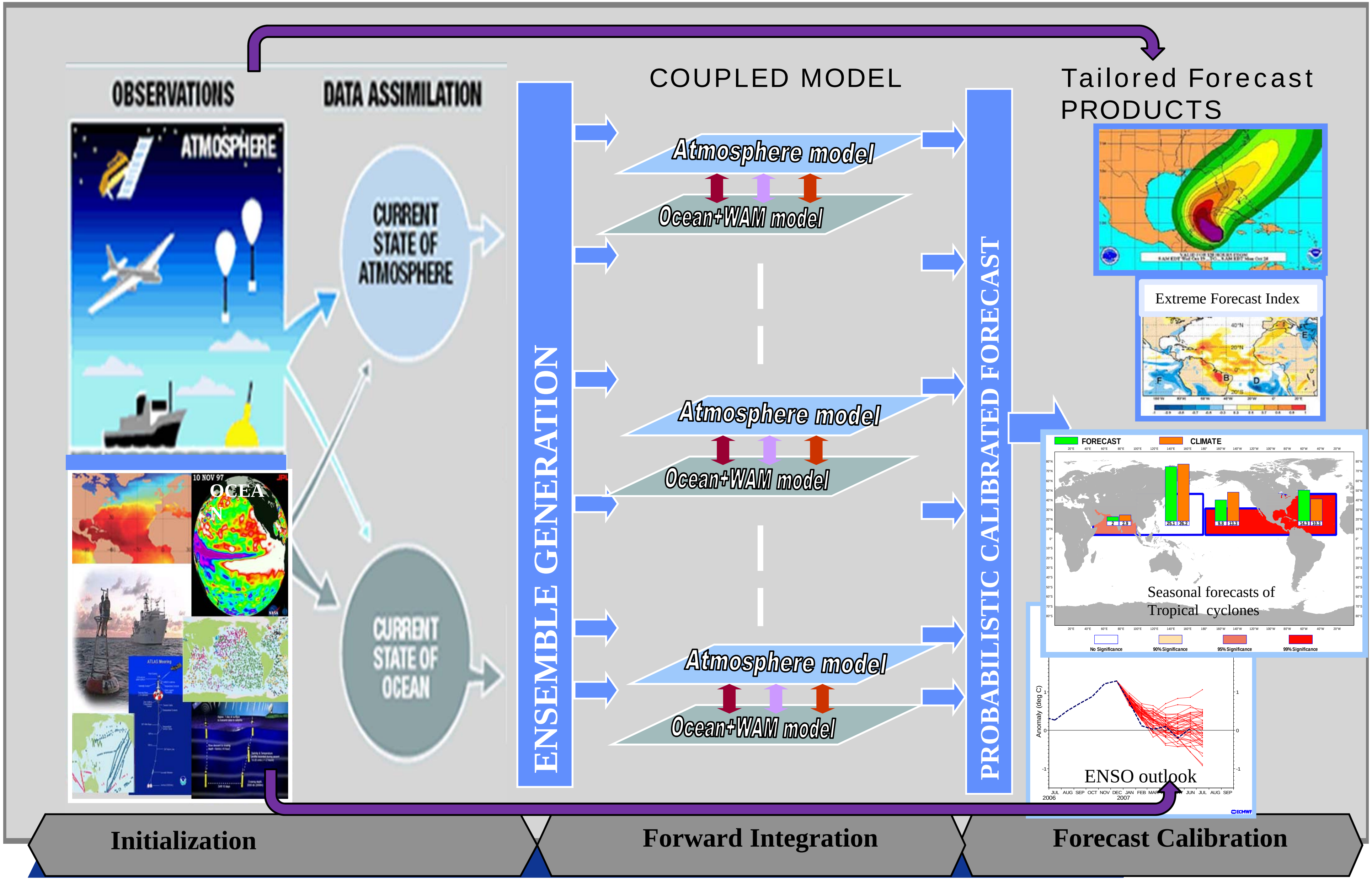
Impact of Active Ocean in the Skill of Weather Forecasts

Coupled Uncoupled

Left: CRPS
Right: Diff CRPS (coupled – uncoupled)

From Janssen et al 2013

End-To-End Coupled Forecasting System

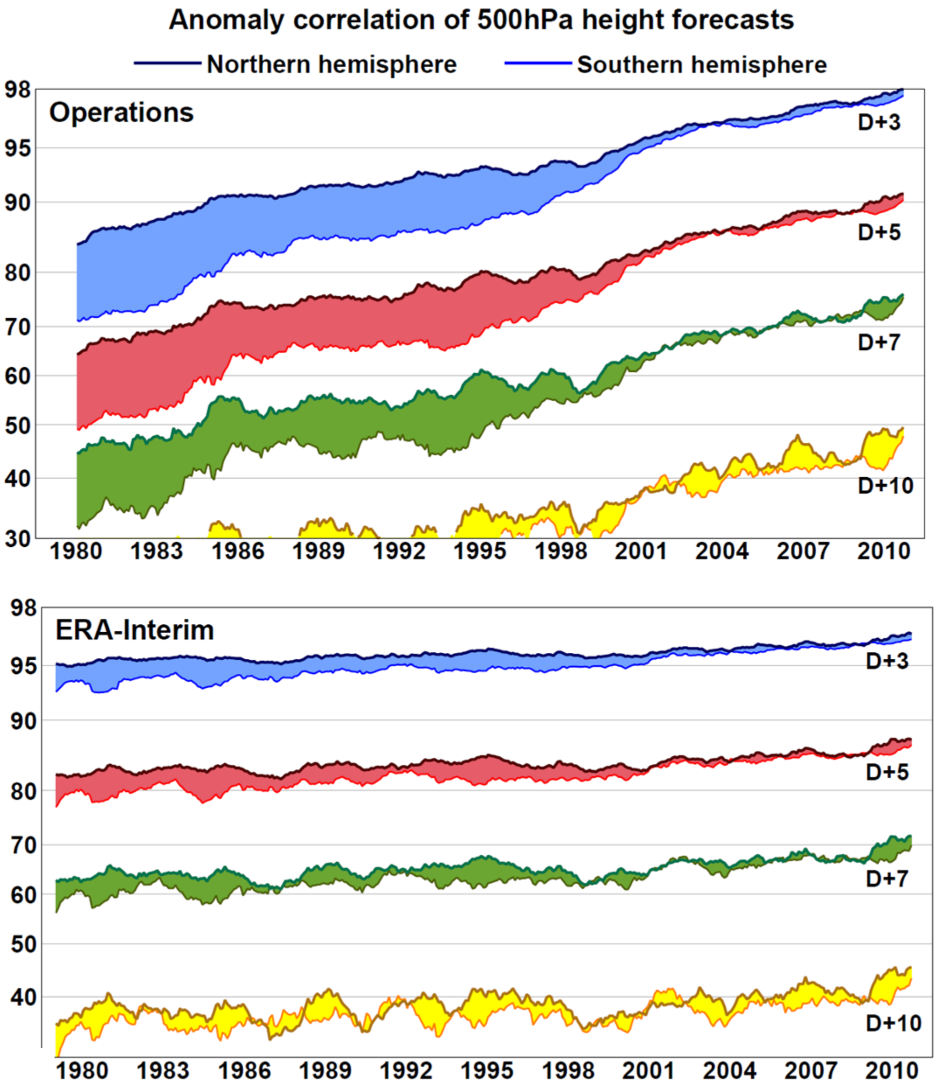


Different lives of one observation

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

Not all these aspects are easy to quantify objectively

NWP: Steady progress in forecast skill



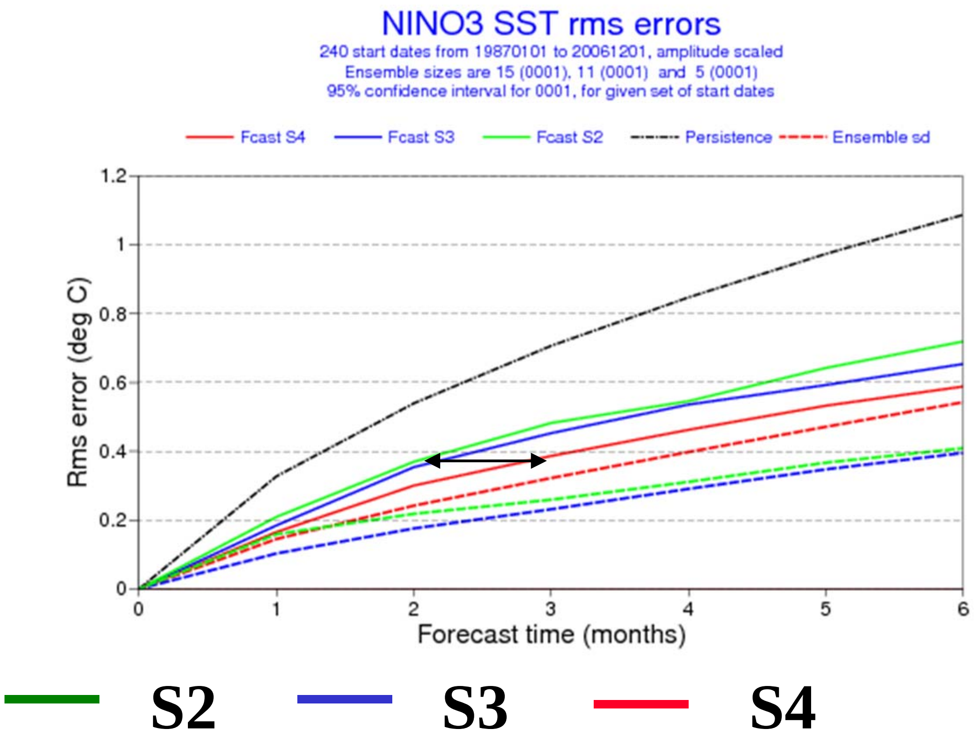
Steady progress ~ 1 day/decade

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

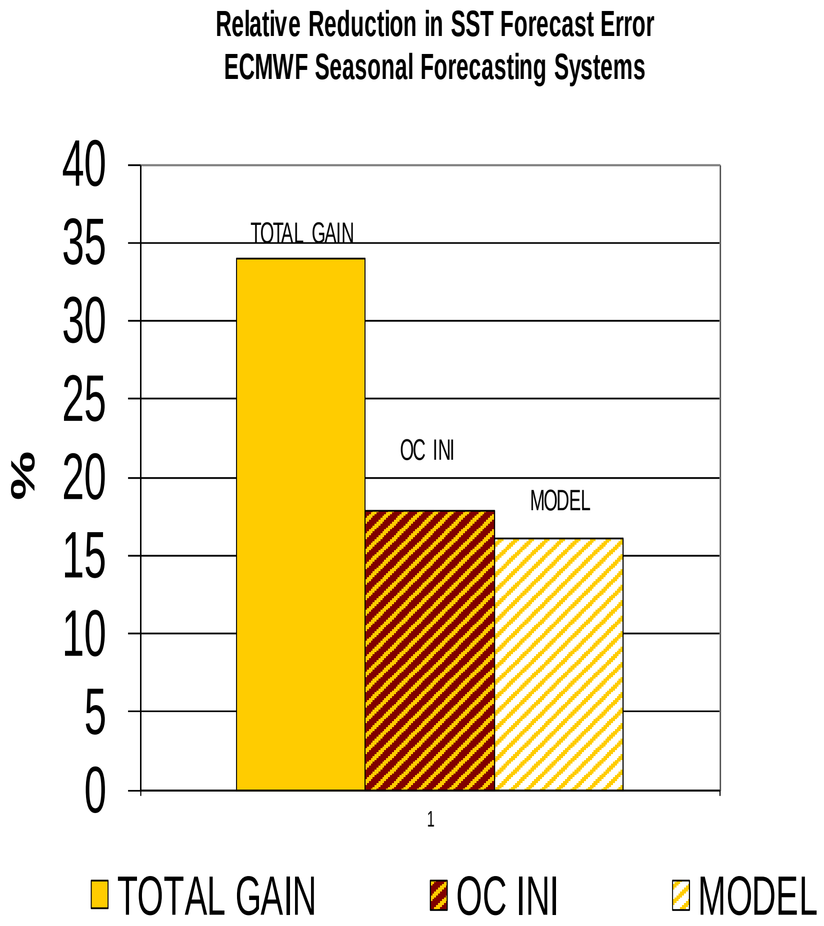
From Adrian Simmons

The quiet revolution of Numerical Weather Prediction, *Bauer et al Nature 2015*

Progress on Seasonal Forecasts



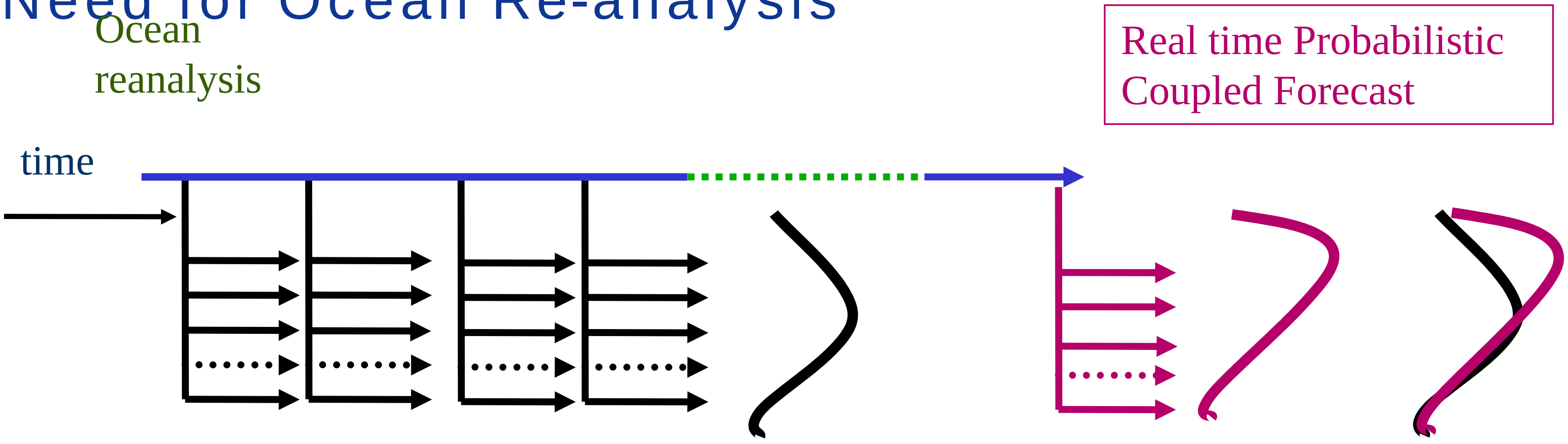
Courtesy of T. Stockdale



•**Steady progress: ~1 month/decade skill gain**

Half of the gain on forecast skill is due to improved ocean initialization

Calibration and Skill Estimation via Hindcasts
Need for Ocean Re-analysis



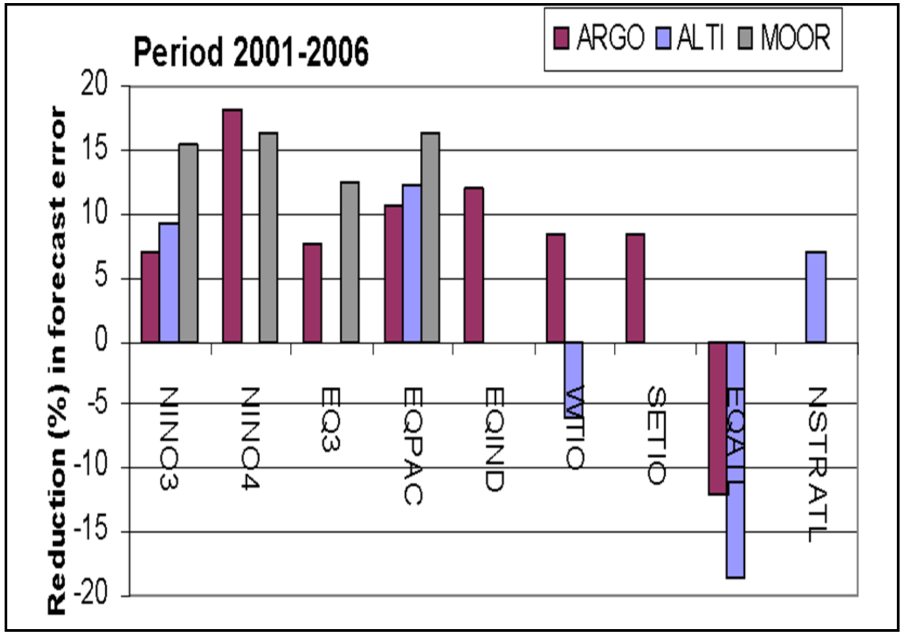
Cost of Seasonal OSES: Some Numbers

Reanalyses time-span	Np ~ 30 years
Number of times per year	Nm ~12
Number ensemble members per hindcast	Neh ~15
Number of ensemble members in forecasts	Nef ~51
Forecast length	M ~6-12 months
Total	Np*Nm*Neh*M > 300 yr of coupled model integrations

Evaluating the impact of ocean observations in seasonal forecasts is expensive, and outcome is not always significant

Seasonal Oses

S3 Seasonal OSES
2001-2006



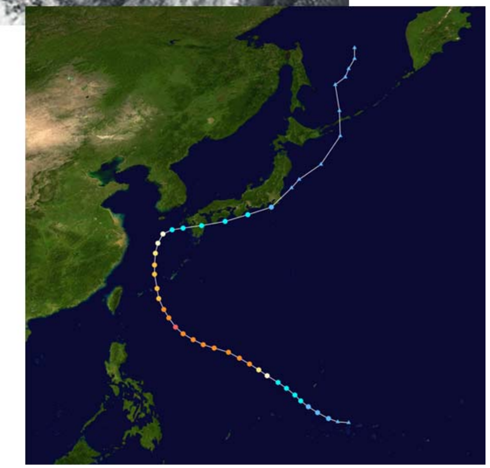
With previous operational S3, it was difficult to demonstrate Observation impact in the Atlantic

Role of the ocean in Prediction of Tropical cyclones in the Medium-Range.

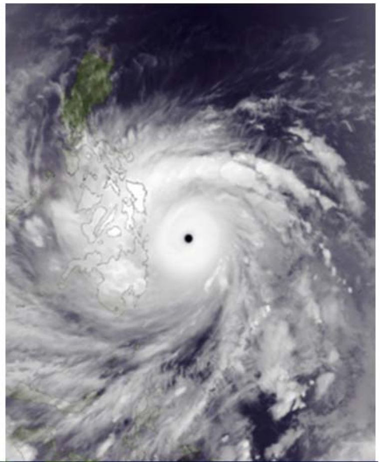
Two different Cases:

Super Typhoon Neoguri and Haiyan

Category 5. July 2014



Category 5. Nov 2013



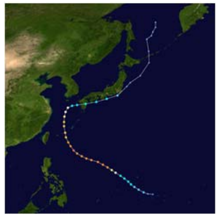
Coupled ocean-atmosphere systems improves the prediction of hurricanes.

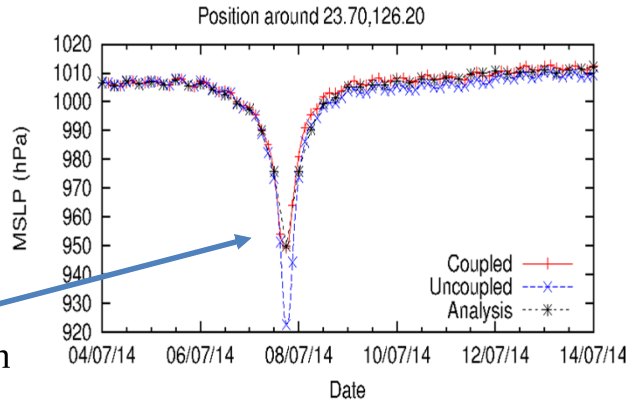
High-resolution atmospheric models in occasions overestimate the intensity of tropical cyclones if the interaction with the ocean is not taken into account.

The ocean initial vertical stratification play a role.

Time series of atmospheric fields at the two locations

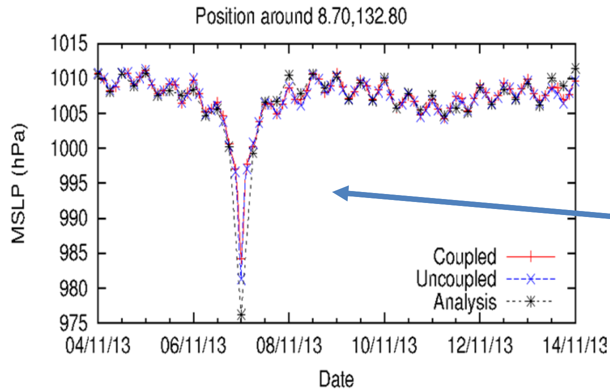
Negouri





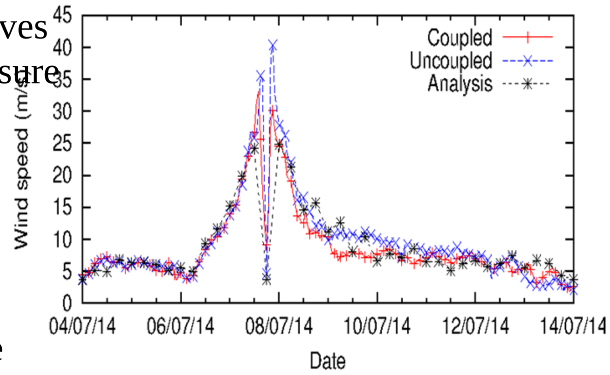
Overestimation

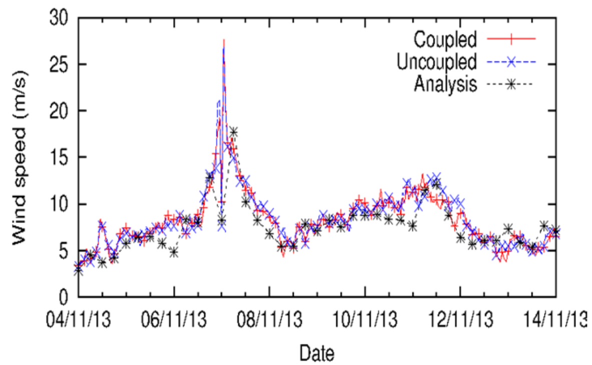
Haiyan



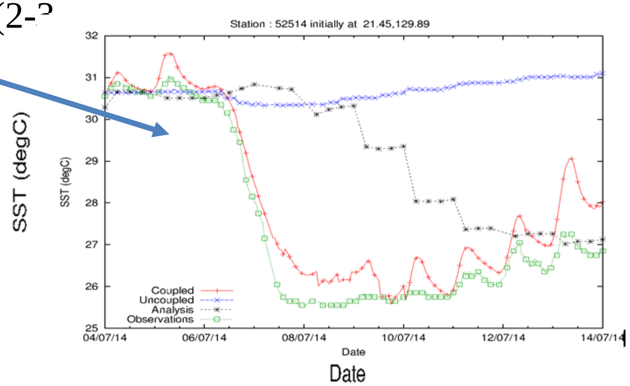
Coupling has little impact

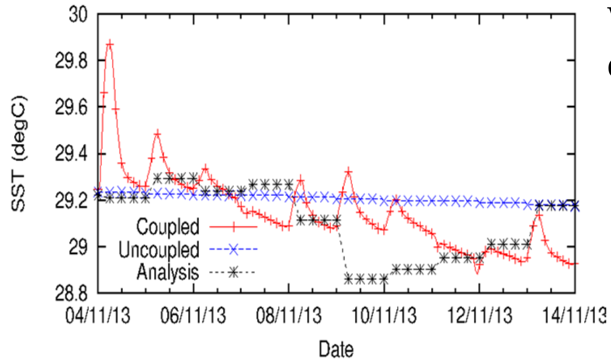
Coupling improves the centred pressure





Strong Negative SST damping (2-ˀ C)

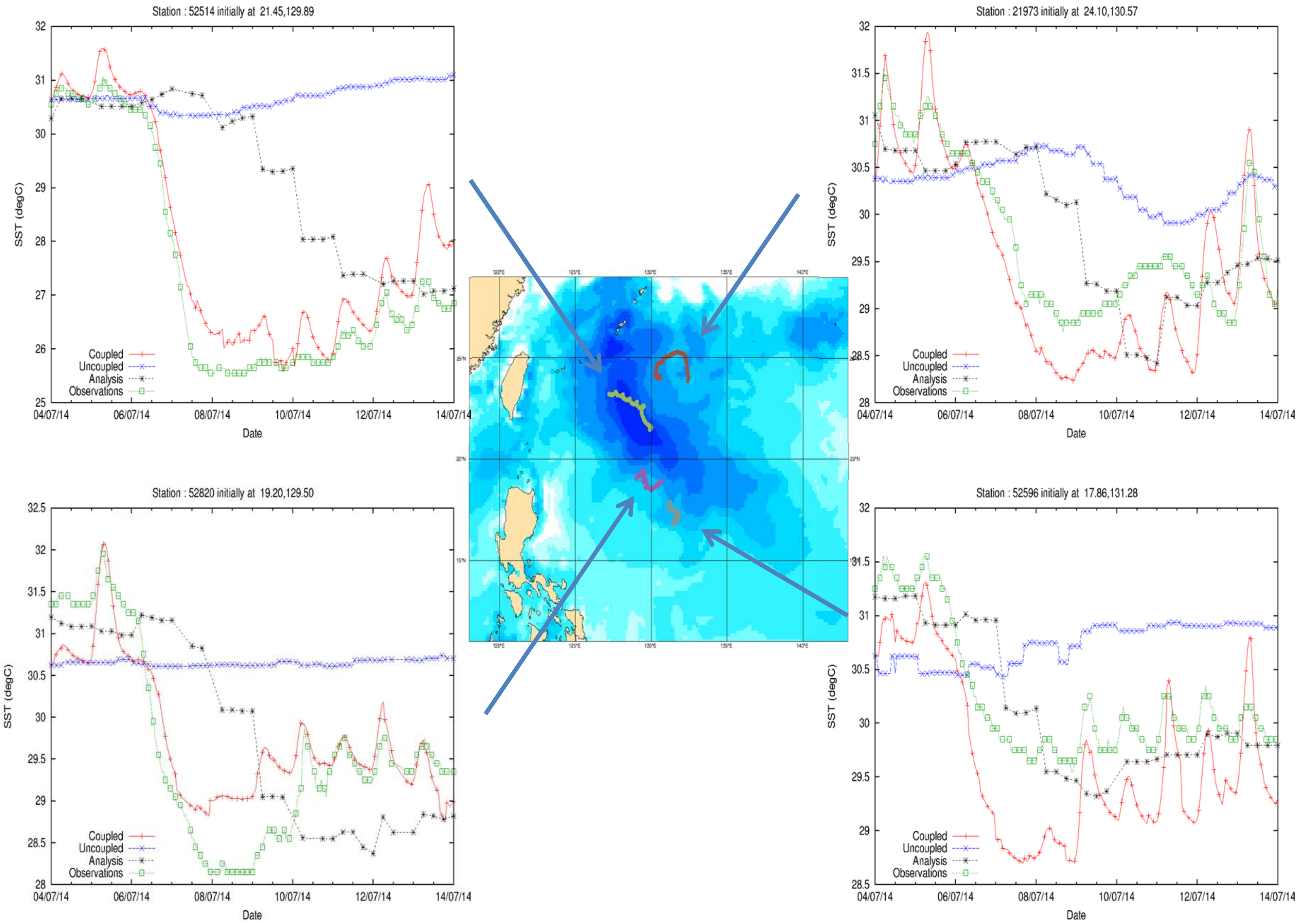




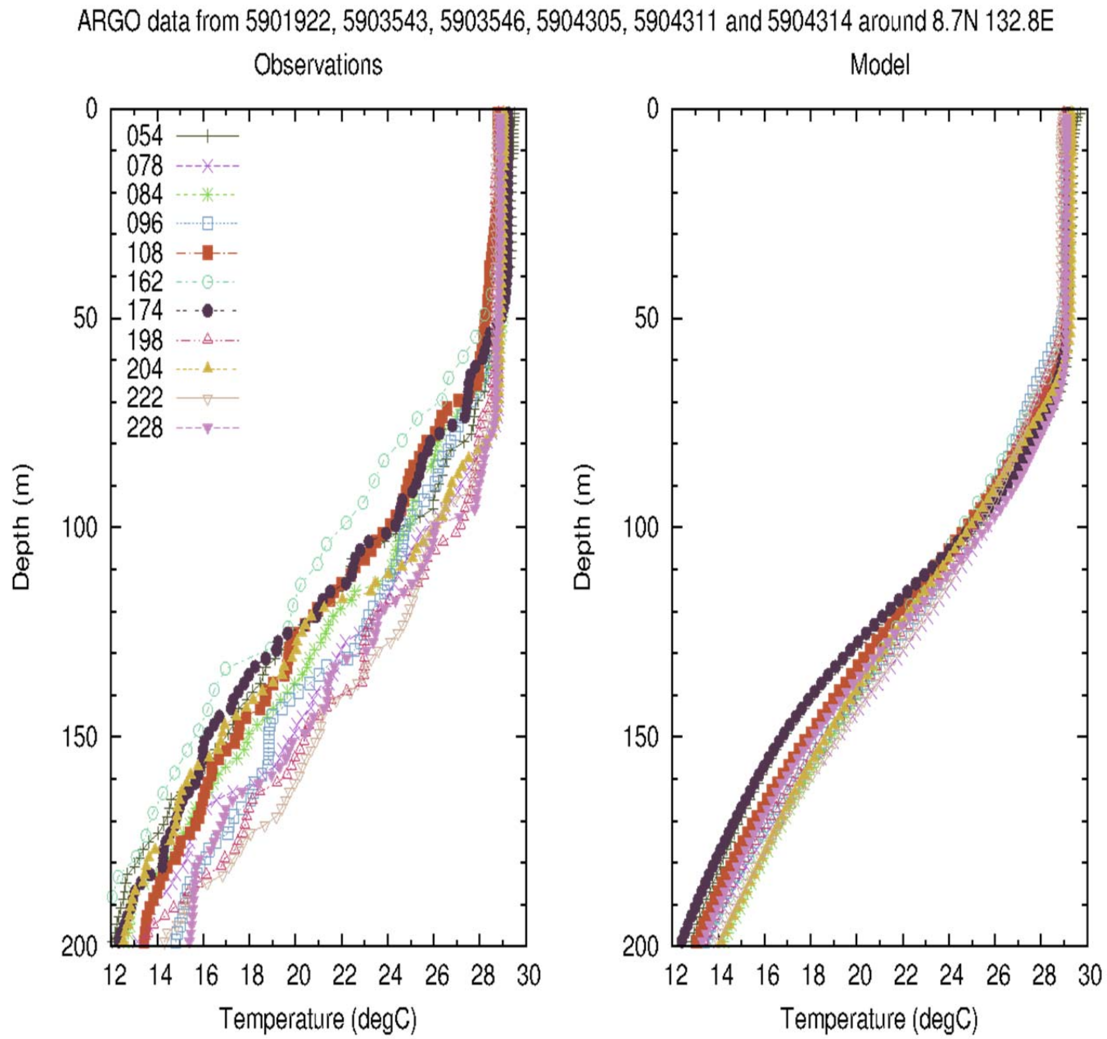
Week SST damping (0.5 C)

Courtesy of K. Mogensen

SST observations for Neoguri



Comparison of ARGO data to Haiyan: deep mixed layer

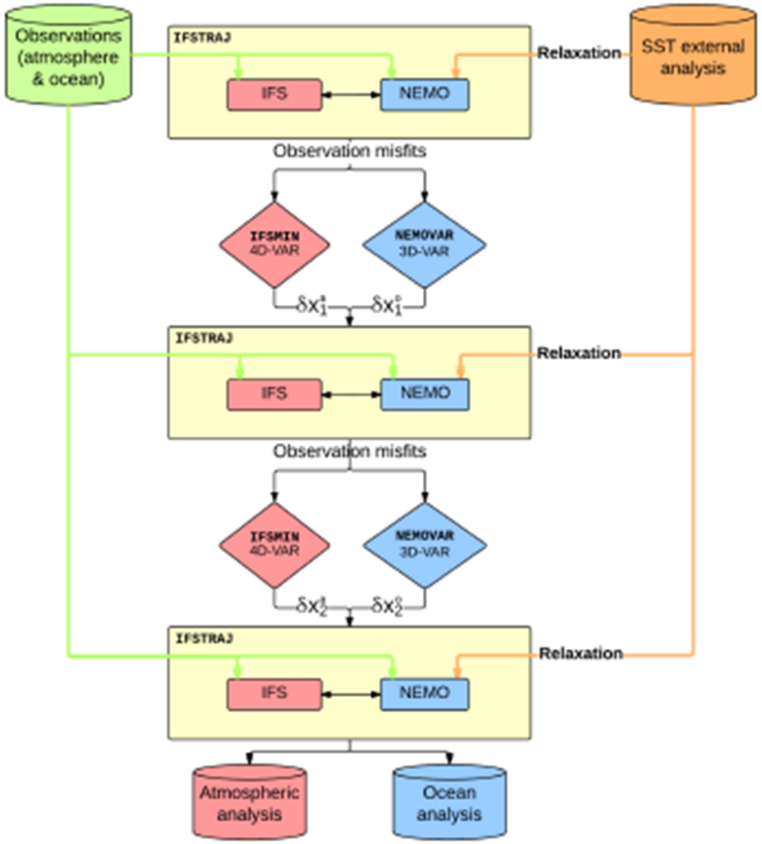


Courtesy of K. Mogensen

- Only observations closer than 250 km to 8.7N,132.8E are considered.
- Model interpolated to the observation position at the closest time stop
- Model integration starting at 2013110400
- Colours represent different model time step.
- **Much more variability in the observations than in the model**

Coupled Data Assimilation and Reanalysis

A prototype for an ocean-atmosphere coupled assimilation system (CERA)



Developed since end of 2012

Implementation based on:

IFS T159L137 - 24-hour window - two outer iterations

Keep incremental variational approach:

Common 24-hour assimilation window

Coupled model to compute observation misfits

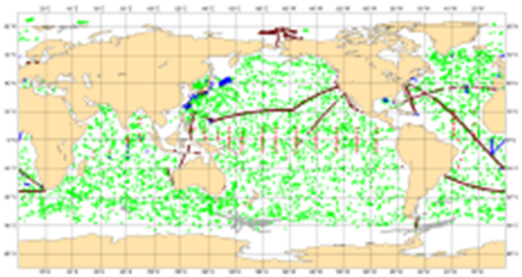
IFS T159L137 and NEMO ORCA1Z42 (1-hour coupling)

Increments computed in parallel

One SST field:

Computed in NEMO and constrained by relaxation

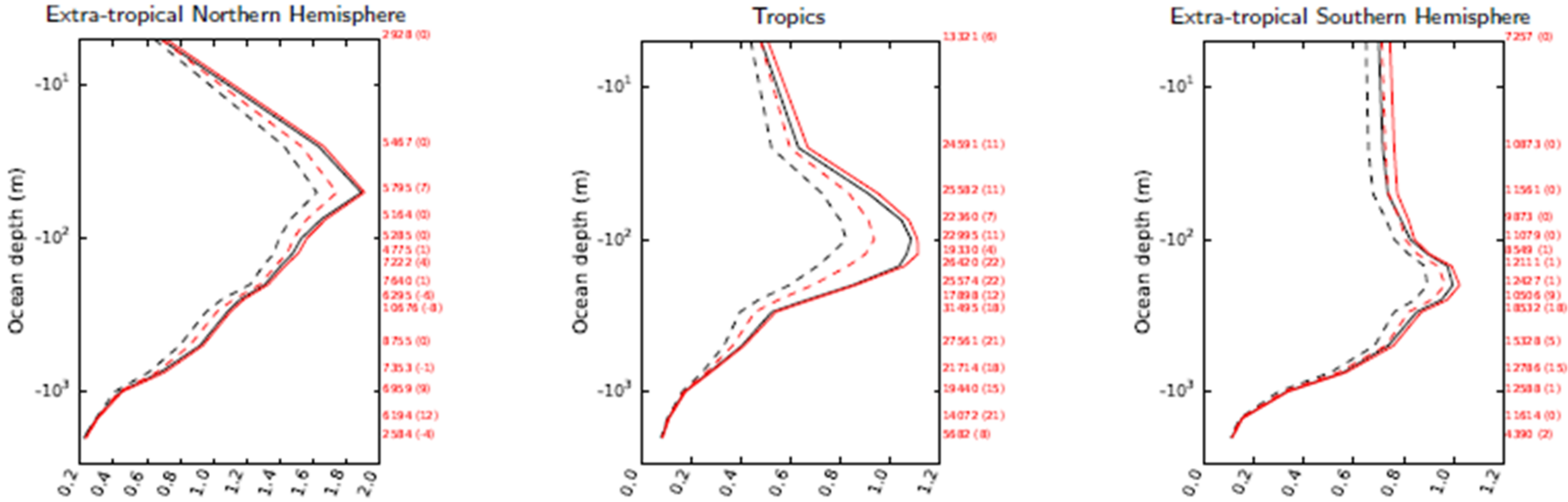
Quality of the coupled analysis - Ocean temperature



Ocean temperature observations

green: Argo
red: moorings
blue: CTD
brown: XBT
grey: marine mammals

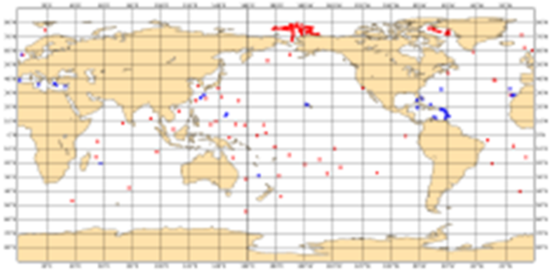
CERA compared to **UNCPL** - Analysis RMSE (dashed) and background RMSE (solid) for 09/2010



⇒ The CERA background and analysis RMSE are smaller in the mixed layer and thermocline
⇒ Same conclusion for May 2010 and January 2011

Laloyaux et al 2015, QJ

Quality of the coupled analysis - Atmospheric temperature

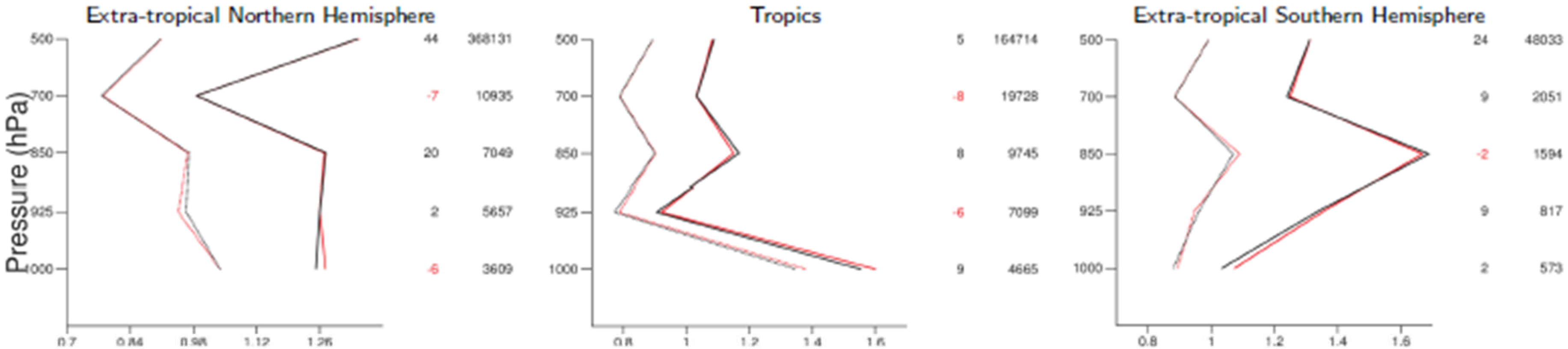


Near-surface temperature observations over sea (lsm<0.1,p<700hPa)

red: radiosondes

blue: aircrafts

CERA compared to **UNCPL** - Analysis RMSE (dashed) and background RMSE (solid) for 09/2010

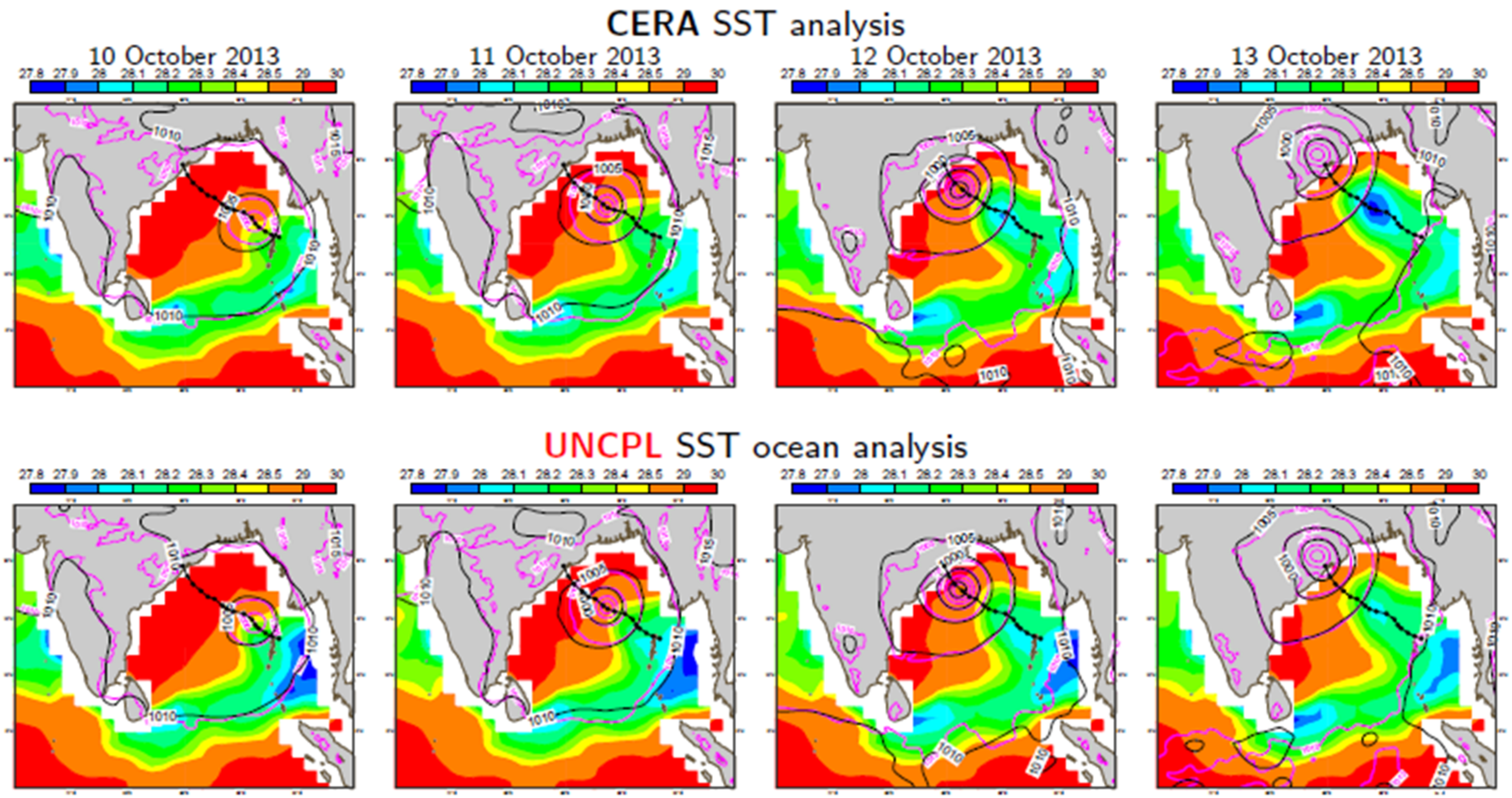


⇒ The CERA background RMSE is slightly smaller near the surface, neutral elsewhere

⇒ Same conclusions for May 2010 and January 2011

Laloyaux et al 2015, QJ

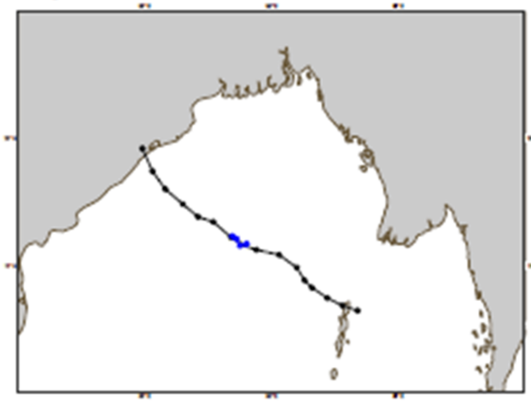
Use of near-surface observations - Tropical cyclone Phailin

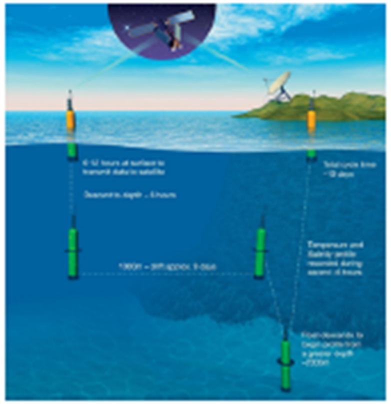


⇒ Fairly good representation of the cyclone in the two systems (still 15 hPa too high)
⇒ Slightly stronger cold wake in the CERA system

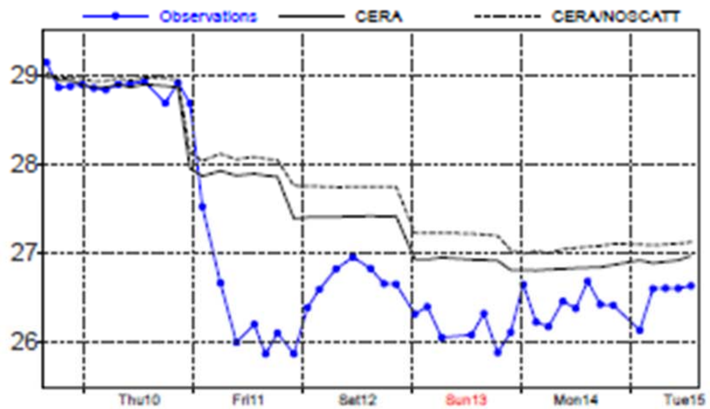
Use of near-surface observations - Tropical cyclone Phailin

Impact of scatterometer data on ocean temperature at 40-meter depth

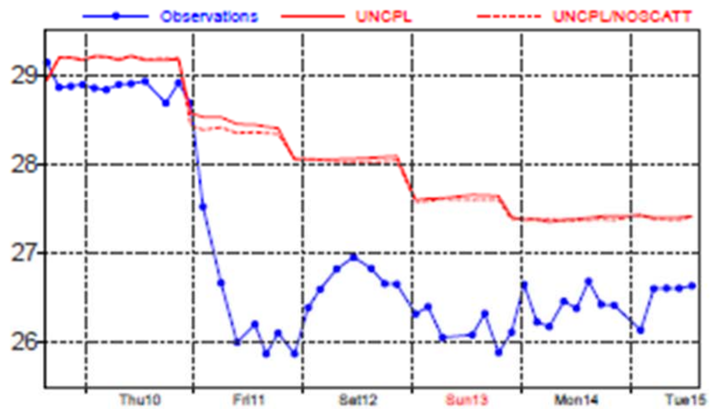




Argo temperature observations
More profiles for the mixed layer



CERA



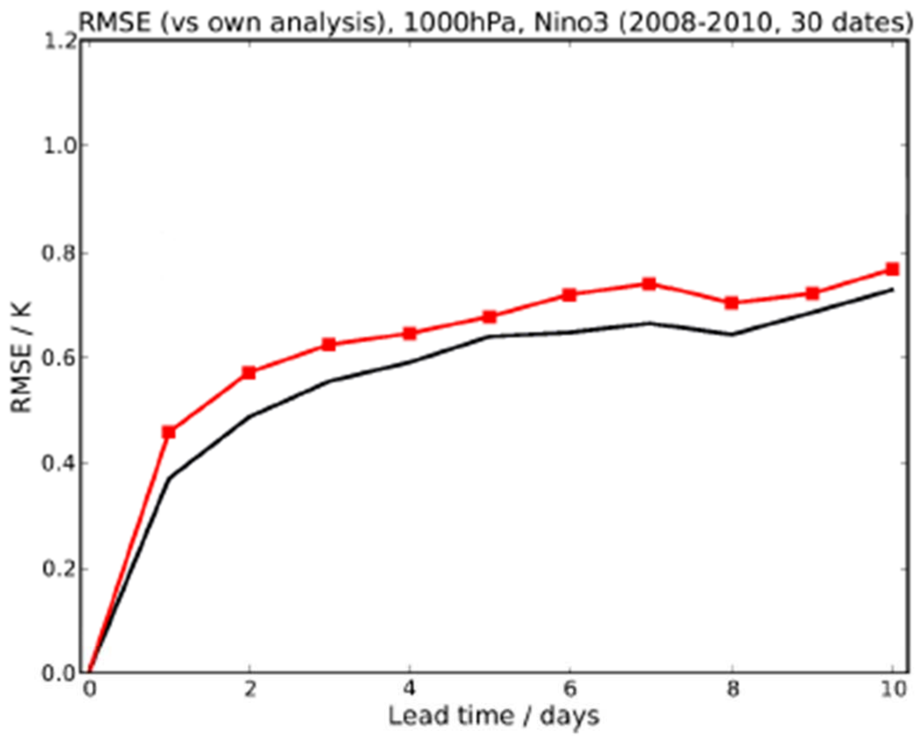
UNCPL

⇒ Positive impact of scatterometer data at 40-meter depth in the CERA system (but not perfect)
⇒ CERA analysis better than UNCPL analysis

Laloyaux et al 2016, MWR

Initialisation of coupled forecasts - shocks/spin-up effect

Score for 1000hPa temperature RMSE in Nino3
(**CERA** and UNCPL versus own analysis, 2008-2010/30 dates)



⇒ Larger error growth in UNCPL compared to CERA (resulting from the SST discrepancies)
⇒ The effects of the shock are felt out to at least 10 days' lead time

Mulholland et al 2015, QJ

Summary

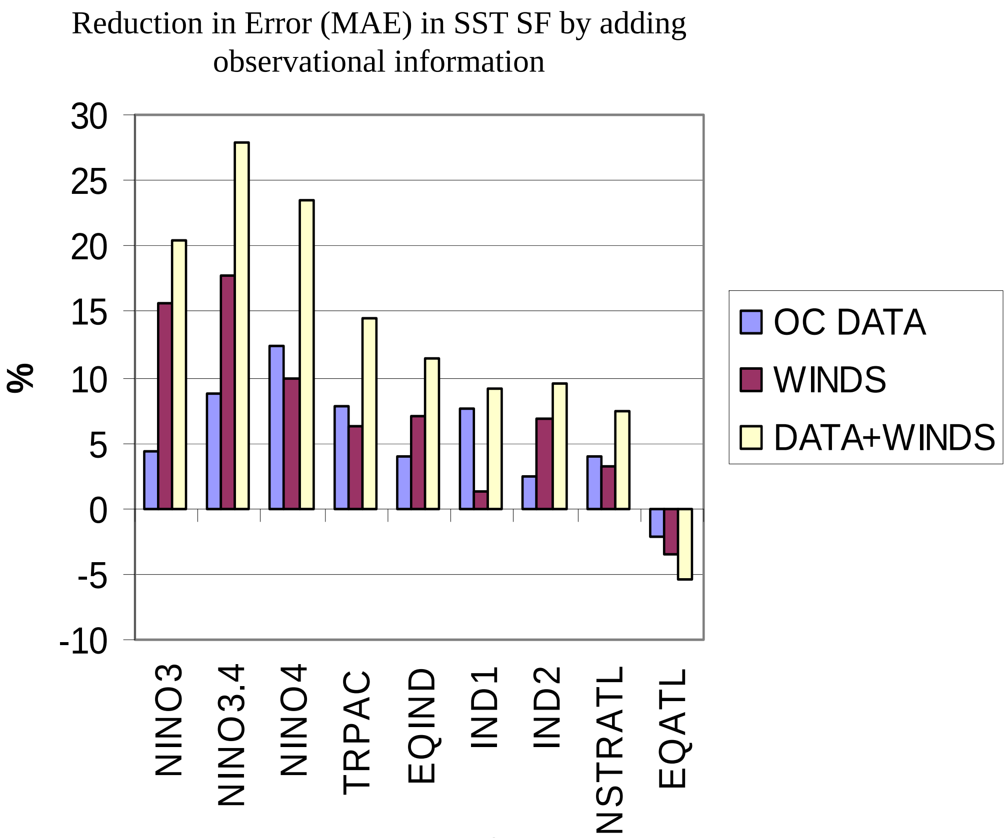
- **One observation influences many aspects of the forecasting system**: initialization, model, calibration, and verification
- **Objective evaluation is difficult**, even for the impact on the initialization.
- **Argo for seamless prediction needs to address many time scales**: from diurnal to decadal and beyond (for reanalysis).
- **Modelling and initializing the coupled O-A boundary laye**r is becoming increasingly important.
- **Need of long and sustained observing system** for verification of reanalyses, extreme events/severe weather warning, and calibration of seasonal forecasts
- **Model & DA errors** in both ocean and atmosphere remain a serious obstacle, and Argo can contribute to model development
  - At the Equator
  - O-A boundary layer.

Requirements

Dependent on application (initialization, model, calibration, verification) and **time scale.**
Attributes Discussed:

- **Stability and life span of a given observing system**: to be discontinued only if new observing systems can cater the same needs.
- **Accuracy:** Unbiased. Random error within 1-5% of signal**. Temporal sampling:**
  - Frequency: 1-3 hours for O-A BL. Daily for subsurface. Monthly below 1000 m
  - Temporal coverage: as long as possible
- **Spatial sampling:**
  - Horizontal: 200-1000Km for in-situ, Higher for satellite.
  - Vertical: 1-10m in upper ocean (~300m). Decreasing with depth. Some below 2000m
  - Focus areas: Equator, mixed layer, WBC
- **Variables:**
  - T(z),S(z),U(z),SSH,SST,SSC,SSS, Ocean Color, Geoid, Bottom pressure…
  - Wind, humidity, SLP, precipitation, waves (height, spectrum, period)…
  - Multivariate (collocated) and derived (fluxes, transports, MLD profiling of OA BL)
- **Delivery streams**: NRT (1-6 hours delay), and BRT (10-days, months, years)
- **Generalized Reference sites: Long time series very valuable.**

Impact of winds and subsurface obs on seasonal forecast skill:

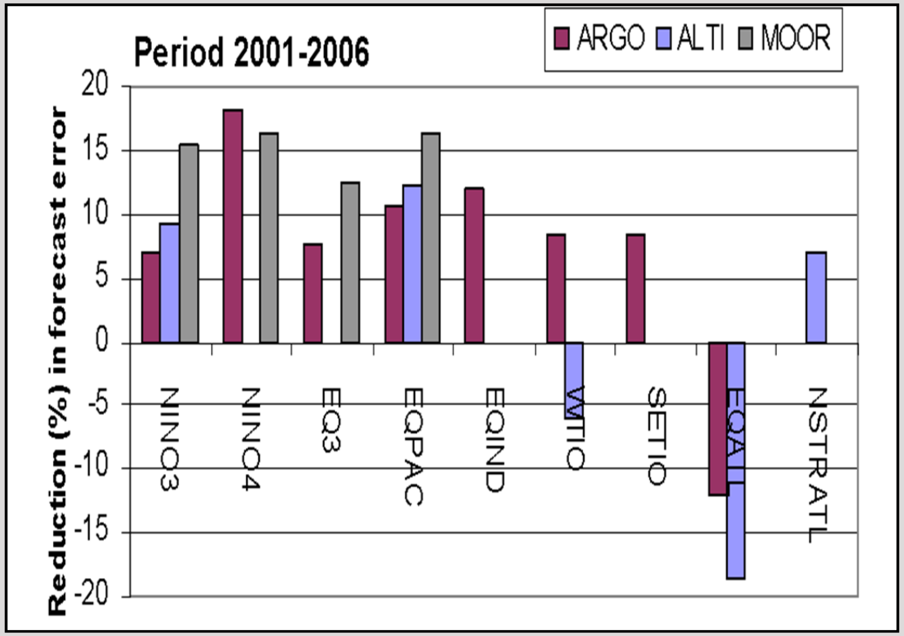


Winds and subsurface observation contribute to the forecast skill, especially in Eq. Pacific

Additional experiments suggested that no observing system was redundant.

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

Assessing the Ocean Observing System (S3)



From Balmaseda and Anderson 2009

See also Fujii et al 2008

1. No observation system is redundant

   Not even in the Pacific, where Argo, moorings and altimeter still complement. Lessons for other basins?

2. There were obvious problems in the Eq Atlantic: model error, assimilation, and possibly insufficient observing system

Important to bear in mind

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

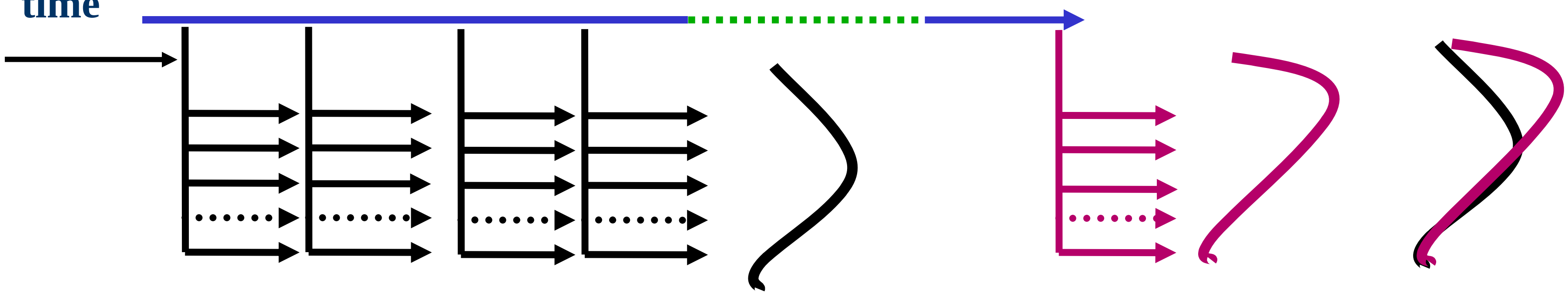
Calibration and Reforecasts:

-Dealing with model error
-Extreme Events
-Tailored products **(health, energy, agriculture)**

Ocean/Atmosphere reanalyses

Real time Probabilistic Coupled Forecast

time



<u>Hindcasts, needed to estimate climatological PDF, require a historical ocean and atmospheric reanalyses</u>

Consistency between historical and real-time initial conditions is required.

Hindcasts are also needed for skill estimation

Seasonal Forecasts

The basis for extended range forecasts

➢ **Forcing by boundary conditions changes the atmospheric circulation, modifying the large scale patterns of temperature and rainfall, so that the probability of occurrence of certain events deviates significantly from climatology.**

- **Important to bear in mind the probabilistic nature of SF**

➢ **The boundary conditions have longer memory, thus contributing to the predictability. Important boundary forcing:**

- **Tropical SST: ENSO**
- **Indian Ocean Dipole, Atlantic SST**
- **Land: snow depth, soil moisture**
- **Sea-Ice**
- **Mid-Latitude SST**
- **Atmospheric composition: green house gases, aerosols,…**

More recently: Even Atlantic improves

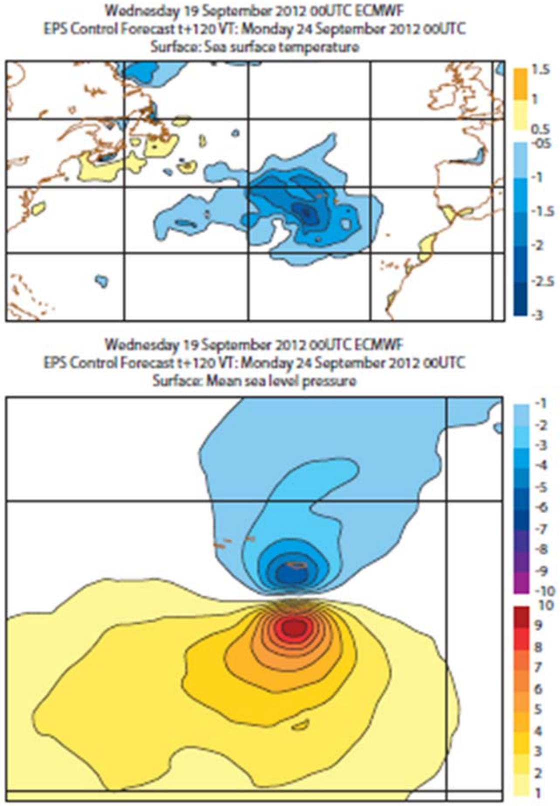


Figure 3: NADINE. Top: ensemble mean sst difference day5-day0. Bottom: ensemble mean pressure difference between coupled and control for day 5 forecast.

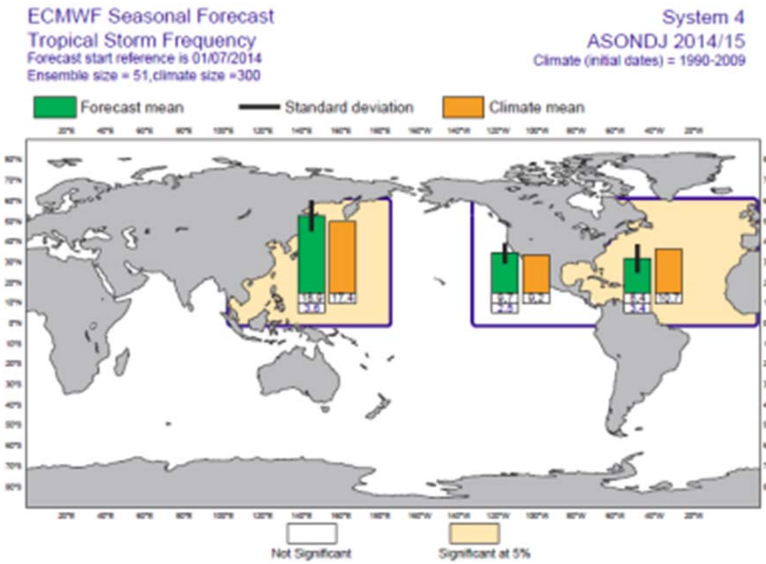
So…

- Careful a-priori Selection of impact indicators
  - Relevant for climate/society
  - Forecasts are skilful
  - There is some evidence of interannual Atlantic SST as a driver

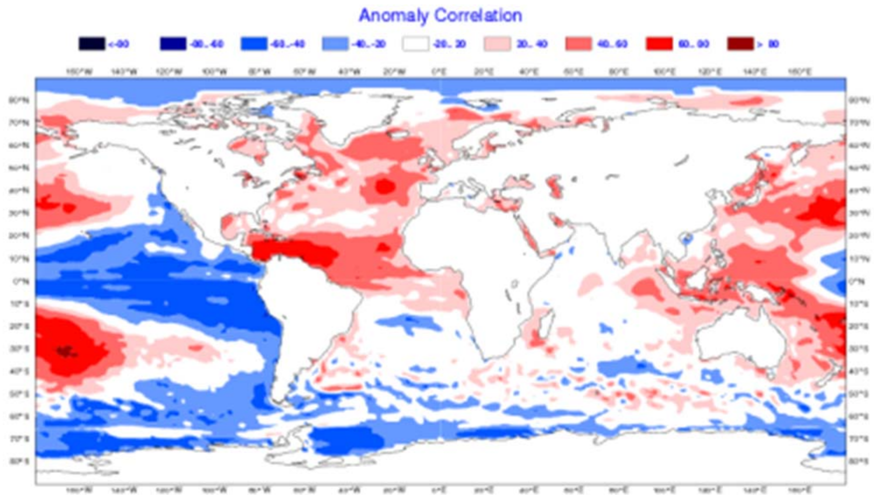
- Explore statistically the relation of the indicator with ocean variables (6 months)
  - Using reanalyses (atmospheric and oceanic)
  - Using model ensembles (perfect model)
  - This will help to identify important areas

- Conduct OSES (9 months)
  - Ocean reanalyses for 10-20 years withdrawing obs
  - Use those OSE-reanalyses to initialize seasonal forecasts

Proposed Indicator:
Atlantic Tropical Cyclones



Observed Correlation
SST- Number of Trop Cyclones

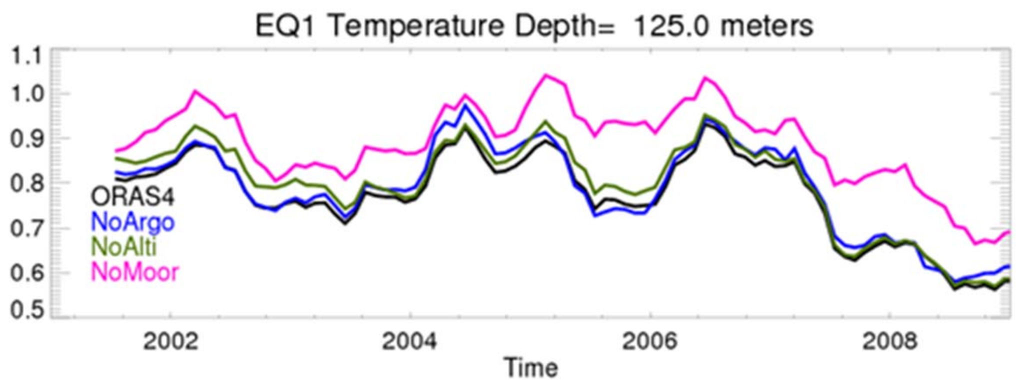


- S4 skill score (acc): 0.57
- Only once a year (June or July)
- Clear relation with SST
- Very relevant for society

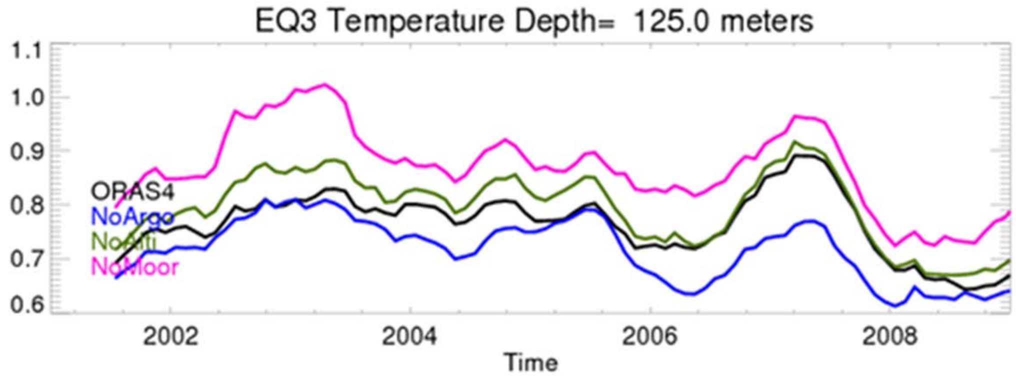
- Investigate the relation with subsurface variables (D26 iso)
- Investigate the relation in the model world using ensembles

More Recent ECMWF OSEs (ORAS4)

Impact on Ocean Analysis: Fit (RSME) to moorings



Eastern Pacific: Argo does not improve the fit to moorings

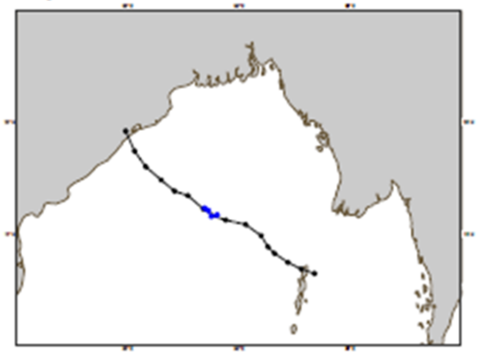


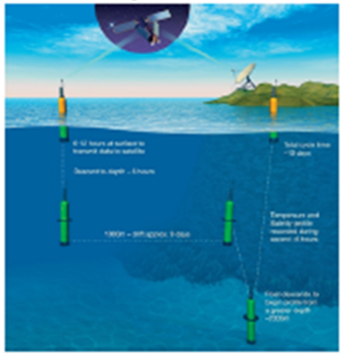
Western Pacific: Argo degrades the fit to moorings

No significant impact found in seasonal forecasts:
Model error? Others?

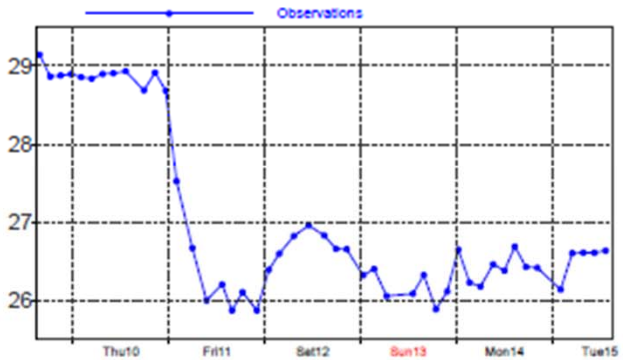
Use of near-surface observations - Tropical cyclone Phailin

Impact of scatterometer data on ocean temperature at 40-meter depth





Argo temperature observations
More profiles for the mixed layer



Monthly Forecasts

MJO is major source of predictability for this forecast range

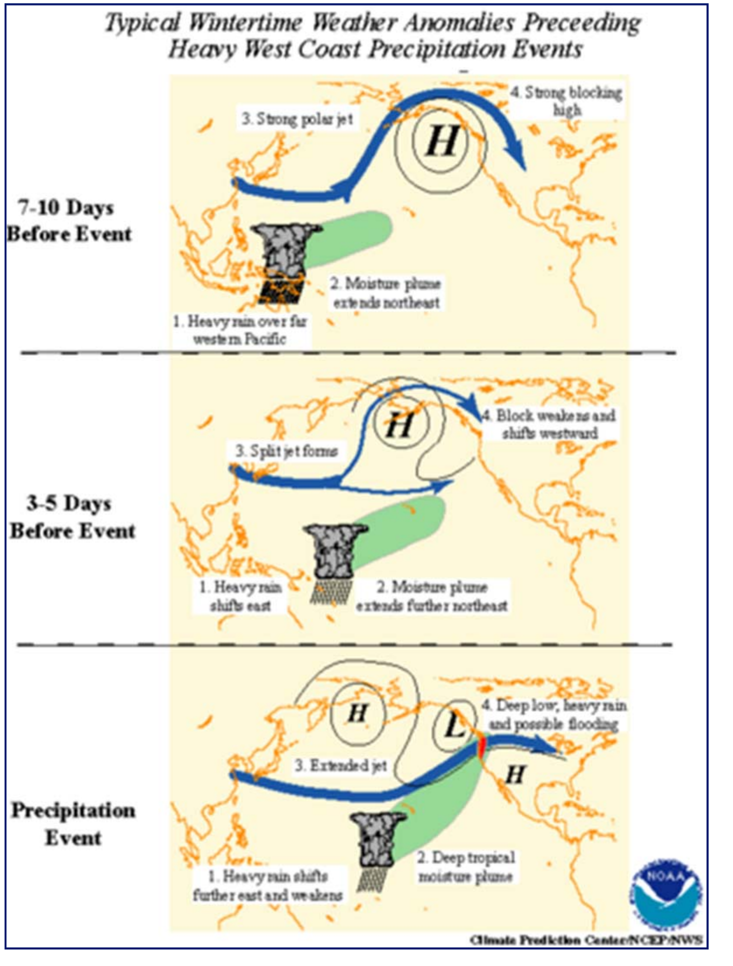
Mid latitude teleconnections (NAO….)

MJO modulating Tropical Cyclones

MJO triggering ENSO

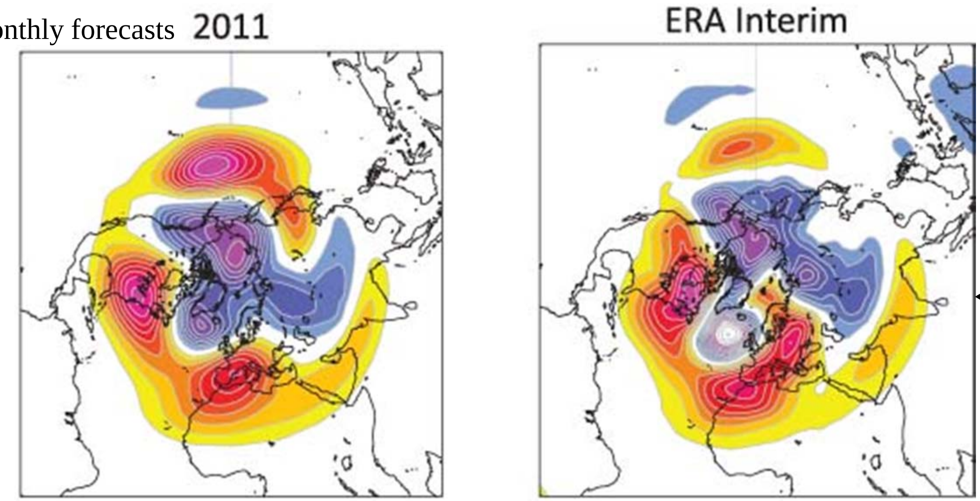
Important for its prediction:

- Coupled Ocean-Atmosphere interaction in tropical convection interaction
- Ocean mixed layer & diurnal cycle.

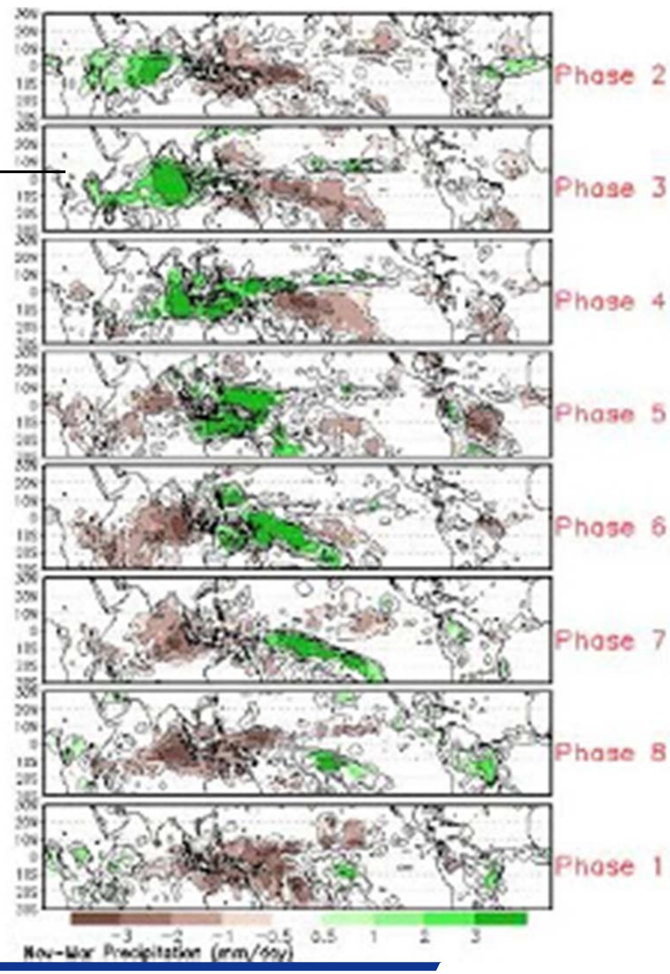


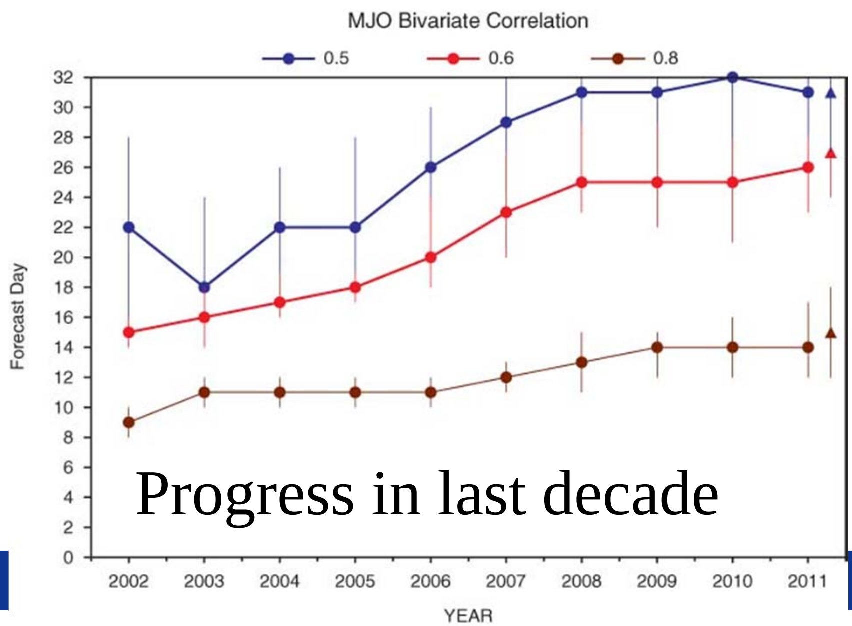
Monthly Forecasts

Monthly forecasts



Composites of MJO phase 3 10-days lagged. Vitart 2013





Progress in last decade

Reanalyses of atmosphere, ocean, land
A wealth of information

- Societal applications: wind energy, insurance, waves, crop yield, risk assessment ….
- Process studies and climate research and applications
- Model development
- Initialization, calibration, verification of forecasts
- Monitoring of observing system
- Benchmark to measure progress

Production:

- **Every few years** as new models/DA/observations become available.
- They can be continuously updated with some delay (behind real time)
- **Few atmospheric**; NCEP, ECMWF, JMA, NASA, NCAR …
- **Several oceanic** : usually linked to seasonal forecasts.

Two Streams:

Highres: satellite period last 30-50 years
Clim: low resolution, conventional observations >100-years