Challenges in Coupled Data Assimilation for state estimation and prediction of the Tropical Pacific

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WHAT SHOULD WE EXPECT FROM CDA?

- CDA can **amalgamate the entire observation network**, creating a full 3D picture of the Earth System using known (modeled) physics to fill in the gaps (both spatially and temporally).

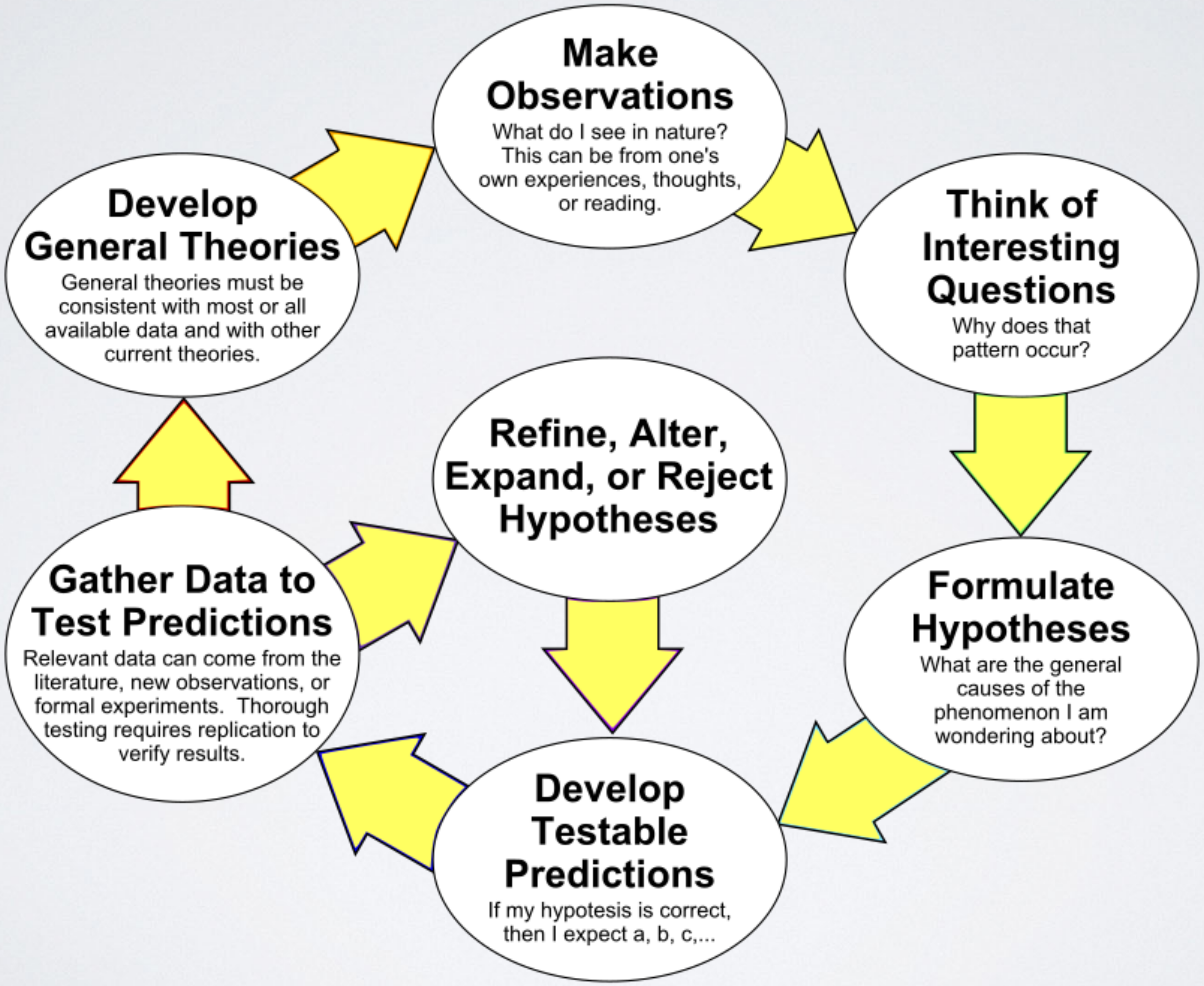
- In this process, CDA can **point to discrepancies** between observing platforms and modeling systems.

- CDA can **amplify the impact of observations** by allowing them to impact across domains (e.g. ocean to atmos or atmos to ocean)

WHAT SHOULD WE NOT EXPECT

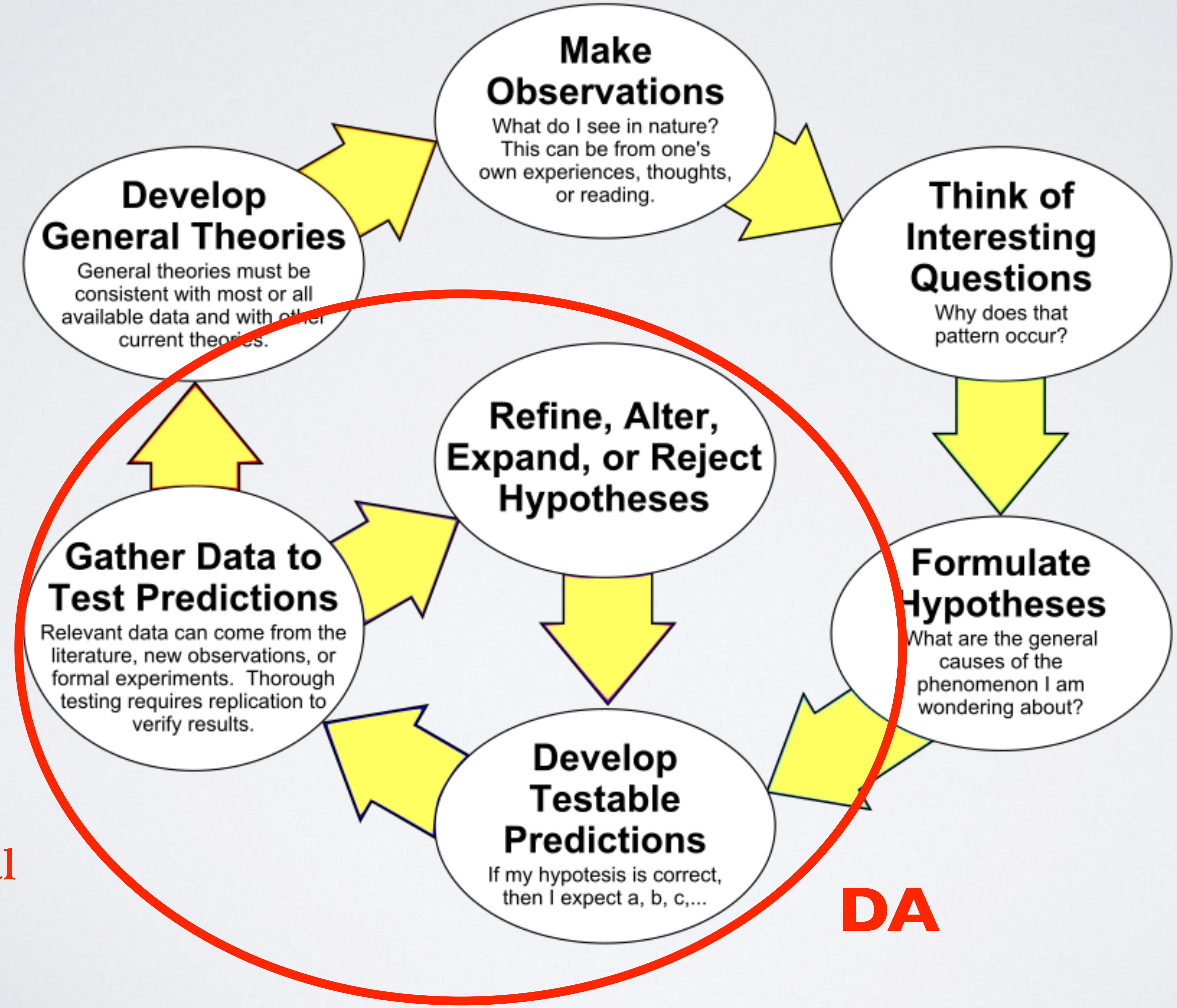
- CDA is **limited by the quality of its inputs** -
  - The **model attractor must map to** the desired scales of **the nature attractor** (otherwise forecasts have mild to severe biases).
  - The **observing system must constrain the unstable modes** of the model system (otherwise even well modeled dynamics produce growing errors).

DA AS PART OF THE SCIENTIFIC METHOD



DA AS PART OF THE SCIENTIFIC METHOD

Data assimilation largely focuses on **automating** this sub cycle **via rigorous mathematical** methods



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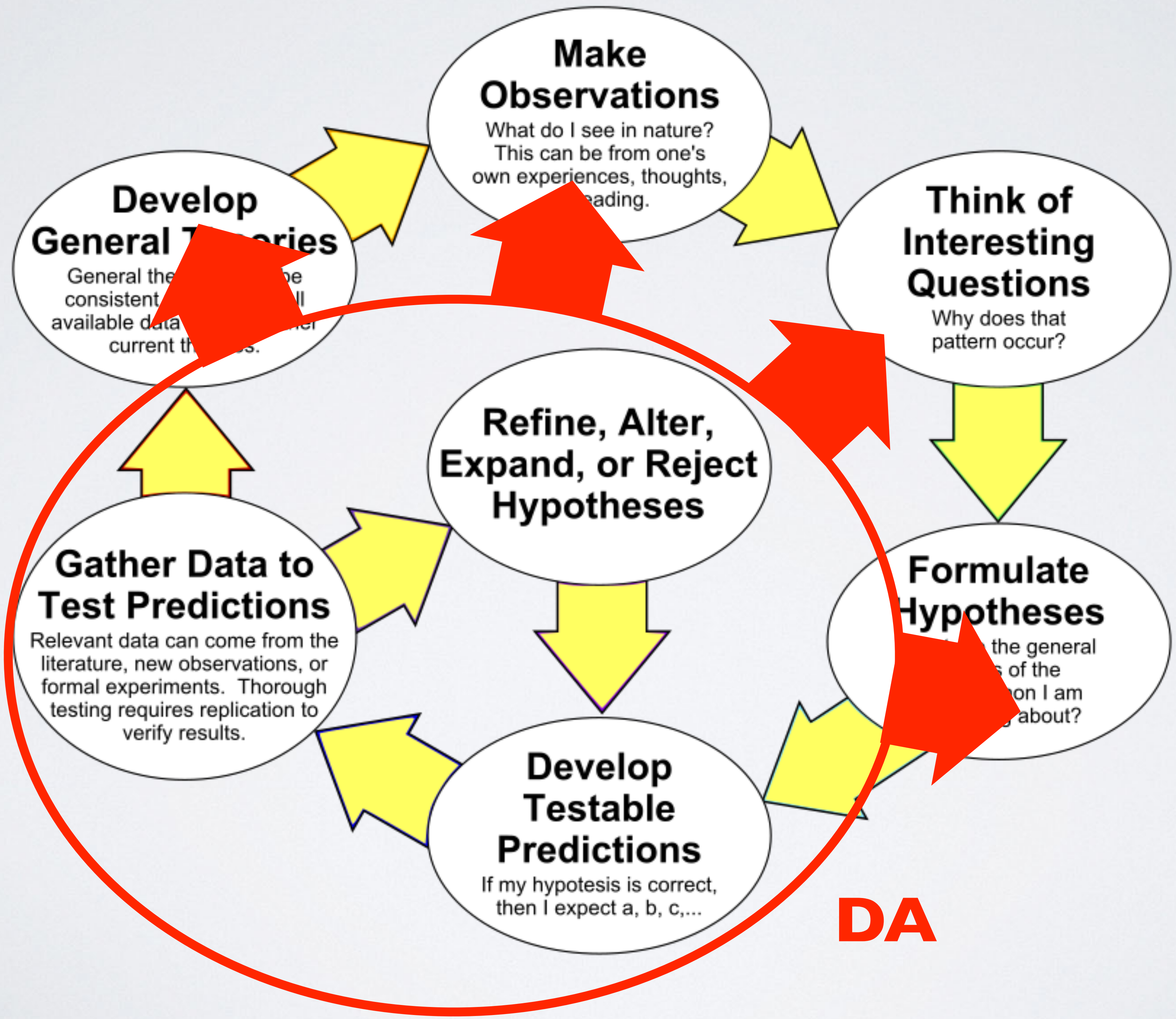
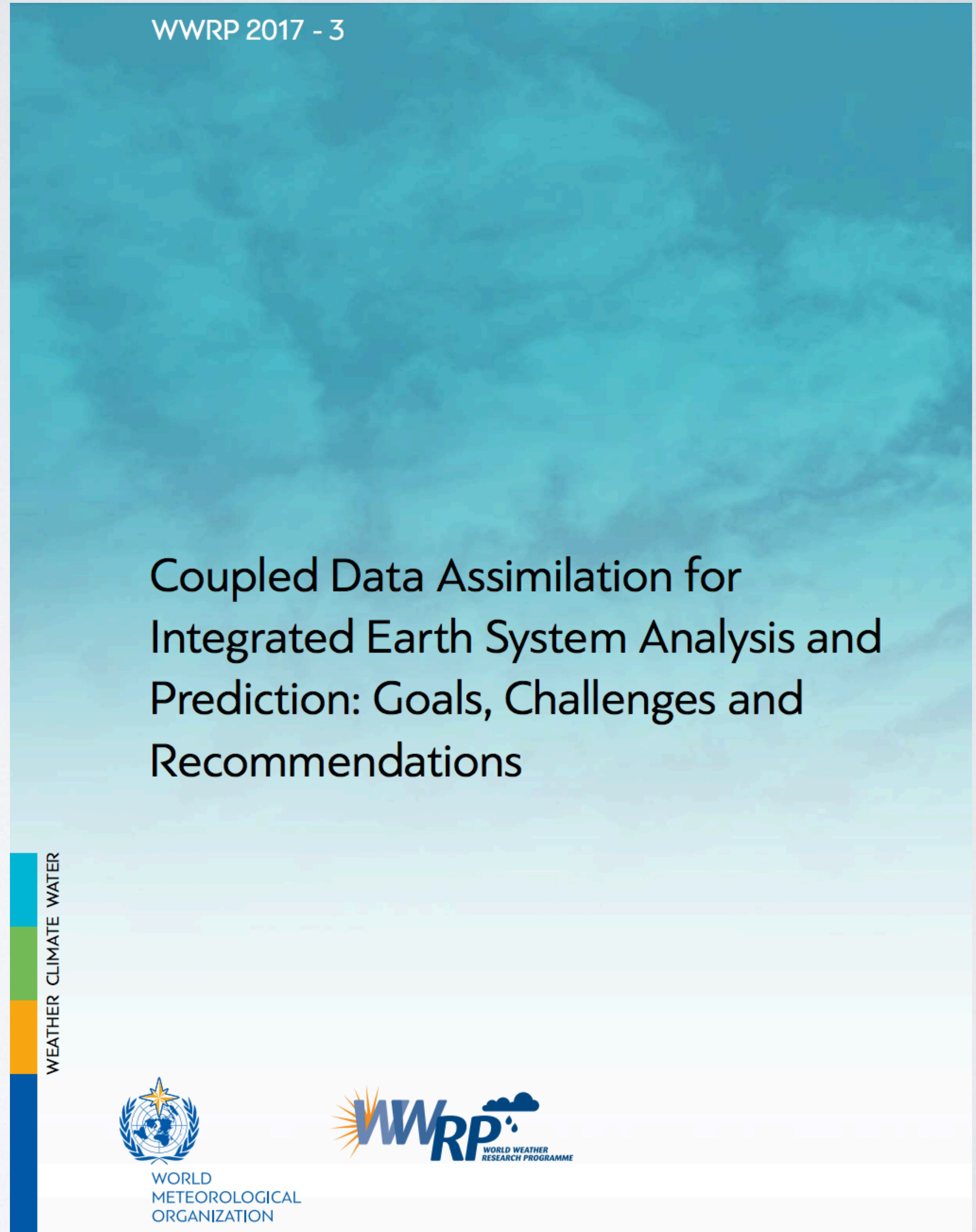


Data assimilation can also **feed back insights** to all phases of this process

WMO WHITE PAPER ON CDA



Penny et al., (2017): https://www.wmo.int/pages/prog/arep/wwrp/new/documents/Final_WWRP_2017_3_27_July.pdf

KEY RECOMMENDATIONS RELEVANT TO TPOS-2020

- **Standardize the observing network** for all Earth system domains in order to meet the timeliness and quality control requirements of NWP
- **Identify gaps in the observing system that are essential for constraining CDA** applications, including fluxes at the domain interfaces;
- Develop CDA methods that can accommodate **multiple spatiotemporal scales** in support of the seamless prediction paradigm;
- Develop methods for CDA to identify, isolate, and elucidate **model errors and biases** that degrade forecast skill, which can then be used to directly improve coupled modeling;
- Promote improved **representation of model uncertainty** in the coupled forecast system using stochastic physics and other advanced methods;
- Perform research to increase knowledge on how to best represent evolving **errors in non-atmospheric model components** (e.g. sea ice, land and ocean) on the timescales of NWP;

Penny et al., (2017): https://www.wmo.int/pages/prog/arep/wwrp/new/documents/Final_WWRP_2017_3_27_July.pdf

HOW WILL CDA USE OBSERVATIONS

- (1) Cross-domain influence
- (2) Constraining chaotic dynamics of a dynamical model (e.g. via state estimation / initialization).
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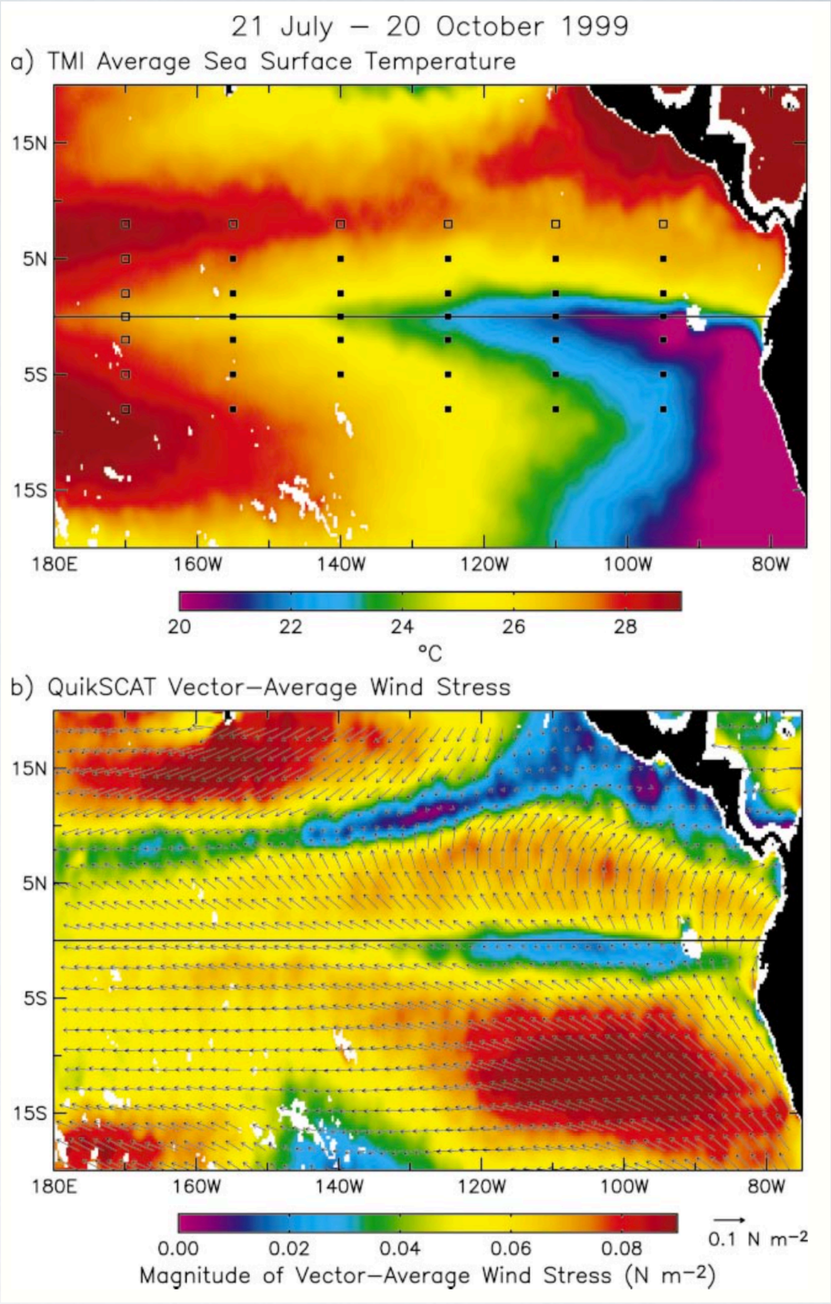
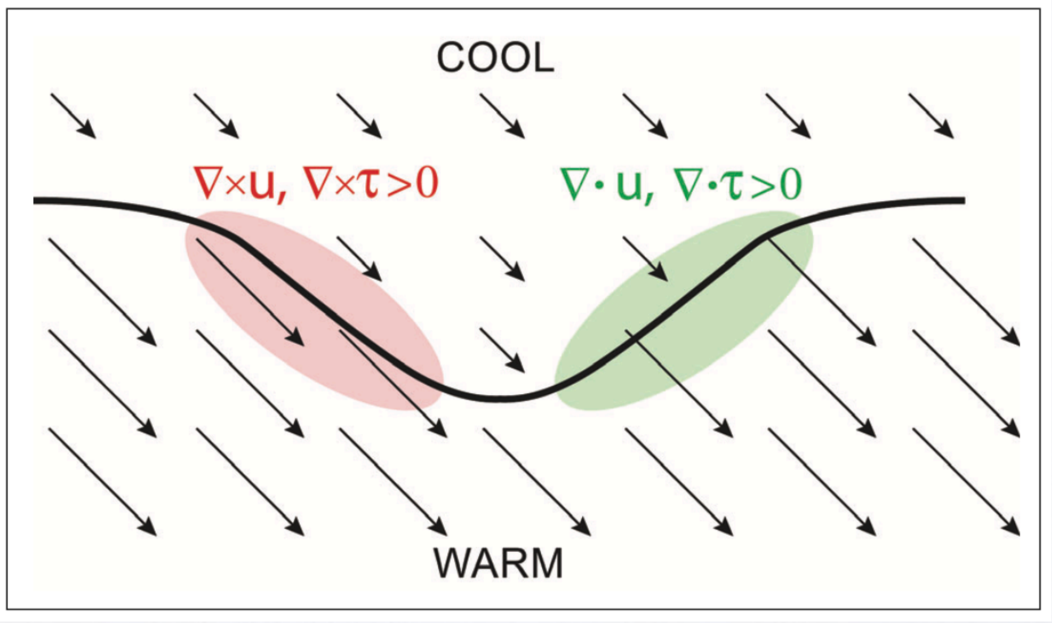
SST AND SURFACE WIND INTERACTION

- Stability of atmospheric boundary layer is affected by SST
- Wind stress divergence correlates with cold to warm SST, and wind stress convergence with warm to cold SST, strongest with winds aligning with SST gradient



Chelton et al. (2001)

- Due to sensitivity in lateral variations, the wind stress curl is strongest where winds align with isotherms.

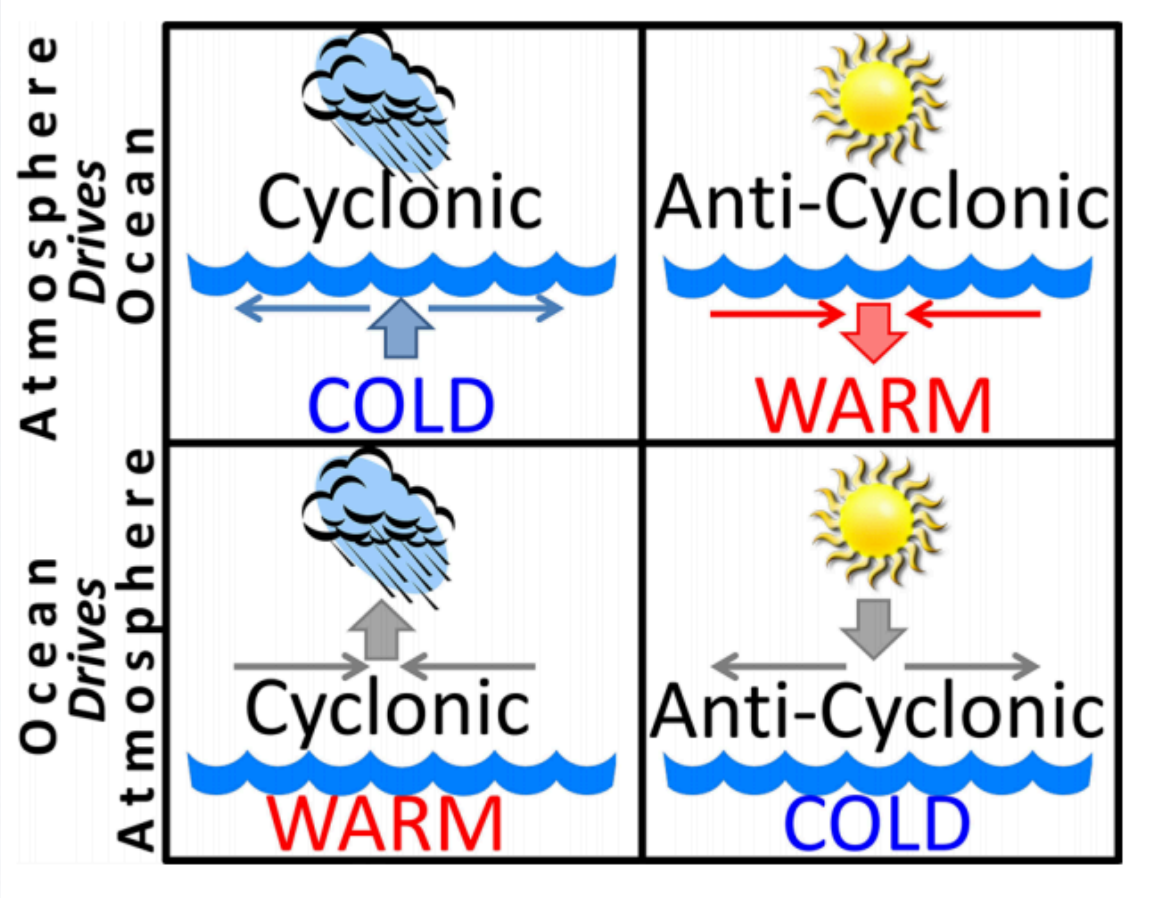


Chelton and Xie (2010)

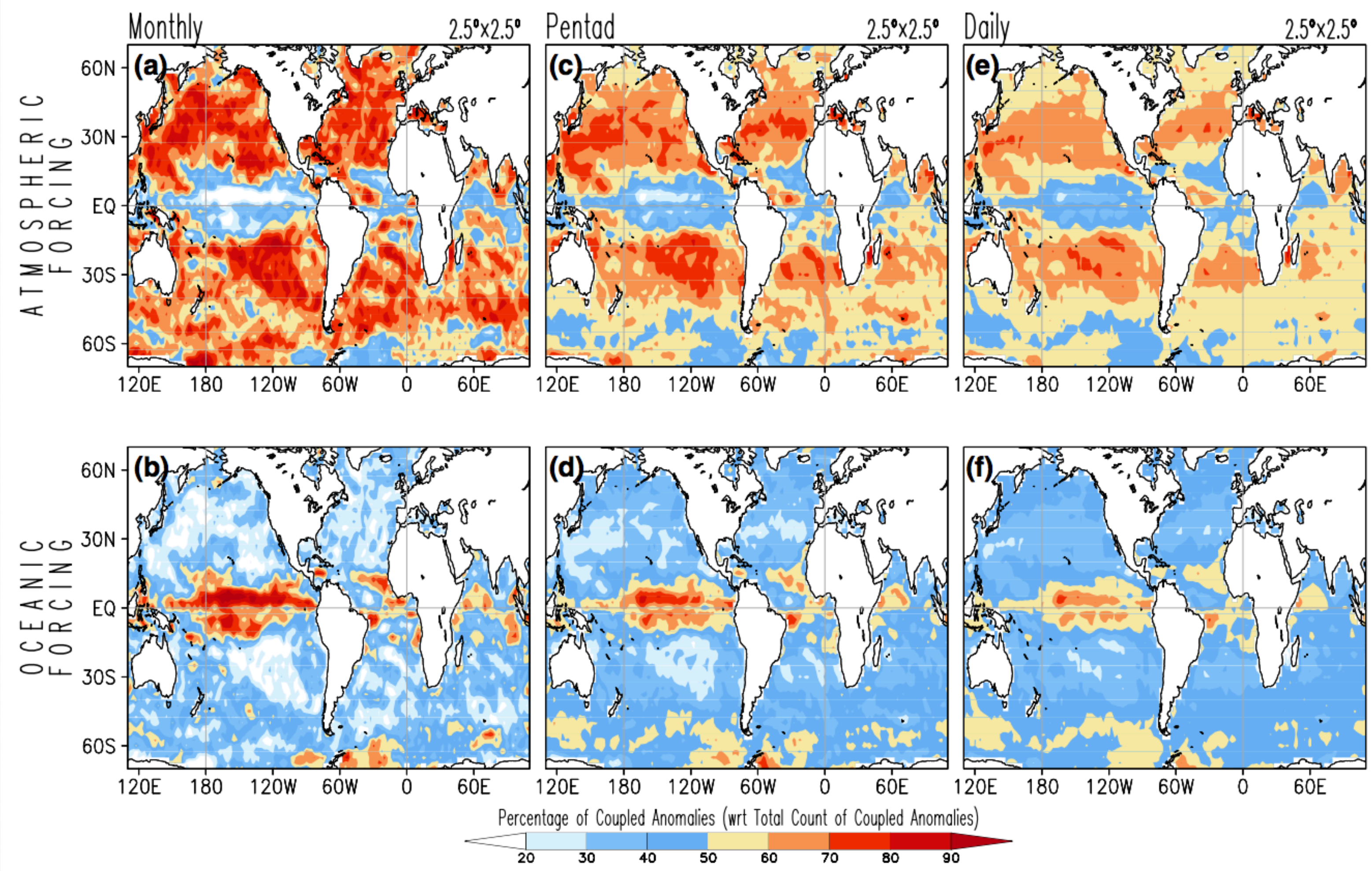
COUPLED ANOMALIES

- Relationship between slowly varying SST anomalies and low-level (850 mb) atmospheric vorticity anomalies.
- Examination of CMIP5 model output and NOAA reanalysis products show coupled anomalies driven by atmos in the midlatitudes and by the ocean in the tropics.
- Coupled anomalies exist in Atmospheric reanalyses due to assimilation of observations

Premise of attribution:

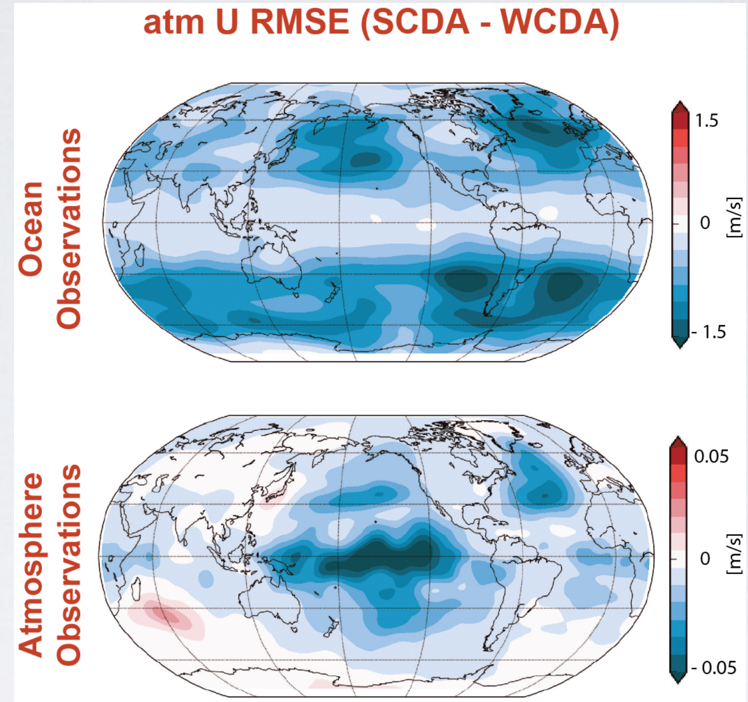


Ruiz−Barradas et al. (2017)



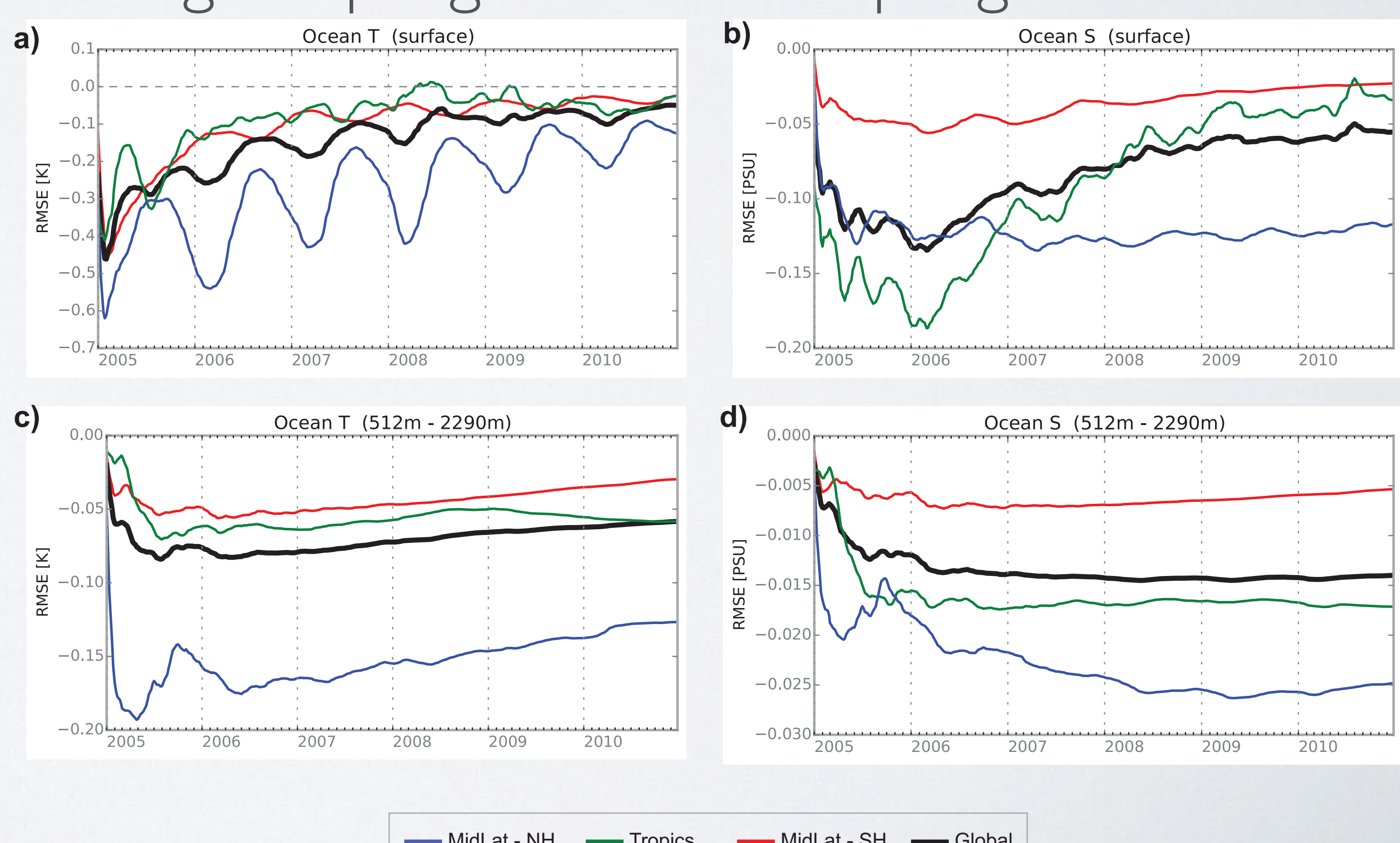
STRONGLY COUPLED DA - USING OBSERVATIONS ACROSS DOMAINS

- Coupled earth system model is analyzed as one system
- Atmospheric observations can be used to update the ocean state, and vice versa
- Strong coupling in DA can accelerate spinup of coupled systems



- Ocean obs reduce error in midlatitude surface winds
- Generally, observations in 'downstream' dynamics improve 'upstream' state

Strong coupling vs. weak coupling baseline:



Sluka et al., 2016

CHALLENGE DUE TO DISPARATE SCALES AND THE CONDITION NUMBER OF THE B MATRIX

- The background error covariance matrix B is ill-conditioned due to the large range of scales (especially when forming a climatological B)
- Methods are needed to rescale and precondition the matrix, particularly for variational methods (e.g. as proposed by Smith et al., 2017).

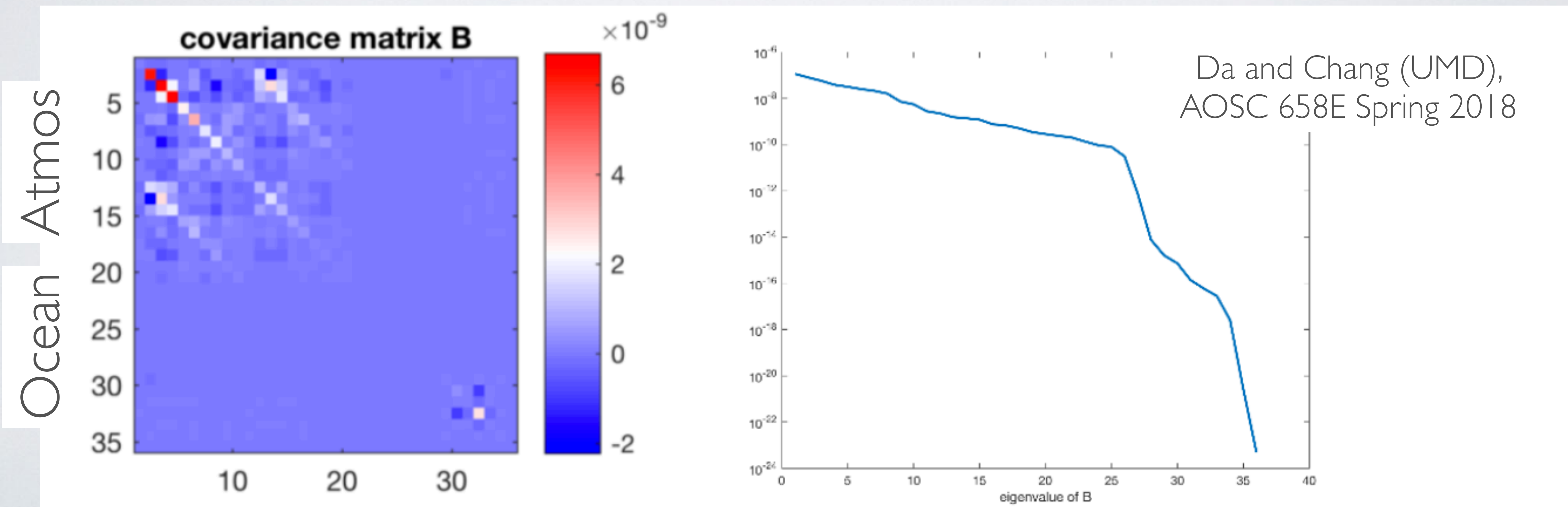


Figure 1: covariance matrix **B** for the coupled system (left), and its corresponding eigenvalues (right).

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CONTROL THEORY CONCEPTS

- Controllability — the ability to guide the system to a specific state by changing the system input
- Reachability — the ability to move a system to a point in its configuration space within a given time interval
- Stabilizability — the ability to move a system to the zero vector
- Observability — the initial state can be determined in finite time using only observations (and knowledge of the dynamics)
- Detectability — All states that cannot be observed decay to zero exponentially

CDA TO IDENTIFY CRITICAL OBSERVATIONS

Trevisan and collaborators

- Models can be used to **identify unstable modes in the system** (e.g. using bred vector, ensemble or TLM/Adjoint methods) **that must be constrained by observations** to make accurate forecasts.

- For example, observations will have **maximum impact** on the analysis **at** the largest component of the bred vector, or **maximum ensemble spread**.

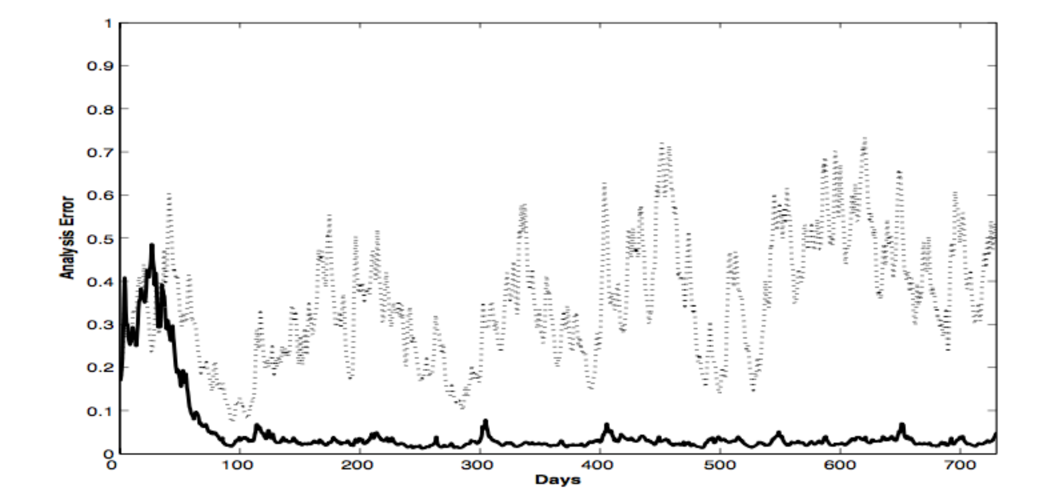
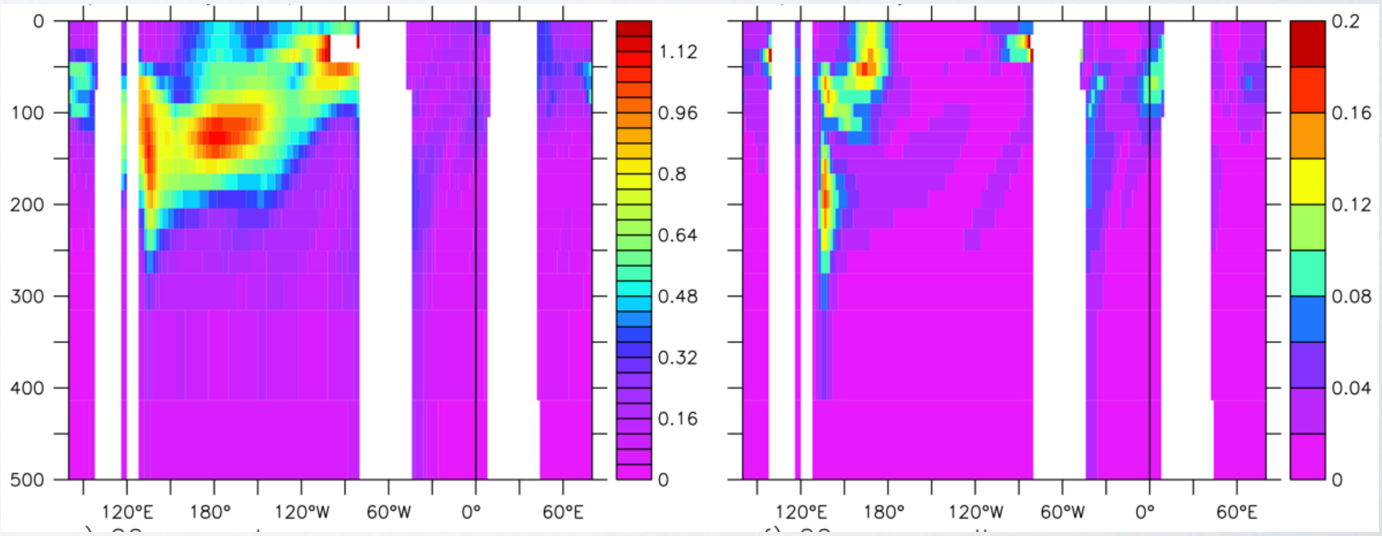


Fig. 3. QG model. RMS analysis error versus time, measured by total enstrophy and normalized by natural variability. 3-D VAR: dotted line. Proposed method: continuous line.

Uboldi et al., 2005

Monthly timescales, S. Zhang, 2018



T/S Ensemble spread at the Equator

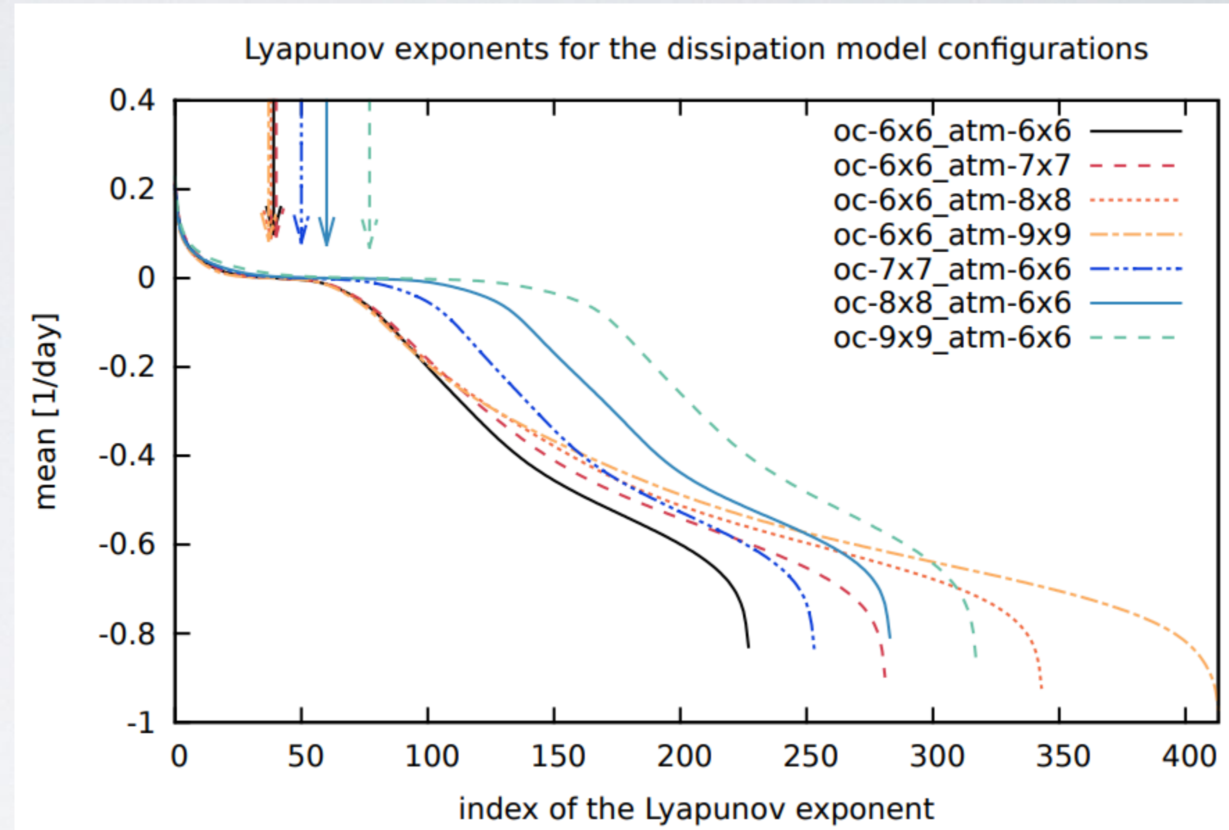
INVESTIGATIONS OF DYNAMICAL SYSTEMS PROPERTIES

De Cruz et al., 2017

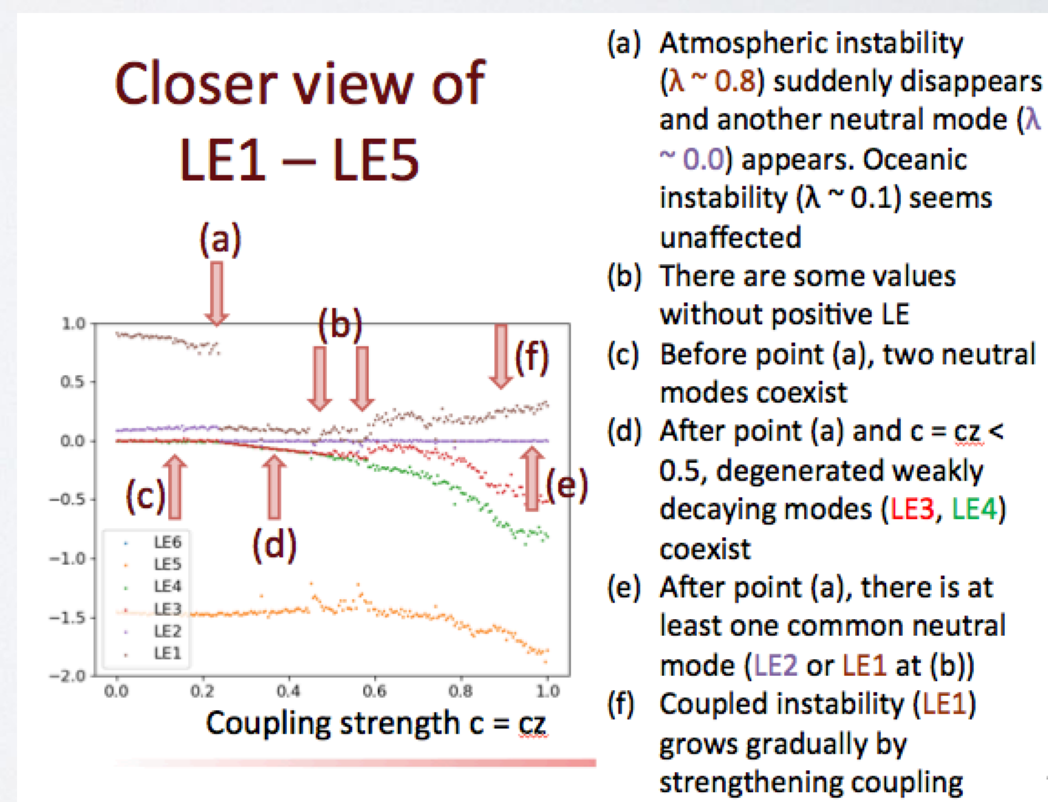
- The Lyapunov spectrum indicates the dimension of the unstable-neutral subspace that must be resolved to constrain prediction errors

- The Lyapunov spectrum is impacted by changes in resolution (a) and coupling strength (b).

(a)

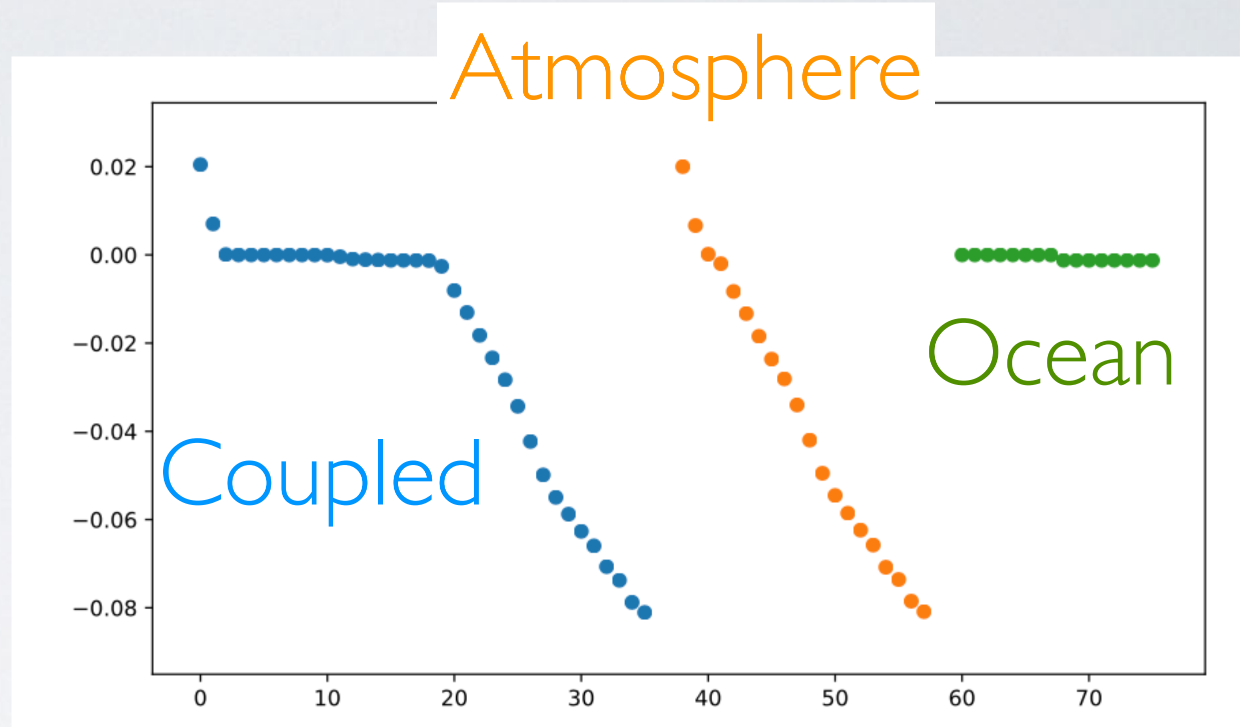


(b)



COUPLING CHANGES THE LYAPUNOV SPECTRUM

- The Lyapunov Spectrum can be decomposed between the atmospheric and oceanic systems (emulating forced atmosphere or forced ocean scenario)
- Less frequent coupling (red) increases synchronization error



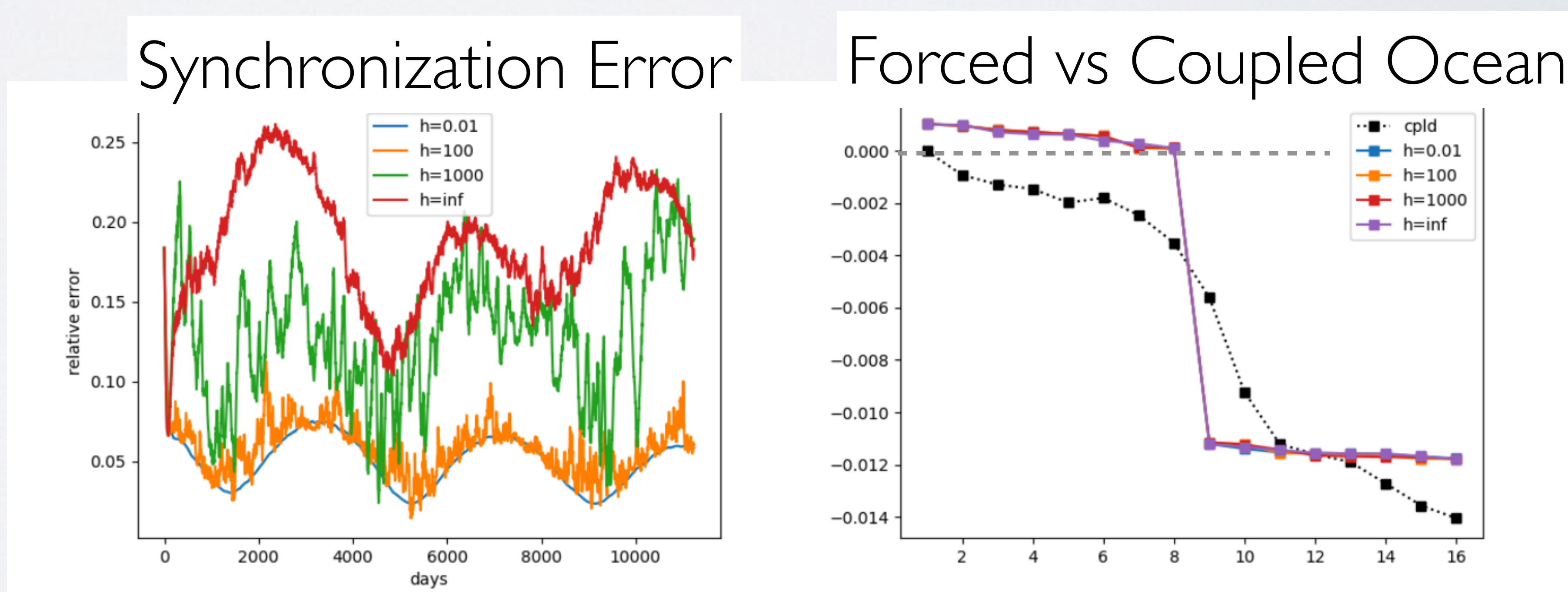


Figure 3: Relative errors (Left) in oceanic states for $h = 0.1, 100, 1000, \infty$. LEs of uncoupled oceanic model with $h = 0.1, 100, 1000, \infty$ are compared with the slow modes of coupled model (right).

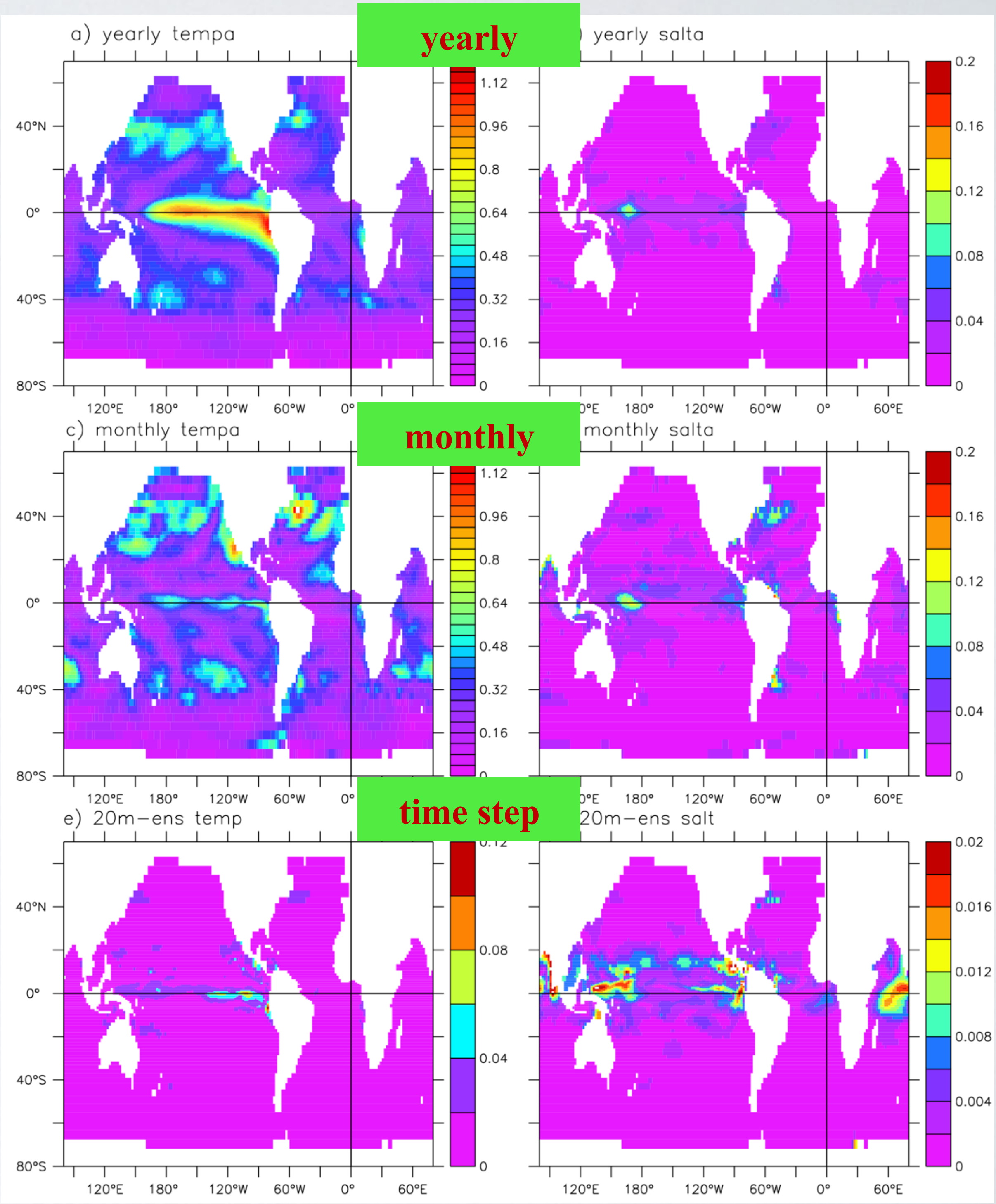
Bach and Sun (UMD), AOSC 658E Spring 2018

CDA REQUIRES HIGHLY ACCURATE CROSS-DOMAIN MODELING

- With poorly specified cross-domain covariances, the quality of strongly coupled DA can be degraded compared to the quality of weakly coupled DA (Han et al., 2013)
- There is insufficient representation of statistics of slow-varying flows by a (small) finite ensemble
- Early pre-operational developments are focusing on the atmos/ocean boundary.

ASSIMILATION OF MULTIPLE SPATIOTEMPORAL SCALES

- Decompose analysis at various timescales: stationary (ENSO), low-frequency, and high-frequency (e.g. active tropical air-sea interactions)
- Allows simultaneous corrections of multiple scales at once.



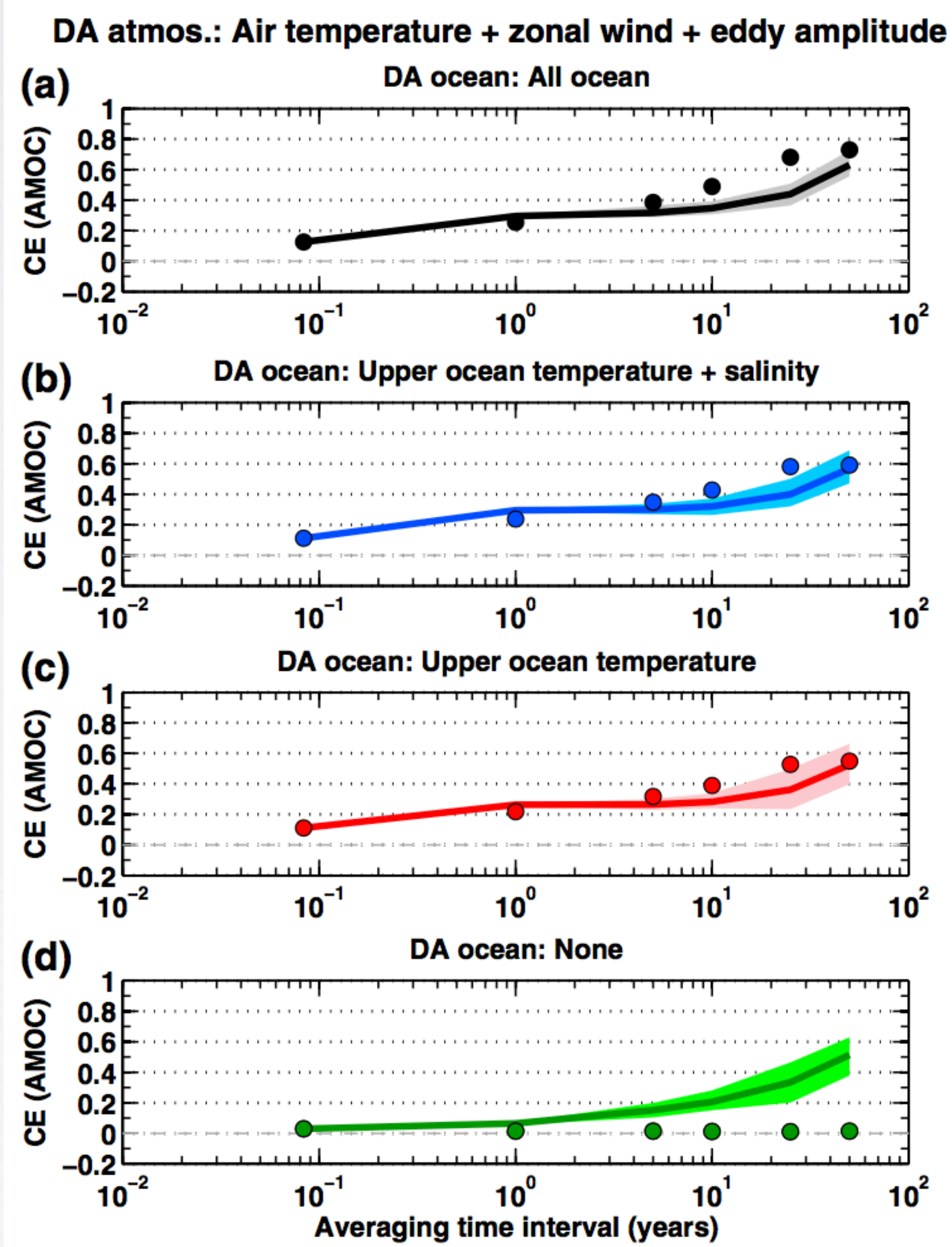
S. Zhang and collaborators

CAPTURING THE LOW FREQUENCY SIGNALS

- Time averaging of observations (particularly from fast dynamics)
- No-cycling DA - background is climatology
- Ensemble drawn from a climatological simulation of an atmosphere–ocean coupled climate model

The accuracy of analyses is evaluated using the coefficient of efficiency (Nash and Sutcliffe 1970):

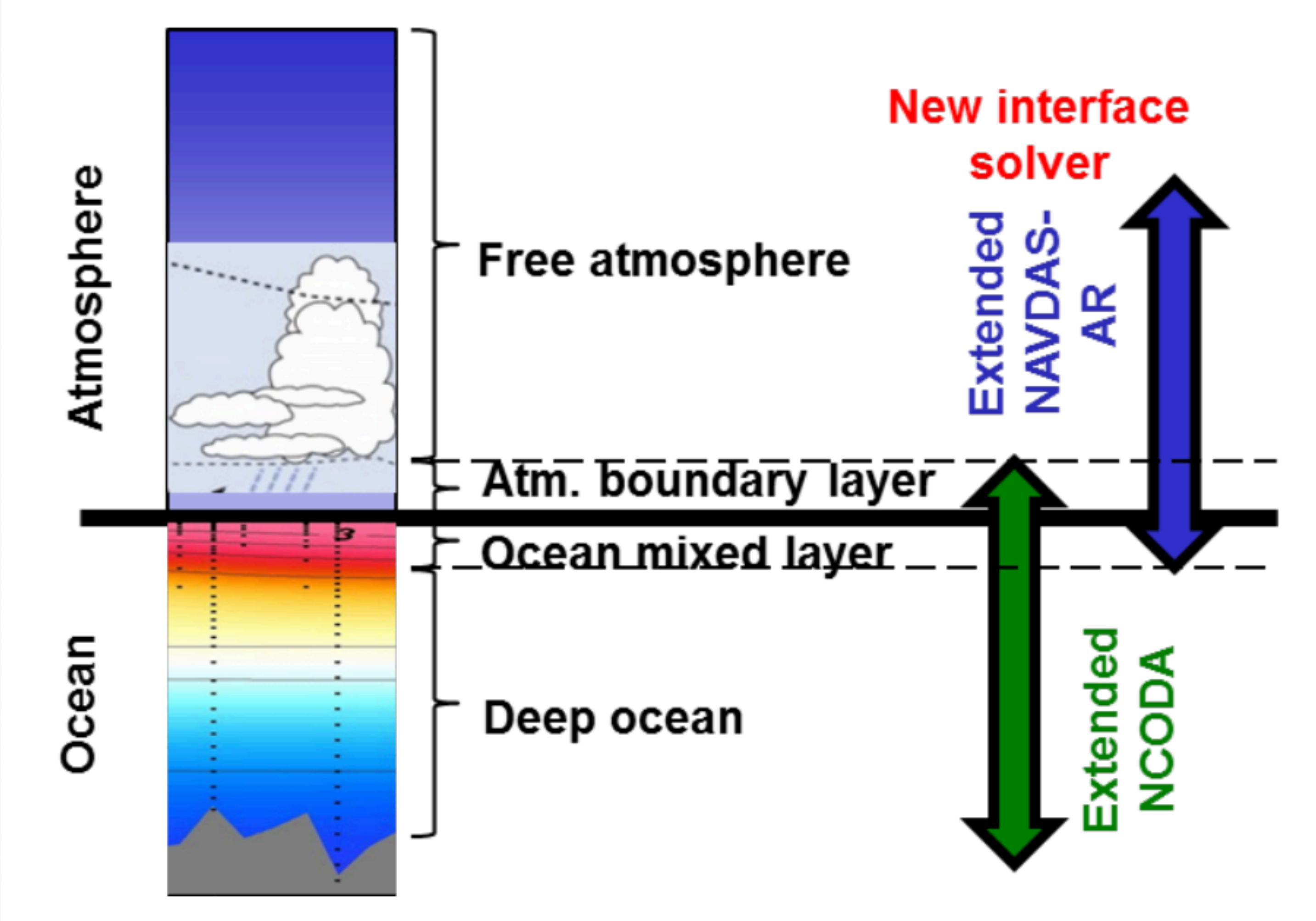
$$CE = 1 - \frac{\sum_{i=1}^{M}(x_i^t - x_i^a)^2}{\sum_{i=1}^{M}(x_i^t - \overline{x^t})^2}, \tag{3}$$



Tardiff et al. 2014/2015

INTERFACE SOLVER FOR BOUNDARY LAYER PROCESSES

- Navy ESPC focusing on assimilation of boundary layer observations with high relevance to coupled dynamics



Bishop and Barron (2015)
Frolov et al. (2016)

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COUPLED MODEL REANALYSIS

- Demonstration of a large-scale coupled DA effort, with indications of spinup-times needed for initialization

- CERA-20C is the ECMWF 10-member ensemble of coupled climate reanalyses of the 20th century, from 1901-2010.

- Improves representation of atmosphere–ocean heat fluxes and mean sea level pressure compared to previous reanalyses

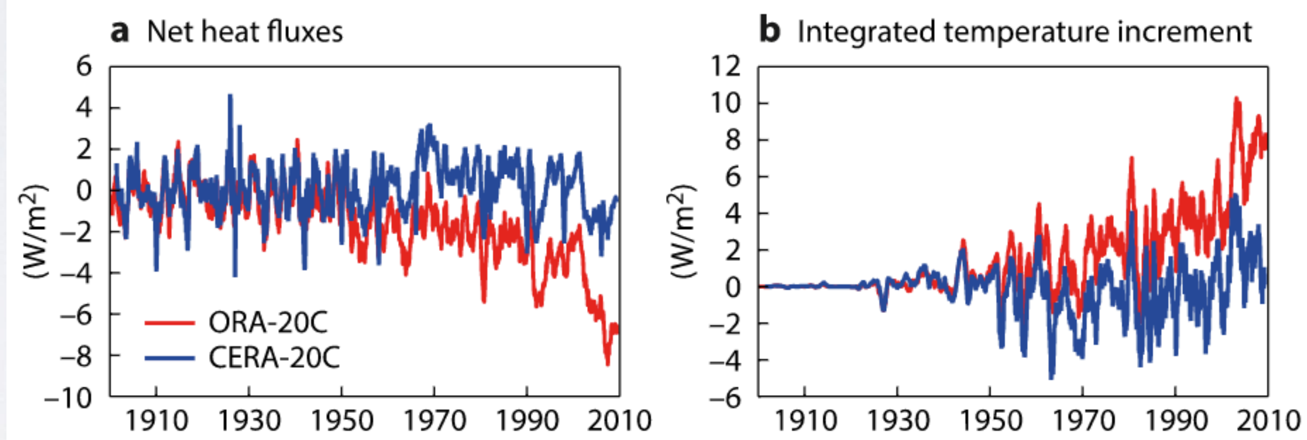


Figure 1 Time series of CERA-20C and ORA-20C control member values of (a) the global average of net air–sea heat fluxes and (b) the integrated temperature increment over the ocean.

Laloyaux et al., 2015; Laloyaux et al., 2017:
https://www.ecmwf.int/en/newsletter/150/meteorology/cera-20c-earth-system-approach-climate-reanalysis

ISOLATING DEFICIENT PROCESSES IN COUPLED MODELS

- UKMO tested CDA versus atmos or ocean only DA
- Comparison of SSH innovations indicated potential problems in the coupled model River Runoff

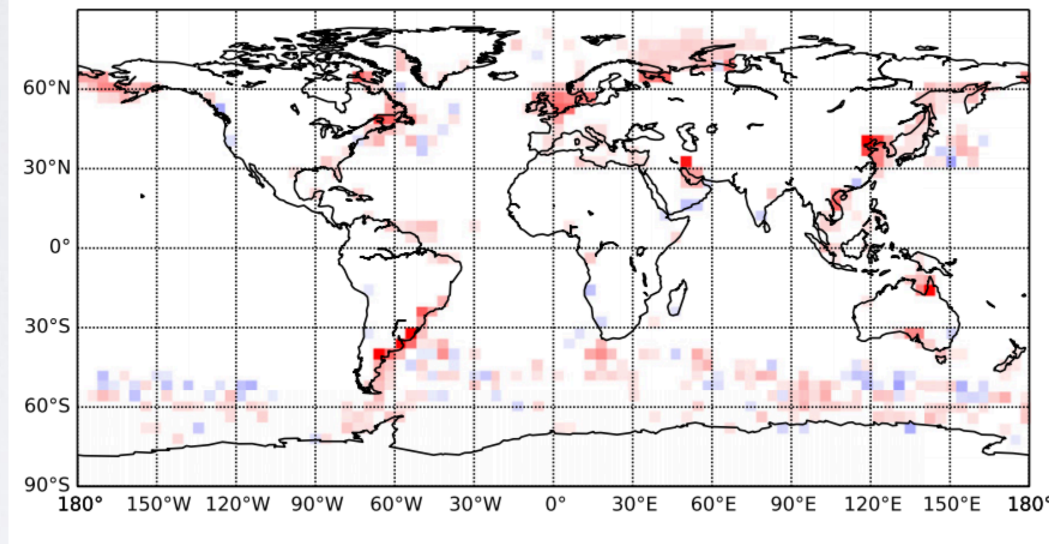


FIG. 3. The difference, coupled minus ocean control, of the RMS SLA binned innovations (in m) (calculated in 4° × 4° bins over all 13 months). Red implies the coupled model background has larger errors than the ocean control.

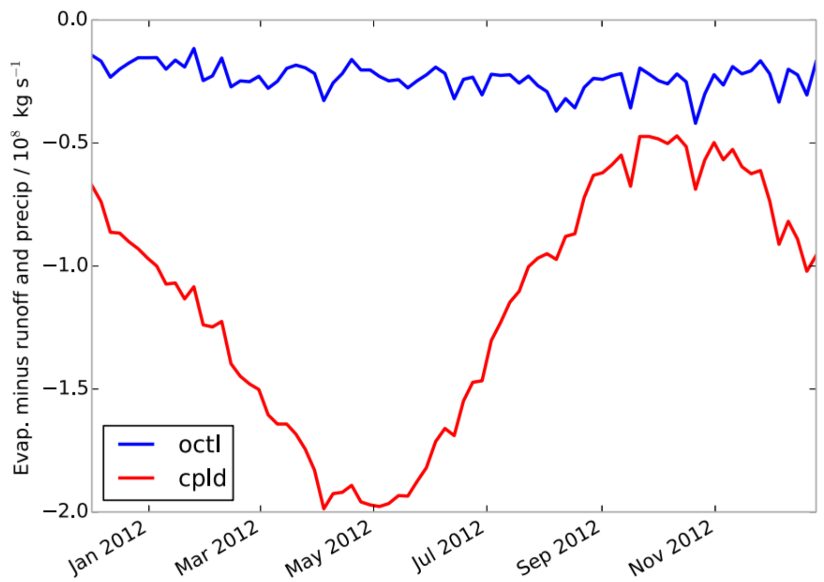
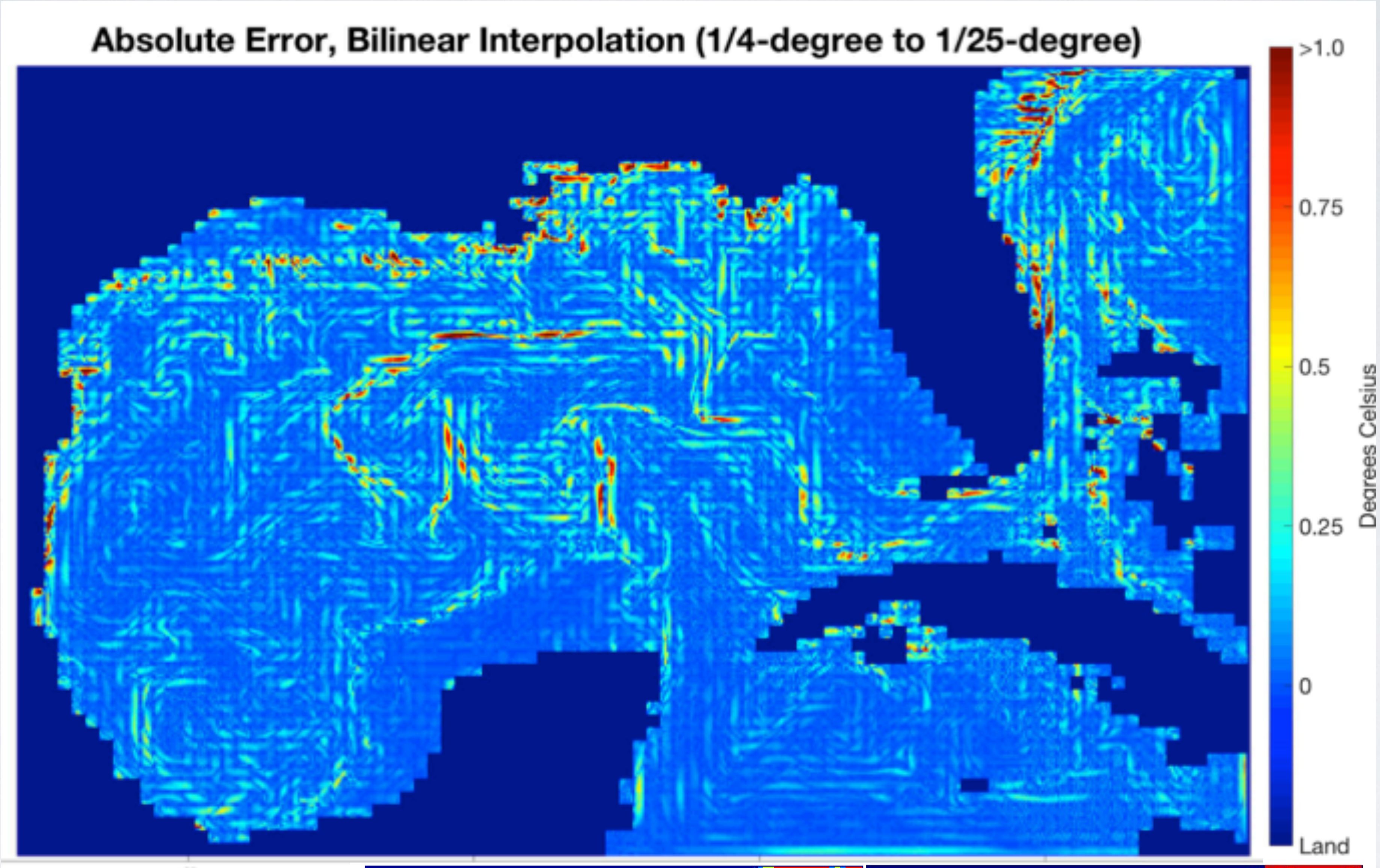


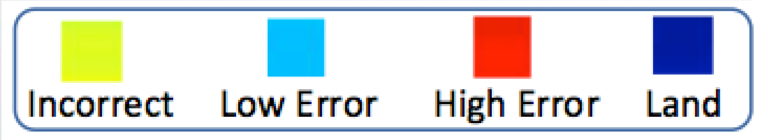
FIG. 6. Ocean evaporation minus precipitation minus runoff applied to the ocean in the Rio de la Plata estuary for the ocean control and coupled analysis runs. The data are averaged over 5-day periods. Ocean values are integrated in a box from 38.48°S, 58.5°W to 33.63°S, 53.5°W. Spikes in the plot show local precipitation events.

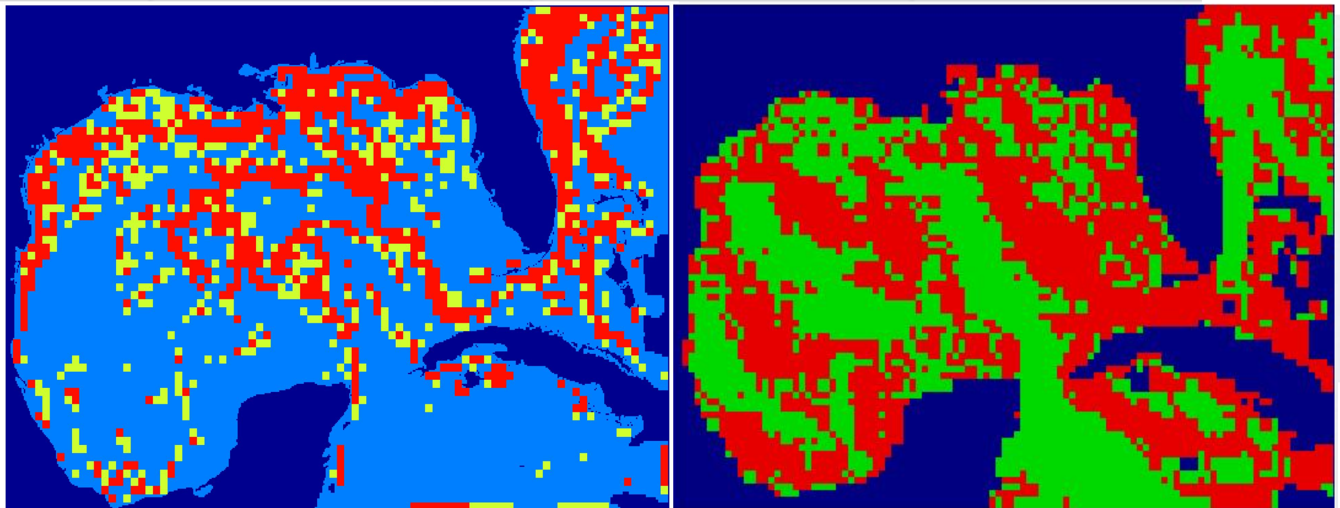
Lea et al., 2015

NEURAL NETWORK CLASSIFICATION OF INTERPOLATION ERRORS

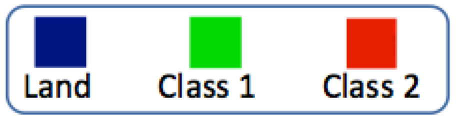


NN-RMSE Performance (2 classes)





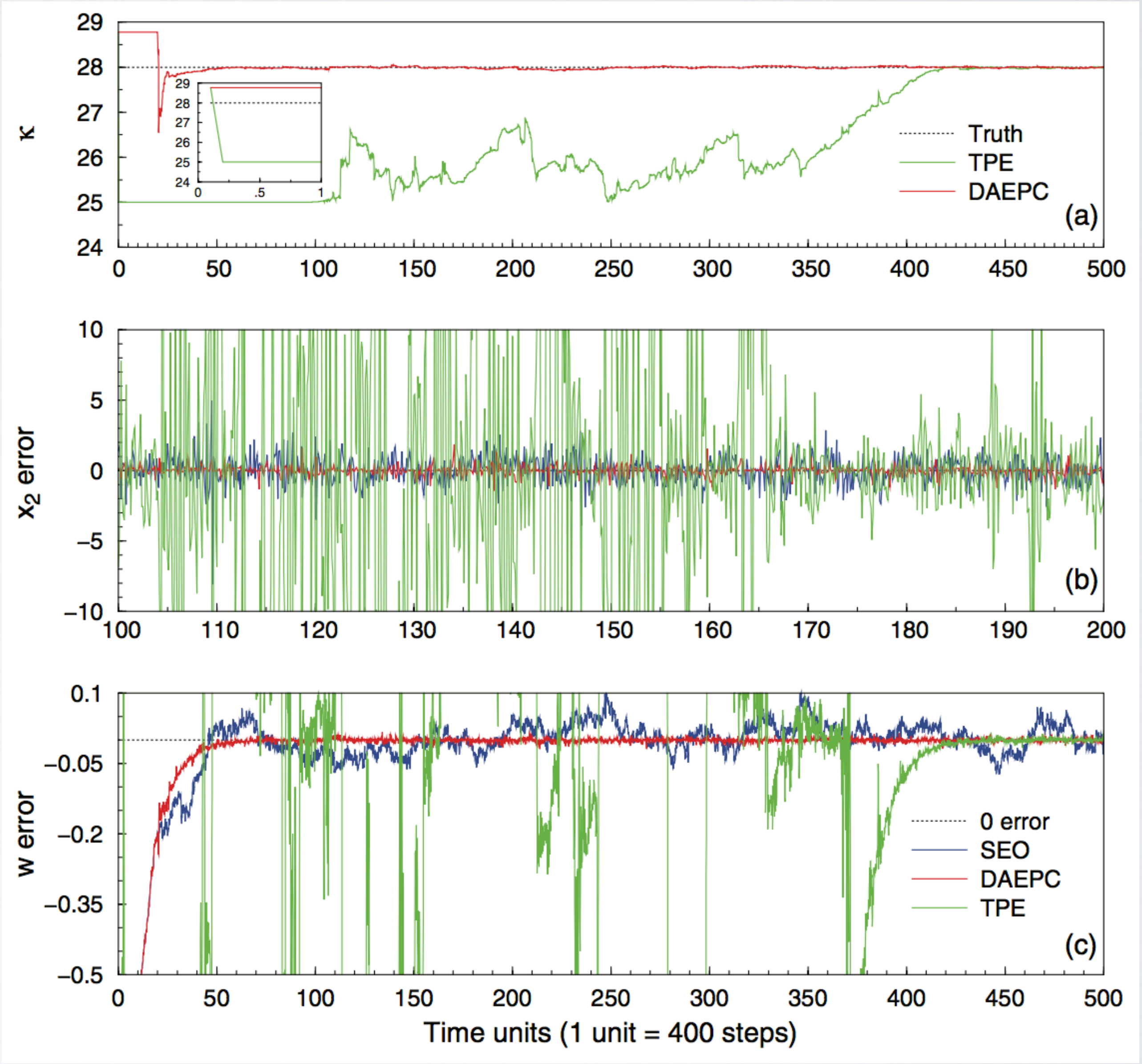
NN-KMeans (2 classes)



Kaplan and Penny, 2018

ESTIMATION OF MODEL COUPLING PARAMETERS

- Coupled models can be sensitive to coupling parameters
- CDA can be applied to estimate and tune coupling parameters to better agree with observed data



S. Zhang and collaborators

CHALLENGES FOR CDA IN REAL WORLD APPLICATIONS

- The **cross-domain modeling must be very accurate** for error covariance information to be used (Han et al., 2013) - ***need to revisit bulk flux parameterizations***

- **Assimilation of multiple spatiotemporal scales is difficult**, so the initial focus of CDA is on isolating various scales to focus assimilation strategies.

- **Sparse observations and biased models** make DA very difficult - in these cases CDA can point to minimum requirements for both in order to achieve skillful forecasts.

OPPORTUNITIES FOR THE FUTURE

- CDA could be used in coordination with comprehensive short-term field campaigns to **identify the largest-impact observations** that should be maintained for long-term monitoring/prediction.

- CDA can help to guide model development by **identifying coupling dynamics in need of improved representation**.

OCEANOBS'19 COMMUNITY PAPER

- "**Observational Needs for improving Ocean and Coupled Reanalysis, S2S Predictions, and Decadal Prediction**" amalgamating 6 different abstract submissions:
- 38: Ocean observational requirements for **skillful near-term climate predictions**
- 44: **The role of ocean observations in Coupled Data Assimilation** for prediction & reanalysis
- 72: Direct **Assimilation of Satellite Radiances** for the SST
- 88: **Synthesis of Ocean Observations using Data Assimilation**: Toward a more Complete Picture of the State of the Ocean
- 328: **Ocean reanalyses**: advances and unsolved challenges
- 376: Ocean observations to **improve our understanding, modeling and forecasting of S2S variability**

FINAL MESSAGES

- The CDA community is developing new methods and tools that will be valuable for model development and observing system validation focusing on the Tropical Pacific
- Challenges exist due to limitations in CDA inputs (i.e. coupled modeling and observations)
- Greater communication and coordination between observing, modeling and CDA communities will accelerate advances

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