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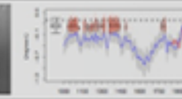


Coupled {model} Data Assimilation (CDA)

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Frontiers in Ensemble DA for Geoscience Applications

Contributors

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- S. Akella (GMAO), C. Draper (GMAO), S. Karol (NCAR), P. Laloyax (ECMWF), C. Snyder (NCAR), R. Tardif (U. Washington), R. Todling (GMAO), among others
- Funding sources:
  - NOAA Climate and Global Change Postdoctoral Program

NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

UCAR COMMUNITY PROGRAMS

What we have talked about…

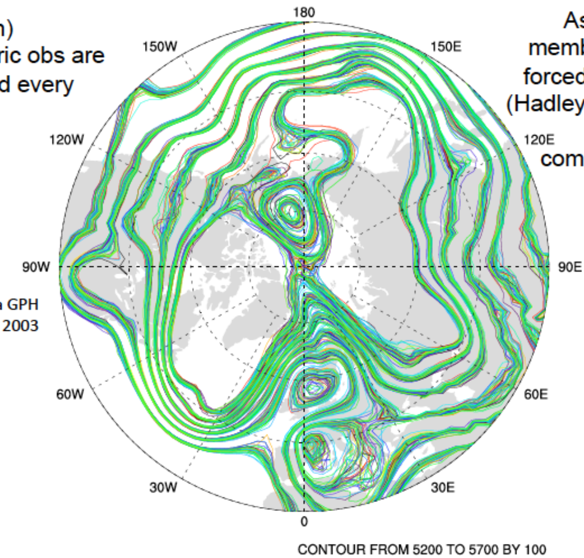
❑ atm-DA

- atmosphere component
- CAM-DART, Raeder et al. [2012], *J. Climate*

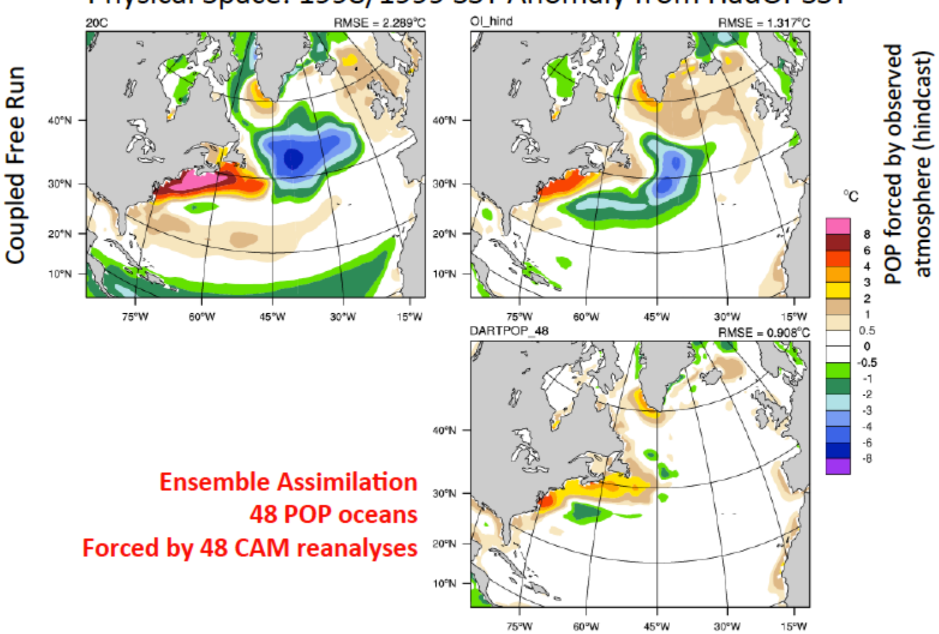
Atmospheric Ensemble Reanalysis, 1998-2010

O(1 million) atmospheric obs are assimilated every day.

Assimilation uses 80 members of 2º FV CAM forced by a single ocean (Hadley+ NCEP-OI2) and produces a very competitive reanalysis.



Physical Space: 1998/1999 SST Anomaly from HadOI-SST

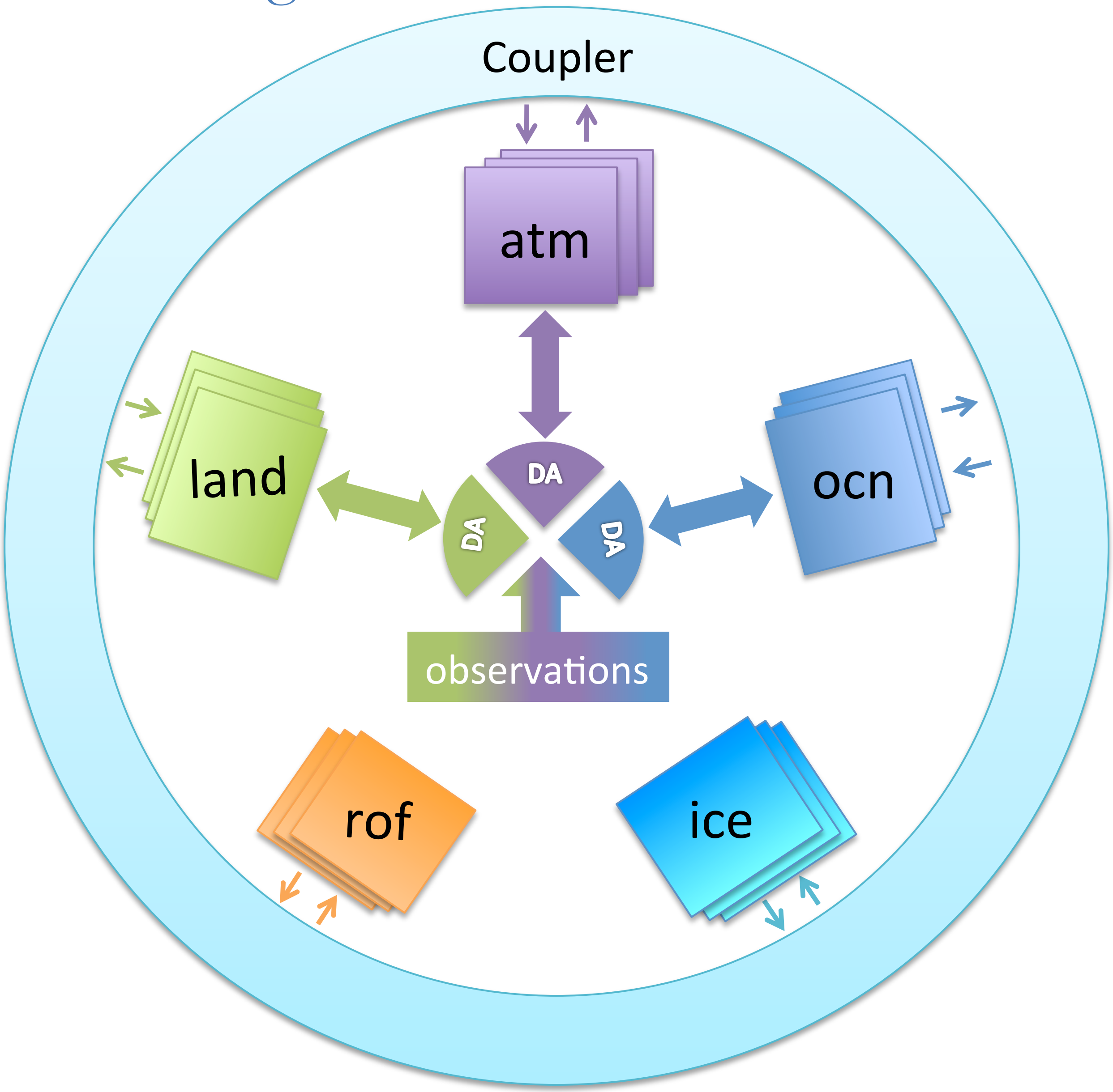


Ensemble Assimilation
48 POP oceans
Forced by 48 CAM reanalyses

❑ ocean-DA

- ocean component
- POP-DART, Karspeck et al. [2013], J. Climate

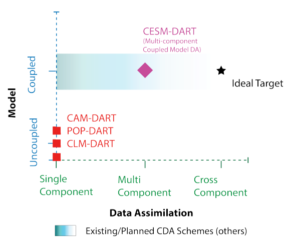
What we'll be talking about…



Outline

Coupled Data Assimilation – general issues

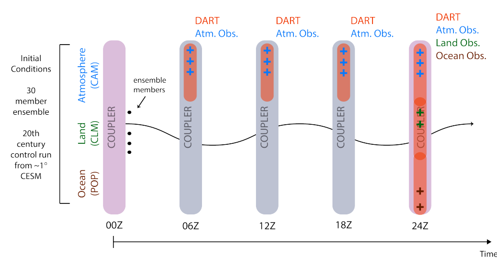
Whys, whats and hows of CDA?

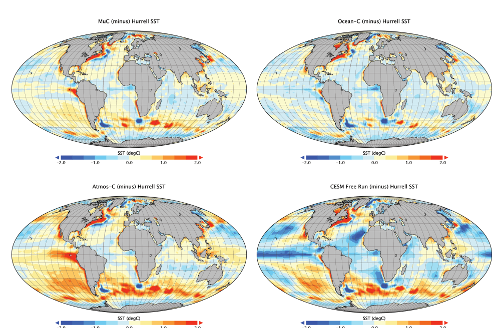


Illustrative Examples

CESM-DART

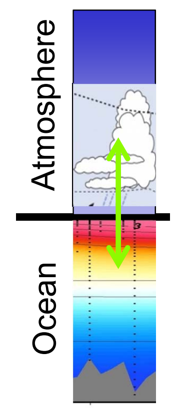
Implementation -> Results





Known unknowns + *Unknown* unknowns

Scientific & Practical Challenges



Introduction

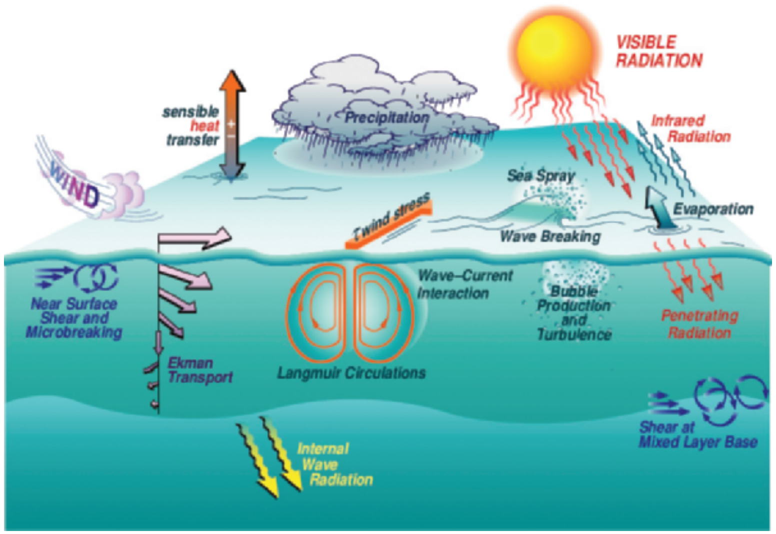
What do we mean by 'Coupled DA'?

A first order definition – Assimilation into a **coupled** model (ESM) where observations in one medium (i.e., atmosphere) are used to generate analysis increments in the other (i.e., ocean)

Why Coupled DA?

- Better and more-balanced (consistent) ocean-atmosphere states
- Better use of near-surface observational data
- Better representation of coupled phenomena
- Better initial conditions for S-I to decadal predictions

Physical processes governing air-sea exchange across the coupled boundary layers



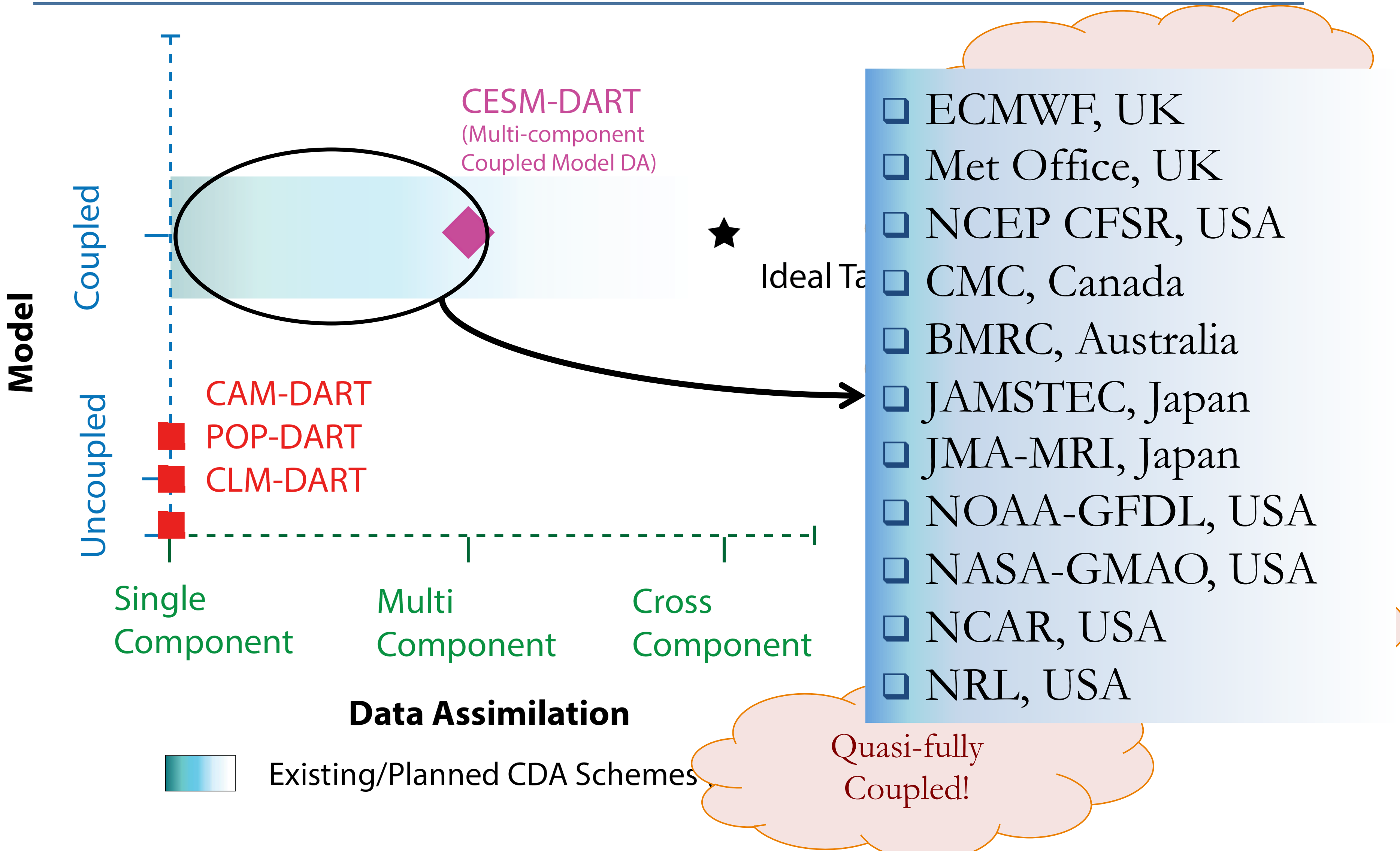
Edson et al. [2007], BAMS

Weak vs. Strong CDA

- **Weak coupling**: background estimates produced by a coupled model, separate analysis updates for each component
- Thus, an observation in one model component cannot directly cause an analysis increment in the other components
  - increments calculated separately - so potentially unbalanced
  - always run coupled model – so background model fields are in balance

- **Strong coupling**: The analysis itself is coupled, so that any observation can affect analysis increments throughout the system
- Strong coupling requires –
  - coupled error covariance models
  - (possibly) well-tuned coupling parameters for mom., buoyancy fluxes
  - (possibly) strong observational constraint for all components

A word of caution about the **Terminology**



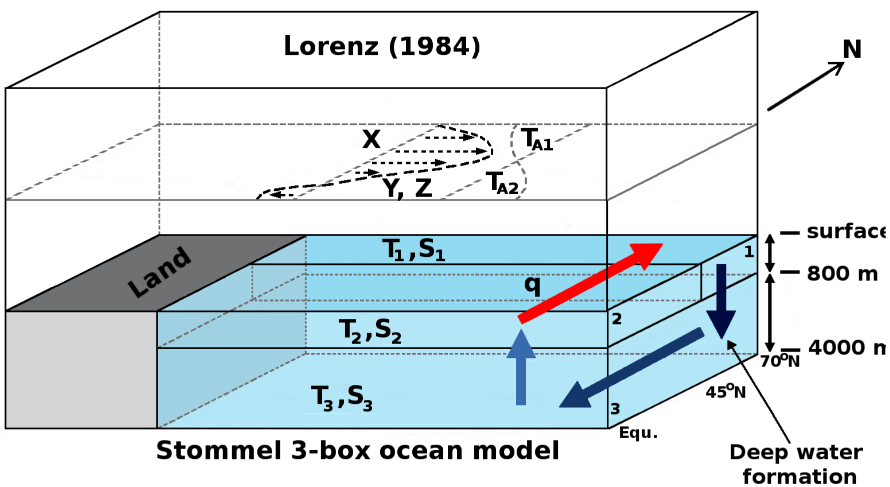
Illustrative Examples: ESMs vs Low-order Models

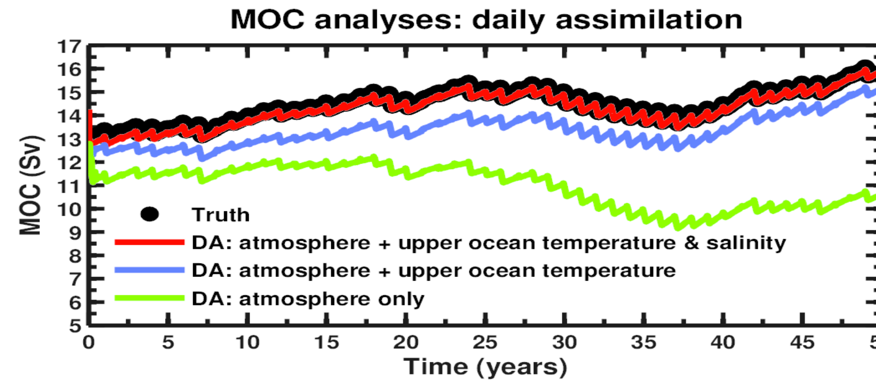
- ESMs
  - CESM, GEOS-5, etc.
  - ✓ Fully simulates coupled atmosphere-ocean-land-cryosphere system
  - ✧ Requires enormous computational resources -> operational centers and/or big research organizations

- Low-order coupled models
  - Slab atm-ocean models, coupled Lorenz models, etc.
  - ✓ Cheap to run, allows multiple realizations/sensitivity experiments, availability of the 'Truth' to rigorously characterize errors in the system
  - ✧ Can never capture the full spectrum of dynamics, model biases
  - ✧ Suffers from inherent 'scaling' issues – proposed algorithms turn out to be incredibly expensive for ESMs

Source: R. Tardif (Univ. of Washington)

Illustrative Examples: Part 1 (Low-order Models)





See Tardif et al. [2014], Climate Dynamics

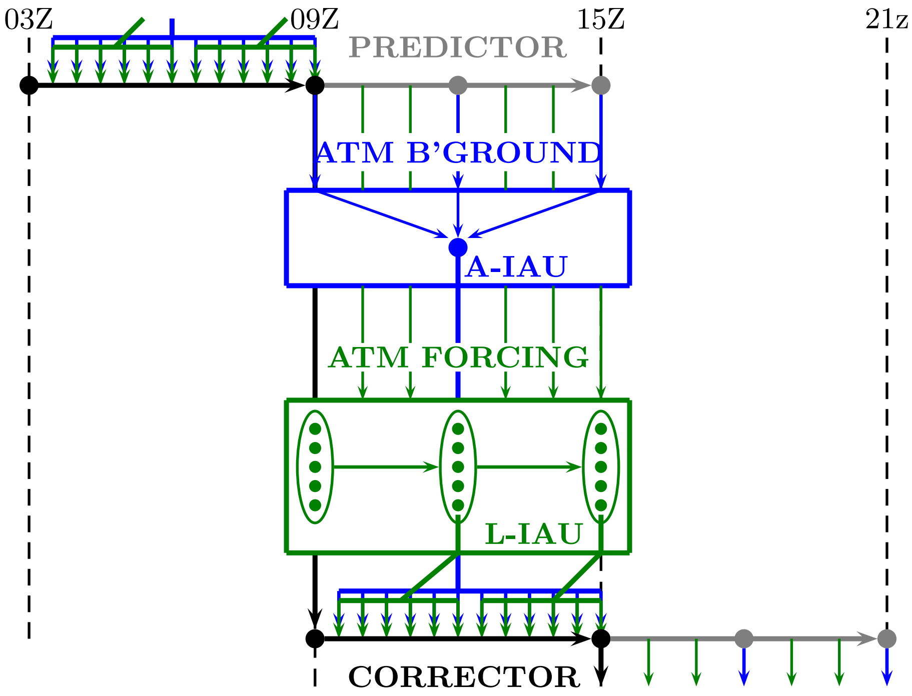
- Lorenz (1984, 1990) wave—mean-flow model: **fast chaotic atmosphere**
- Stommel (1961) 3-box model of overturning ocean: **low-frequency AMOC variability** (i.e. no wind-driven gyre)
- **Coupling**:
  - upper ocean temperature affects mean flow & eddies (**ocean -> atmosphere**)
  - hydrological cycle affects upper ocean salinity (**atmosphere -> ocean**)

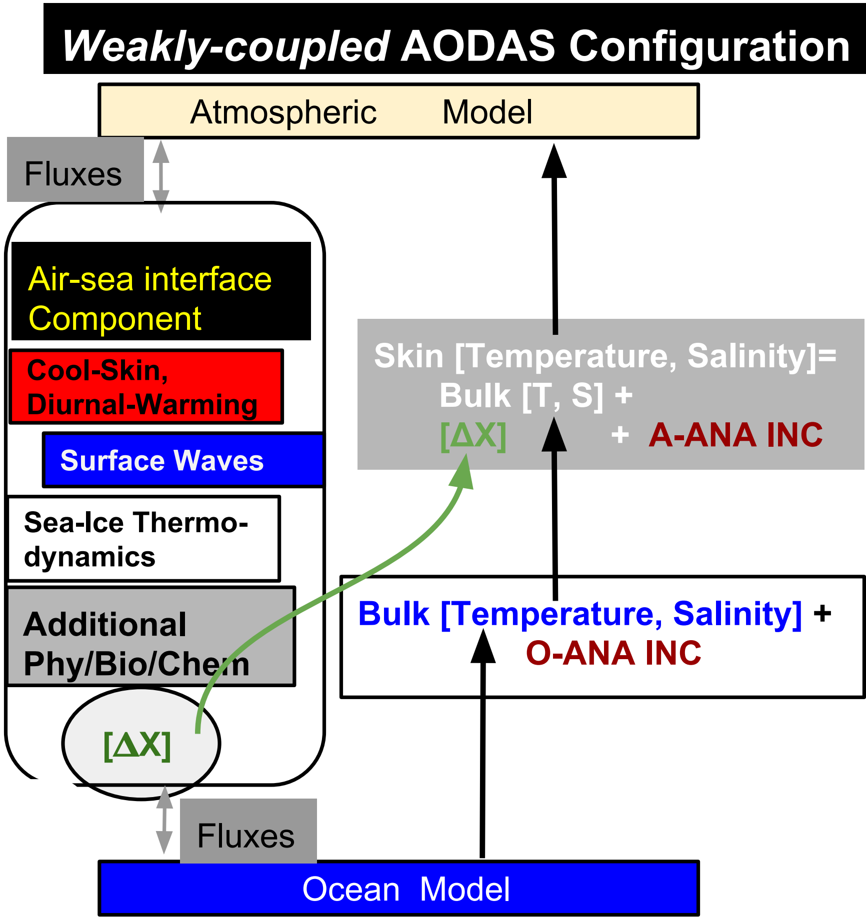
State vector: 10 variables!

Source: S. Akella, C. Draper (NASA GMAO)

Illustrative Examples: Part 2 (ESMs)

NASA GMAO GEOS-5 (Atm-Land CDA & Atm-Ocean CDA)

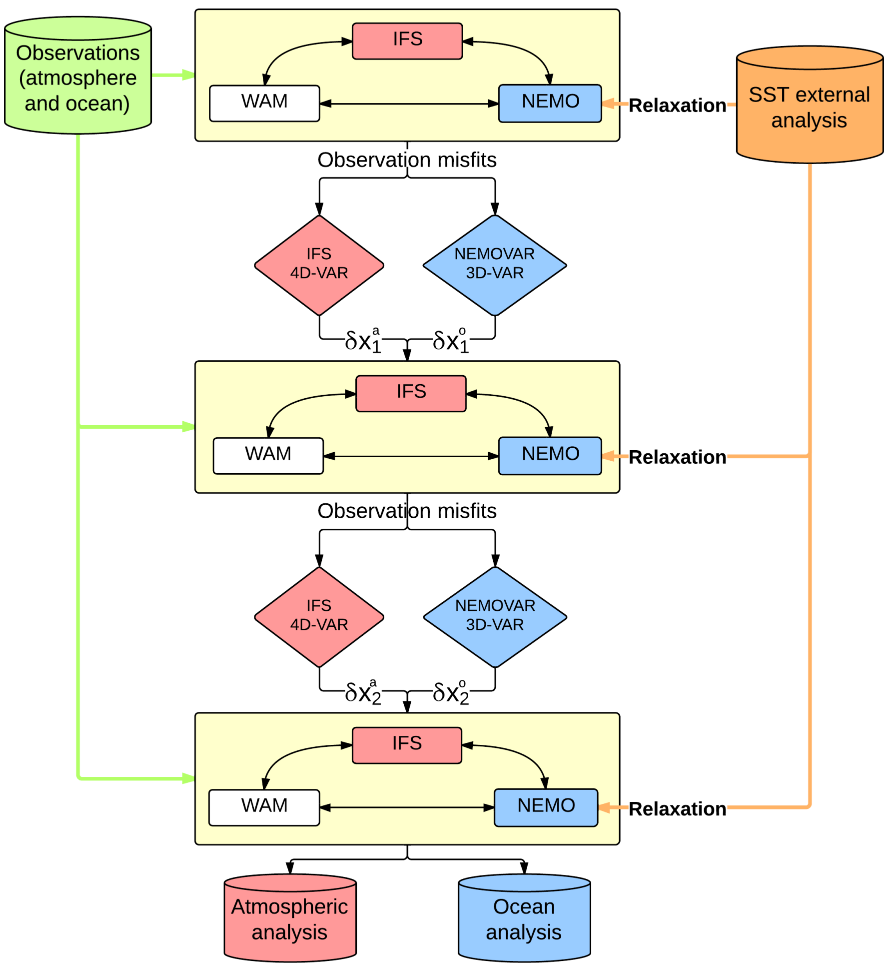




Source: P. Laloyax (ECMWF, WWOSC'14)

Illustrative Examples: Part 2 (ESMs)

Coupled ECMWF ReAnalyses (CERA)



Incremental variational approach:

A common 24-hour assimilation window

Coupled model to compute observation misfits

Increments computed separately and in parallel

Separate background-error covariance model

Sea Surface Temperature:

SST relaxation scheme towards a daily SST analysis product

Model resolution:

Atmosphere: 1.125° horizontal grid with 137 levels

Ocean: 1° horizontal grid with 42 levels (first layer of 10 meters)

Wave: 1.5° horizontal grid

Experiments:

Run successfully on short recent periods

Summary

- CDA is expected to produce self-consistent state estimates as well as optimal initialization for coupled model predictions
  - growing field of DA application
  - still ironing out consistent terminology, analyses frameworks, etc.

- For ESMs - (currently) CDA falls under two categories – always run coupled model in the background but do DA in a single component or in multiple components

- For low-order models – growing research on the need for CDA, how to specify coupled covariances, what types of observational constraints we need, etc.

Useful References (good starting point…)

- **Presentation by Michele Rienecker** (WMO CAS 2010 Workshop): Good discussion of coupled DA, practical issues

- **Presentation by Keith Haines** (ECMWF Seminar on DA for atmosphere and ocean, 2011): Review of coupled DA implementations and plans from different centers (Met Office, GFDL, JAMSTEC, BMRC, NCEP, Canada)

- **White Paper by Vitart et al.** on 'Sub-seasonal to Seasonal Prediction: linking weather and climate' (WWOSC Montreal, 2014): Argument for coupled DA, utility for initializing S2S prediction

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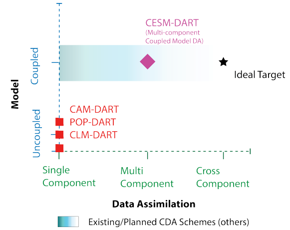

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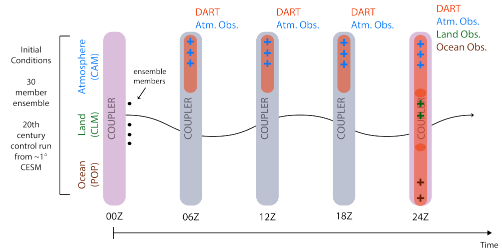
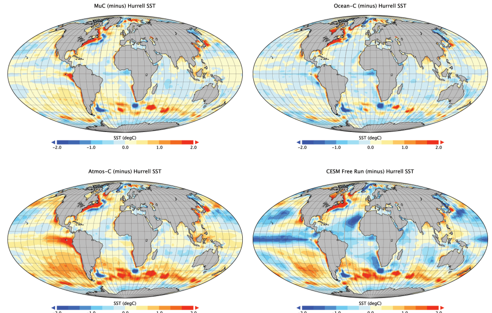
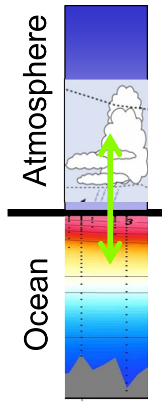




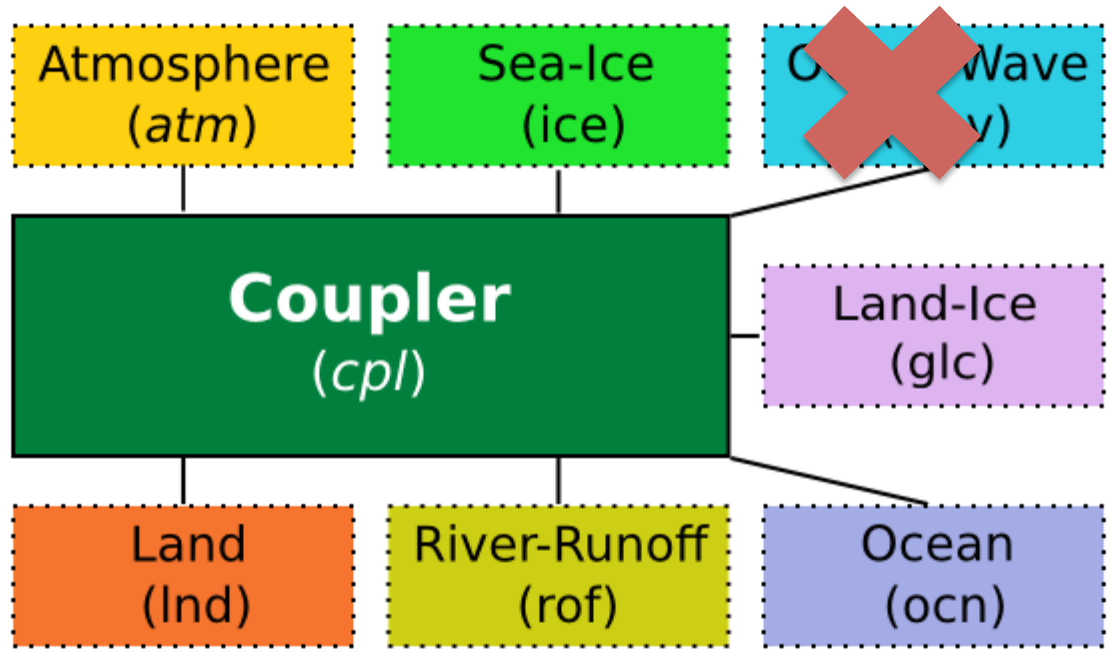
Known unknowns + *Unknown* unknowns

Scientific & Practical Challenges



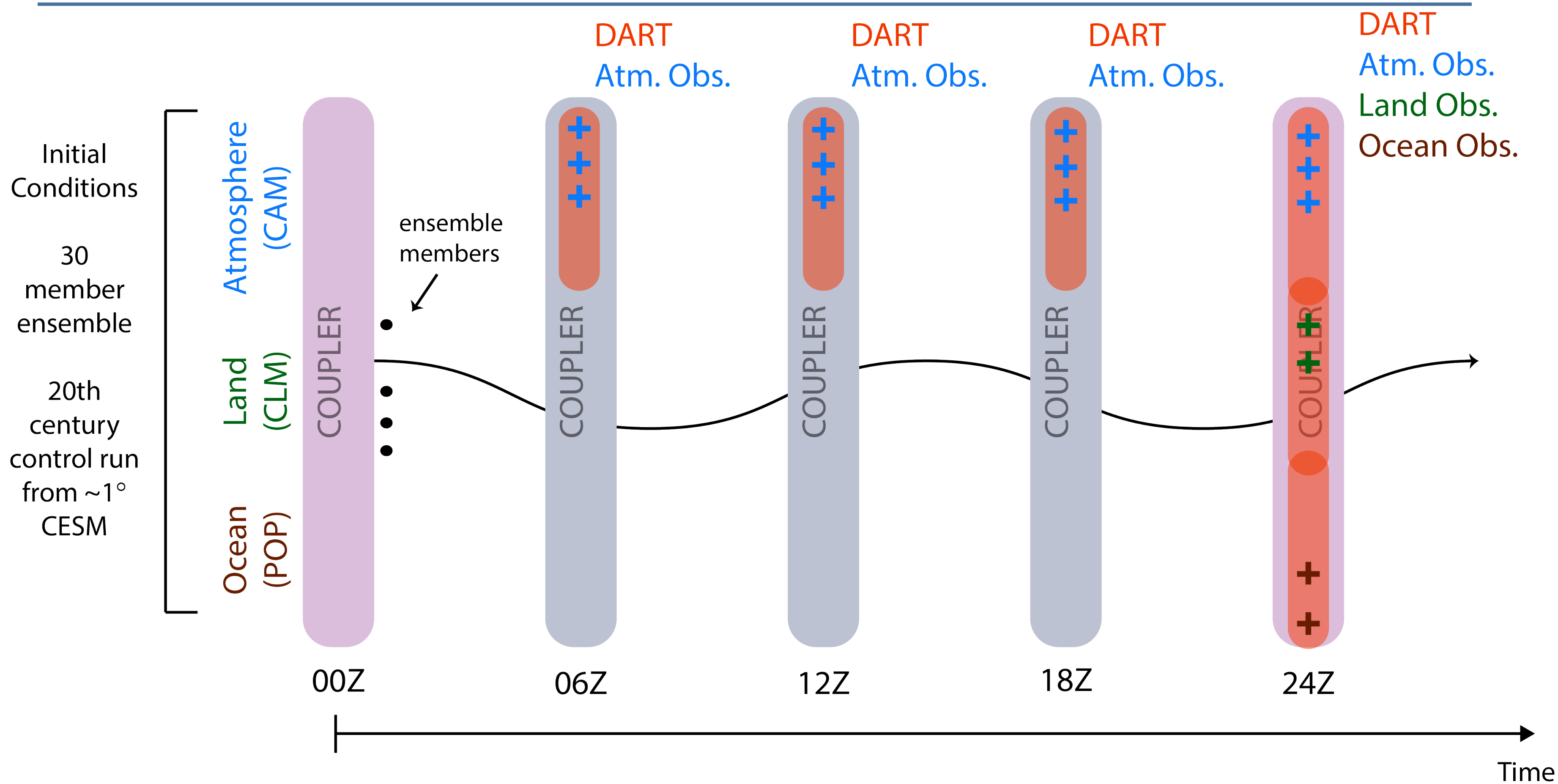
Community Earth System Model (CESM) Components

- All active components (B COMPSET)
- Horizontal Res: Nominal ~1°
- Vertical Discretization:
  CAM5 – 30 levels (~2 hPa)
  POP – 60 levels with 10 m resolution in the upper 200 m, gradually expanding to 250 m resolution below 3000 m depth
- **6-hr ocean-atm coupling**



CESM Components – High Level Diagram
The coupler is in the middle and communicates with all other components
(adapted from - https://summerofhpc.prace-ri.eu)

Multi-Component Coupled Data Assimilation (MuC)



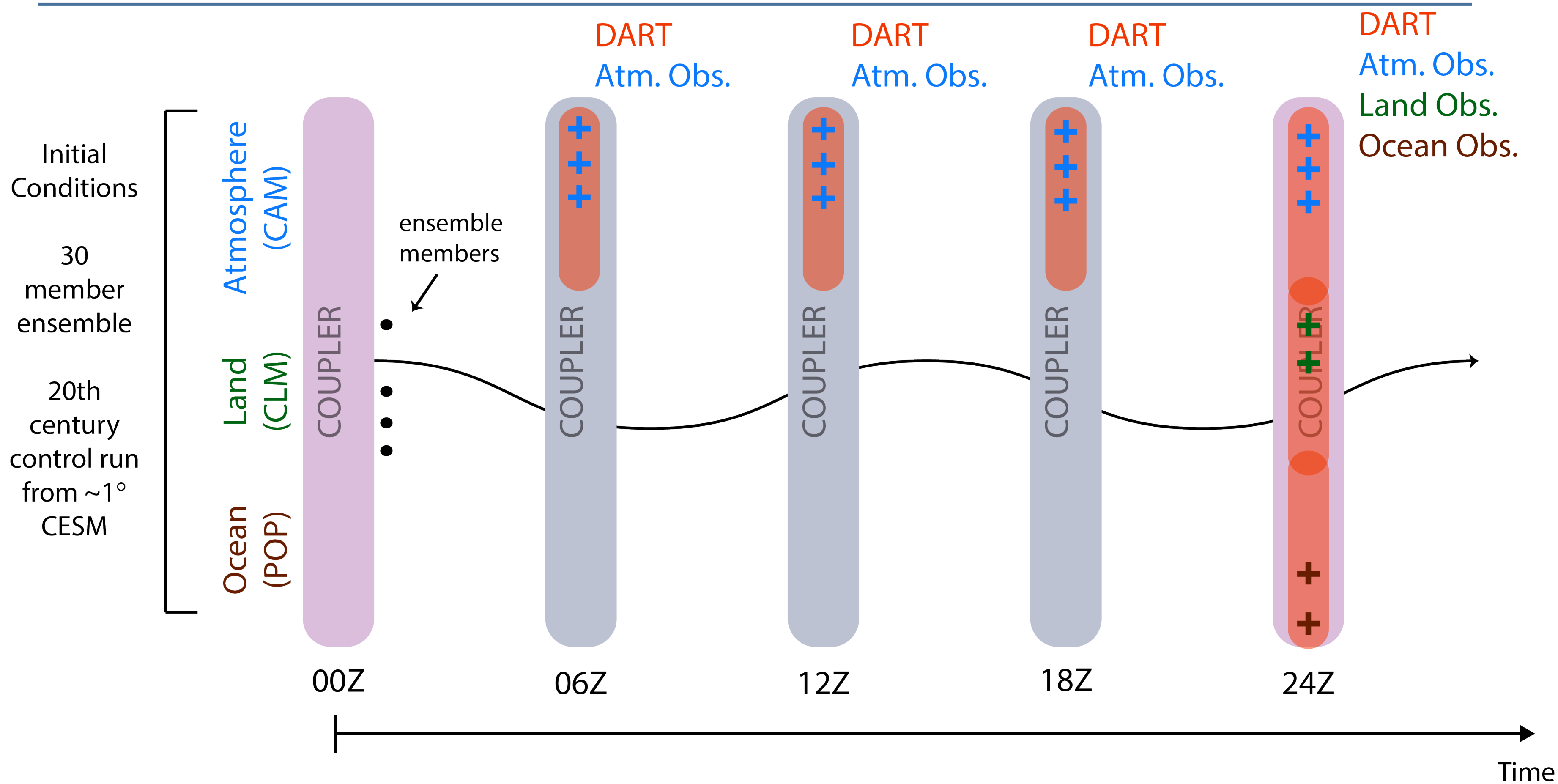
- Coupler exchanges fluxes and other necessary information between component models at equal or higher frequency than assimilation update
- Assimilation of conventional (surface, aircraft, etc.) observations independently in each component

Timescales Involved in CDA

Timescales	CESM-DART	Relevance
(internal) Time step of model components	Different for individual models	Dynamics, physics time step (not much control for CDA)
Coupling frequency of model components to CESM coupler	For example, CAM – 30 minutes POP – every 6 hours	At what time do model components pass information to other components?**
DA time step for model components	For example, CAM – every 6 hours CLM, POP – every 24 hours	Take into account different timescales at which atm and ocn processes operate
CESM stop/start	6 hours	--

** "In summary, users should ensure that the following is true,
ATM_NCPL = LND_NCPL = ICE_NCPL >= ROF_NCPL >= OCN_NCPL"

Multi-Component Coupled Data Assimilation (MuC)



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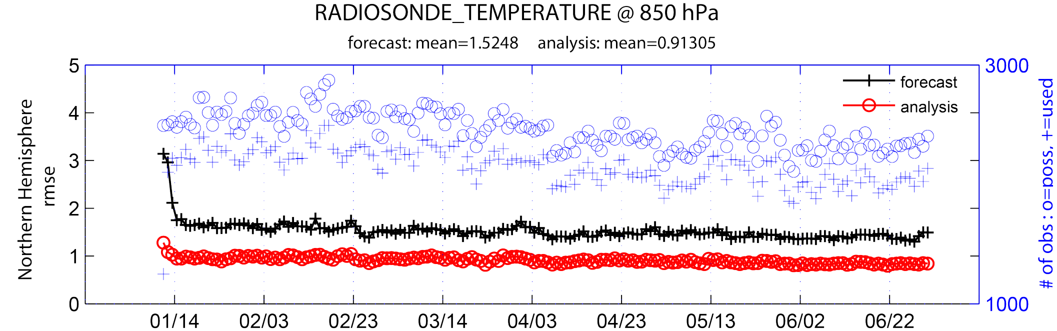
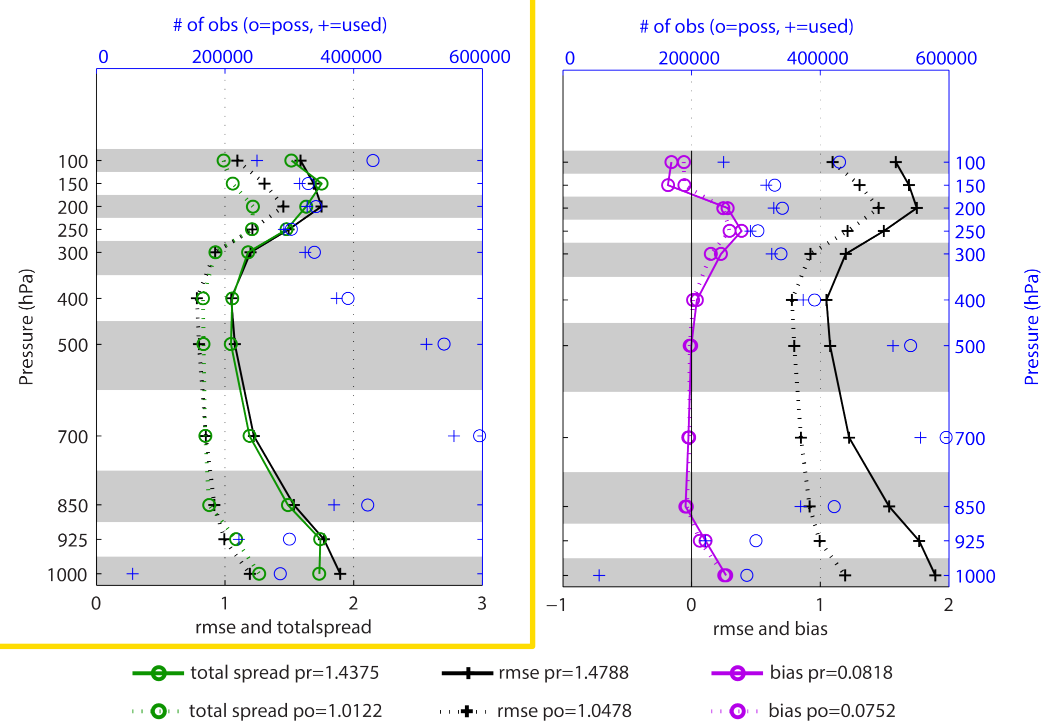
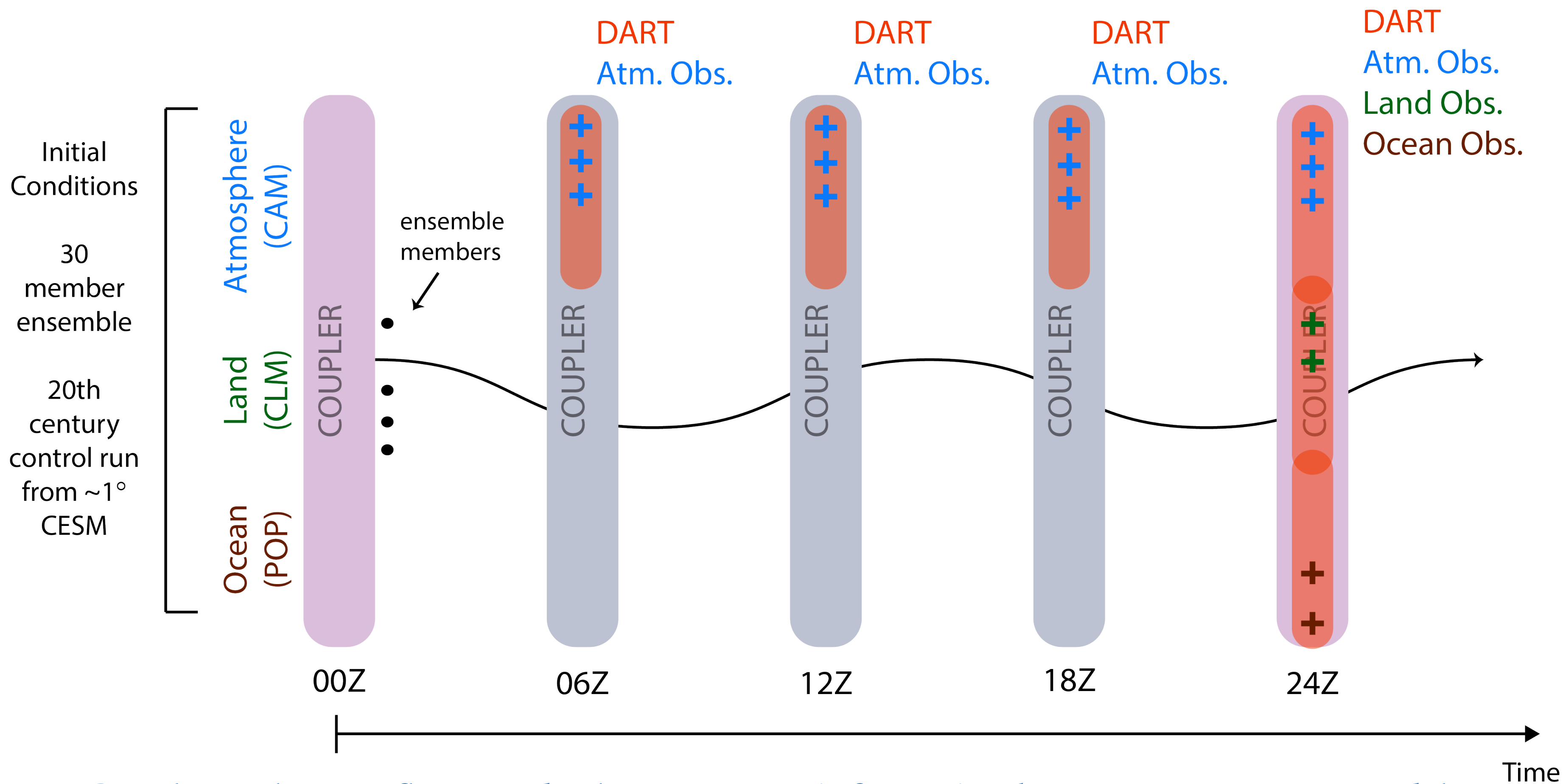
Initial Performance Check – Observation Space Diagnostics

- Ensemble analysis provides an estimate of analysis and forecast uncertainty
  - (Top Panel) evolution of prior and posterior RMS error
  - (Bottom Panels) profile of time-averaged prior and posterior RMS error, total spread and bias relative to the actual radiosonde temp. observations





Multi-Component Coupled Data Assimilation (MuC)



- Coupler exchanges fluxes and other necessary information between component models at equal or higher frequency than assimilation update
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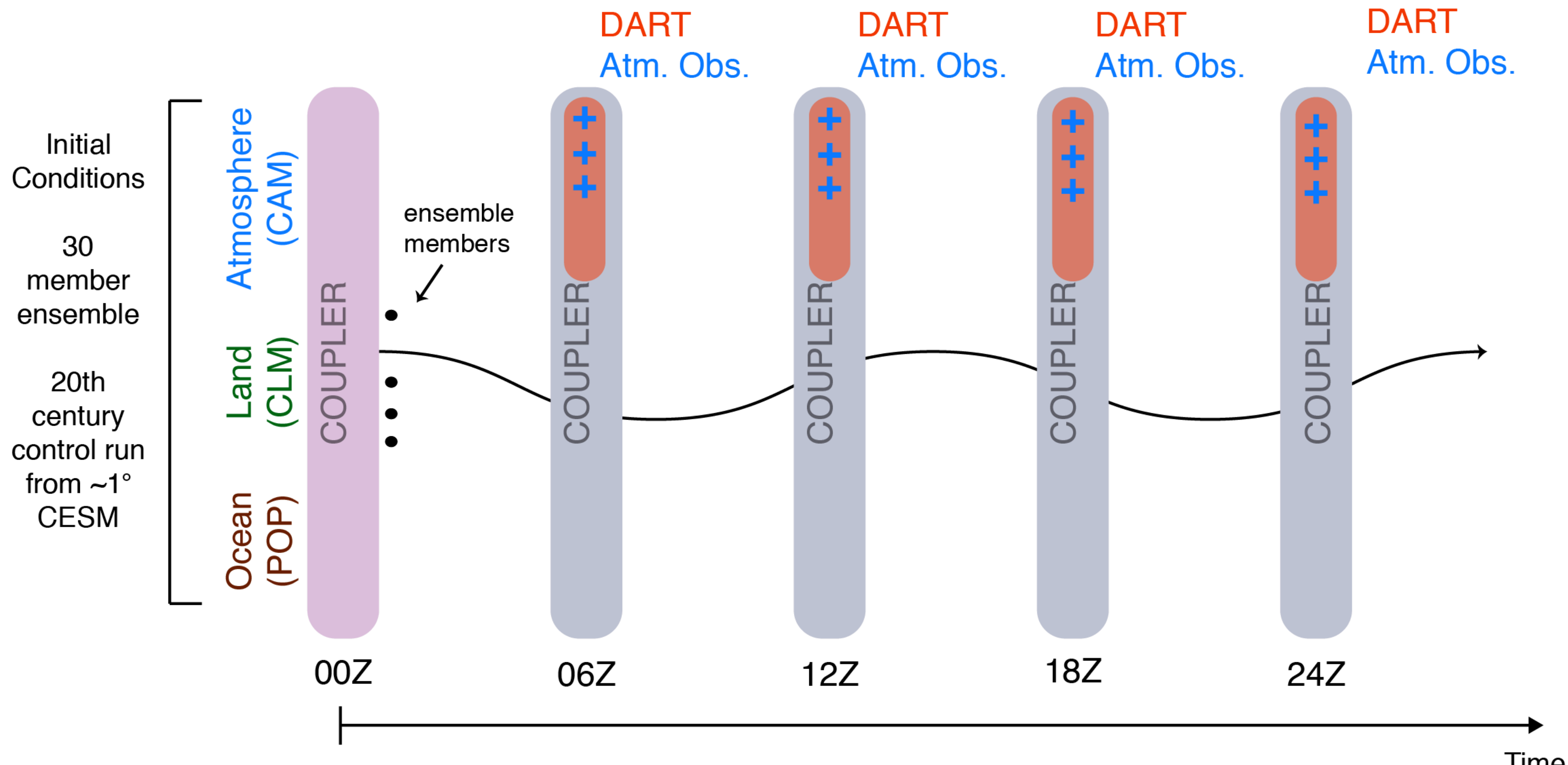
Atmos-Component Coupled Data Assimilation (Atmos-C)



- Coupler exchanges fluxes and other necessary information between component models at equal or higher frequency than assimilation update
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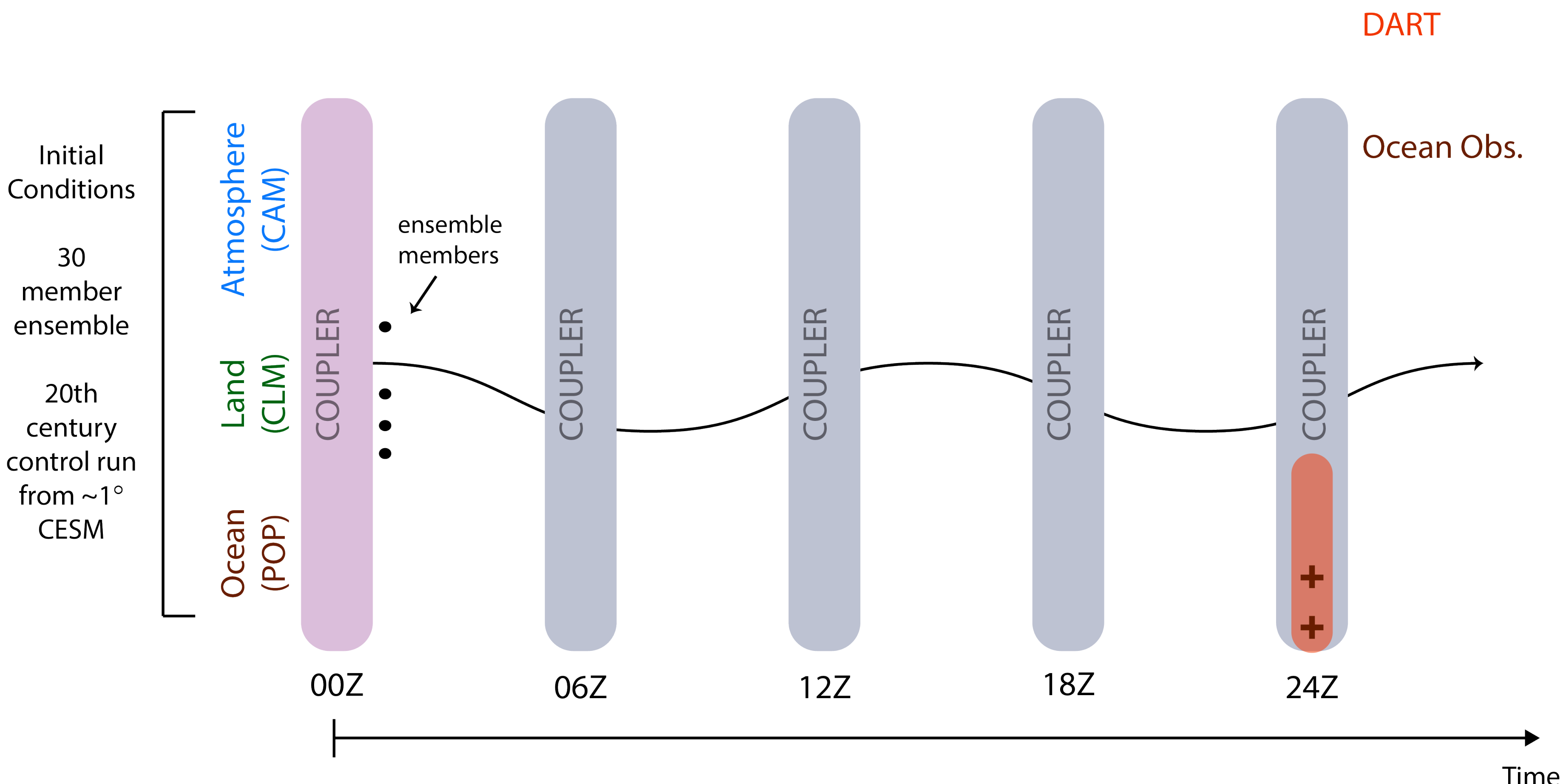
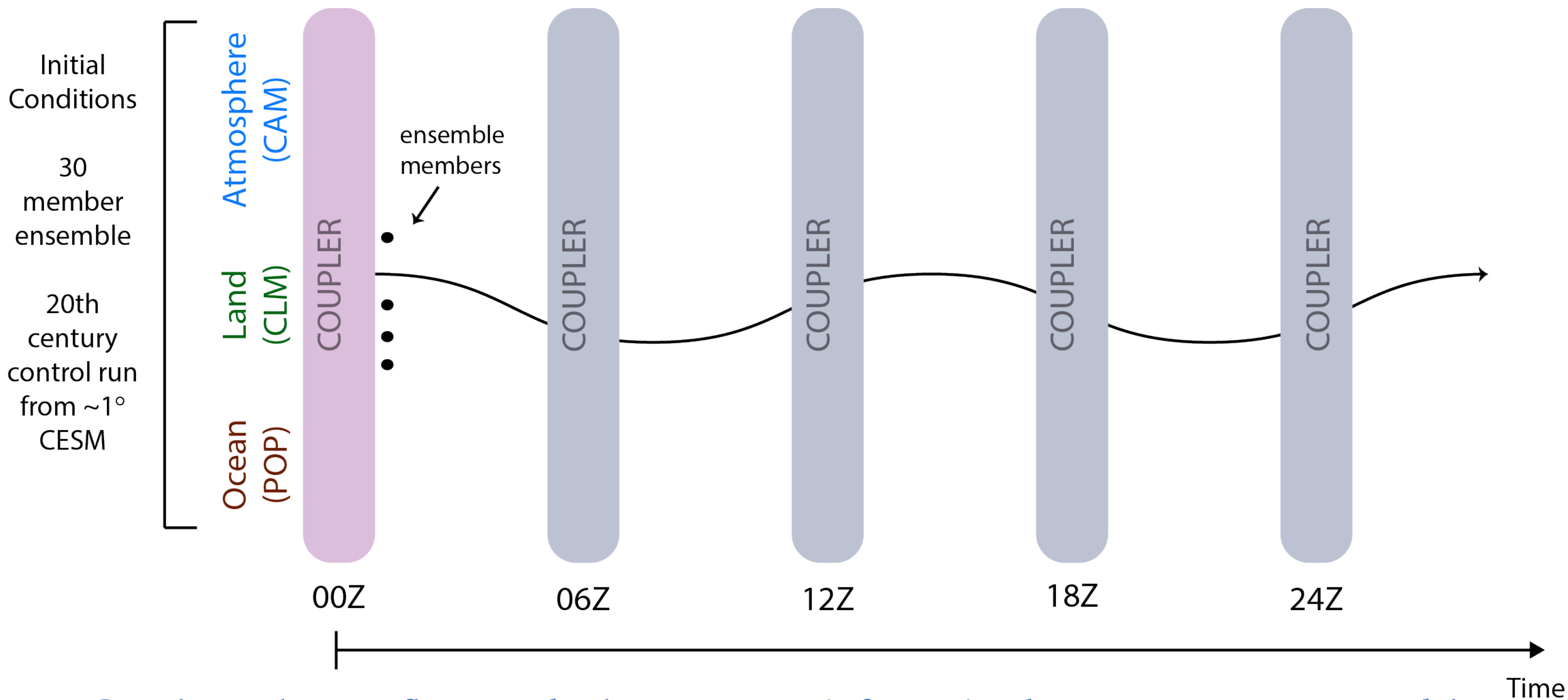
Ocean-Component Coupled Data Assimilation (Ocean-C)



- Coupler exchanges fluxes and other necessary information between component models at equal or higher frequency than assimilation update
- Assimilation of conventional (surface, aircraft, etc.) observations independently in each component

No-Assimilation Coupled Model Run (CESM Free Run)



- Coupler exchanges fluxes and other necessary information between component models at equal or higher frequency than assimilation update
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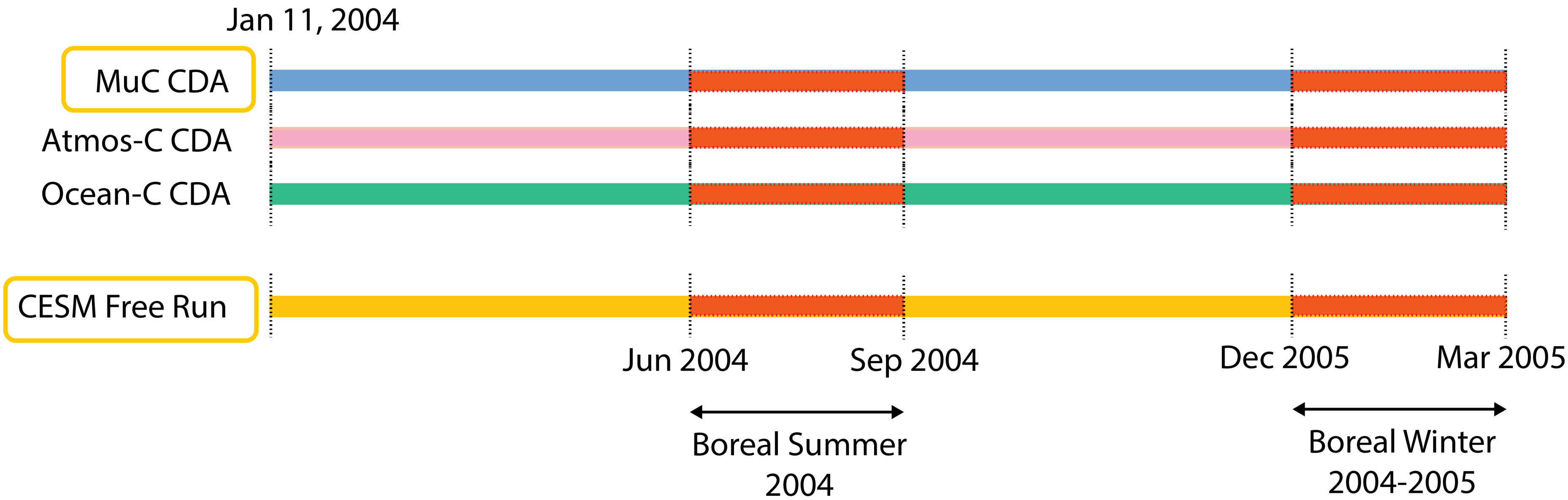
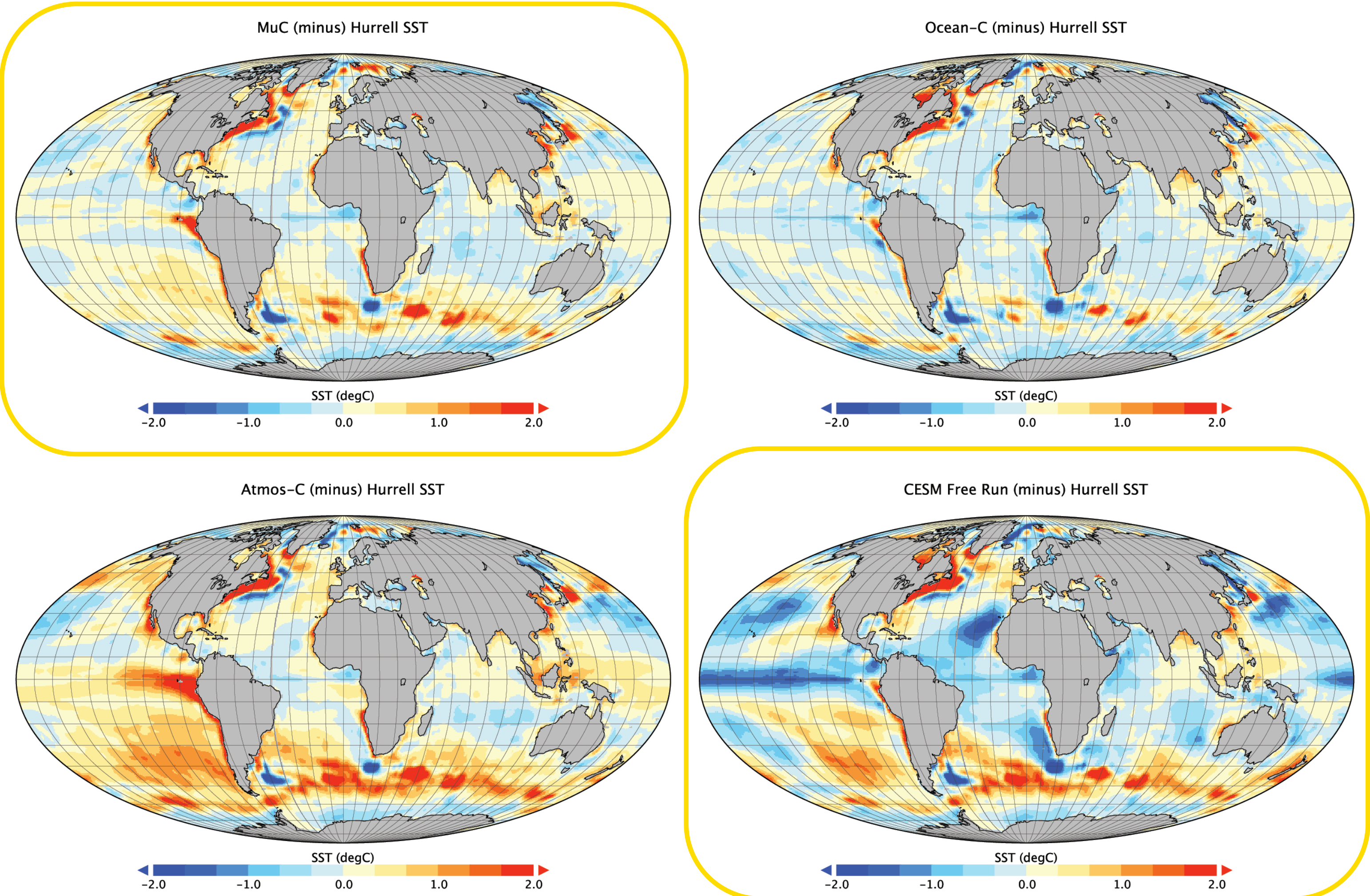
Experiment Configurations



- ❑ What are the **impacts on model biases** due to assimilation of observations in **multiple** CESM components?
- ❑ What are the **impacts on the modes of tropical intraseasonal variability**, for e.g., Madden-Julian Oscillation?

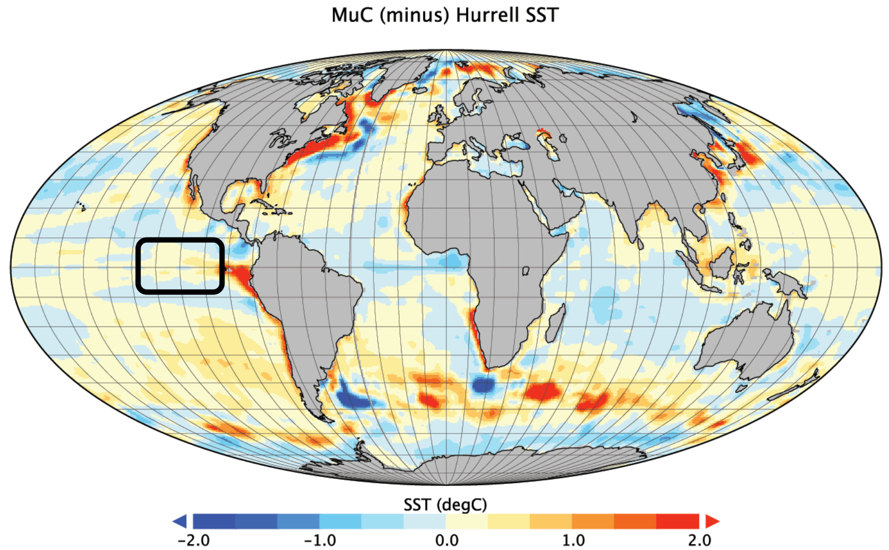
Reduction in SST Biases

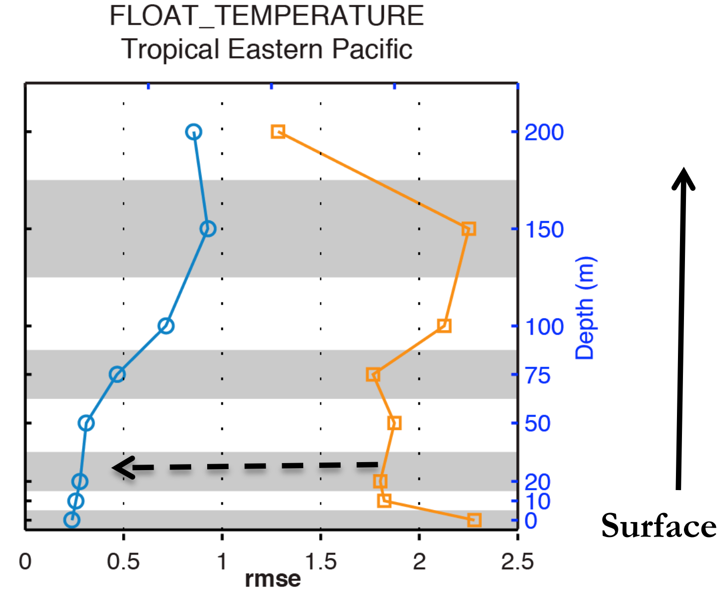
2004 Annual Mean SST

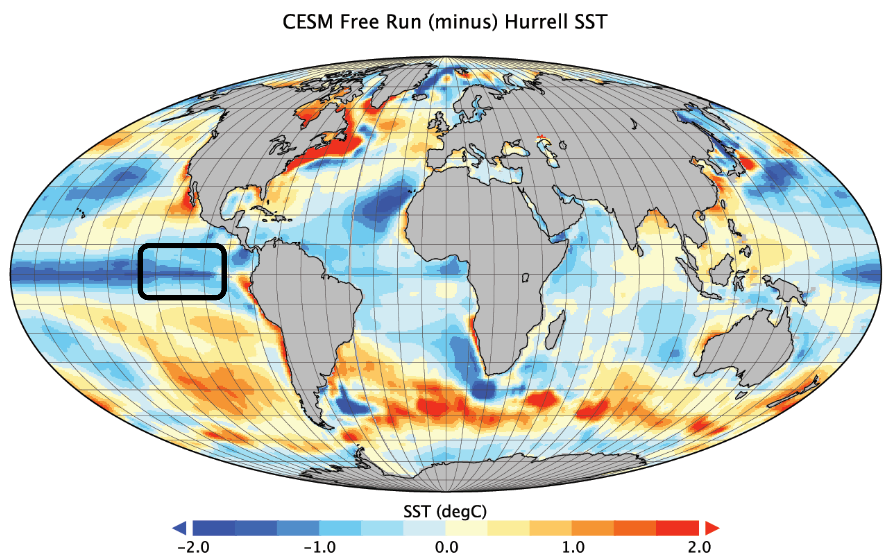


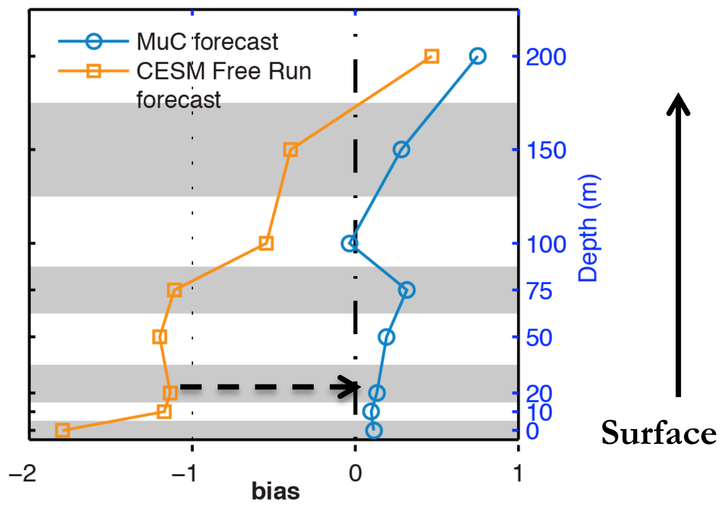
Reduction in SST Biases

2004 Annual Mean





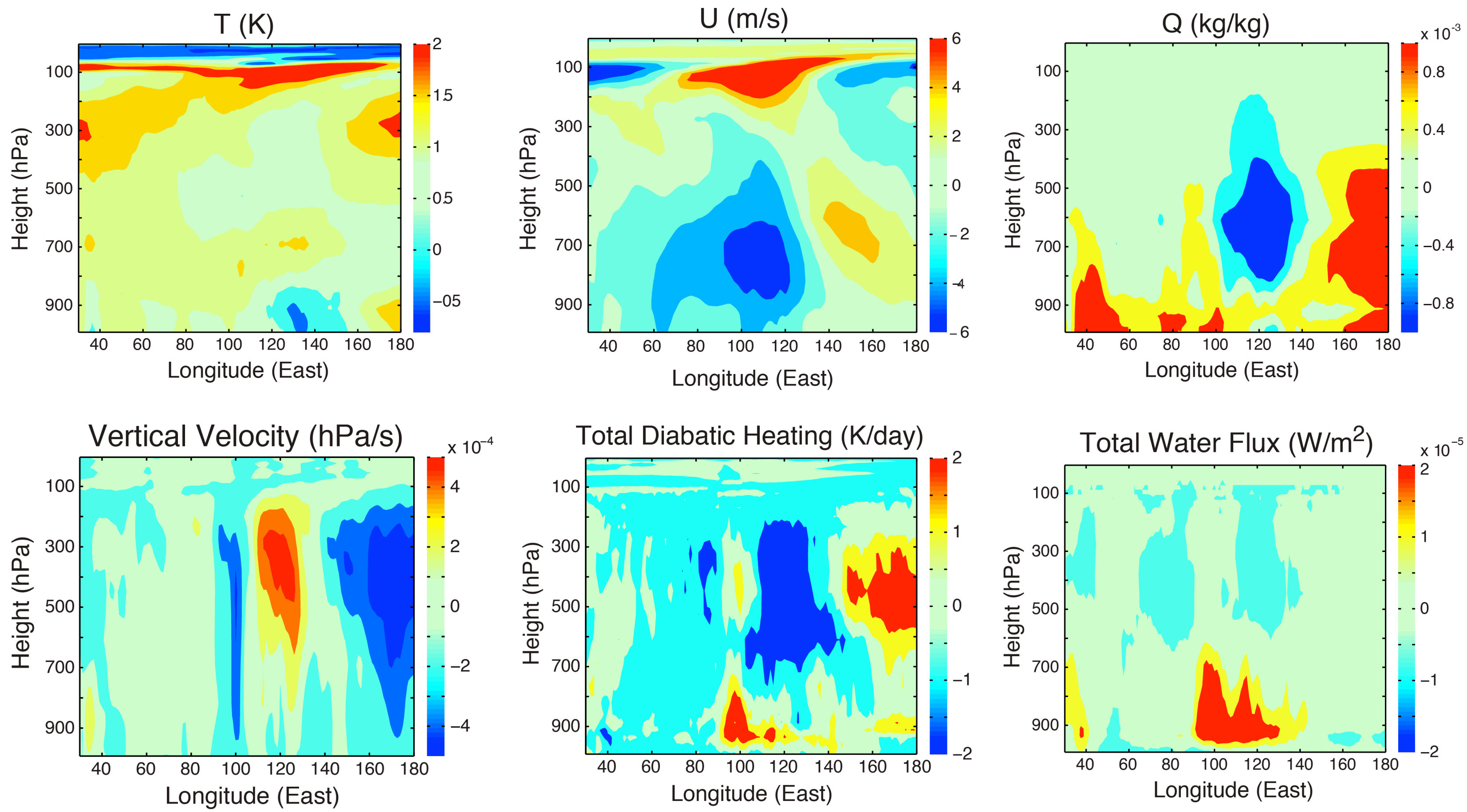




CAM State Variables

State Vector Variables

Physical Variables



- Differences between key variables from MuC and the free run of CESM
- 10N-10S averages over DJFM 04-05

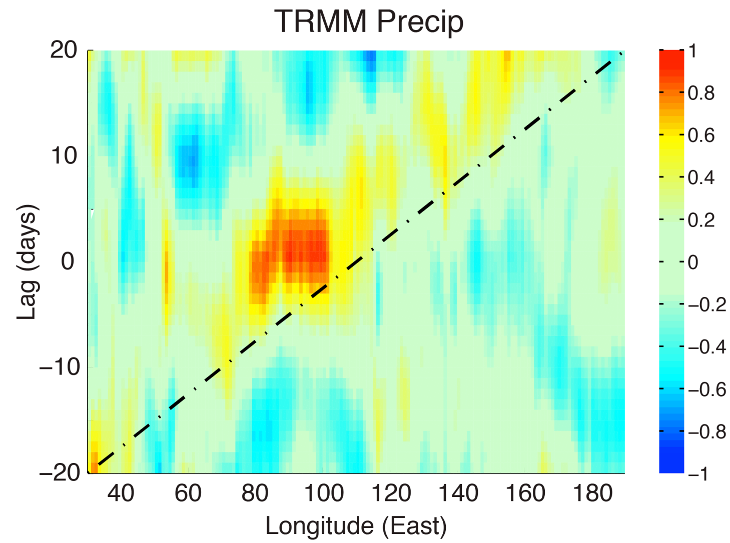
Madden-Julian Oscillation (MJO)

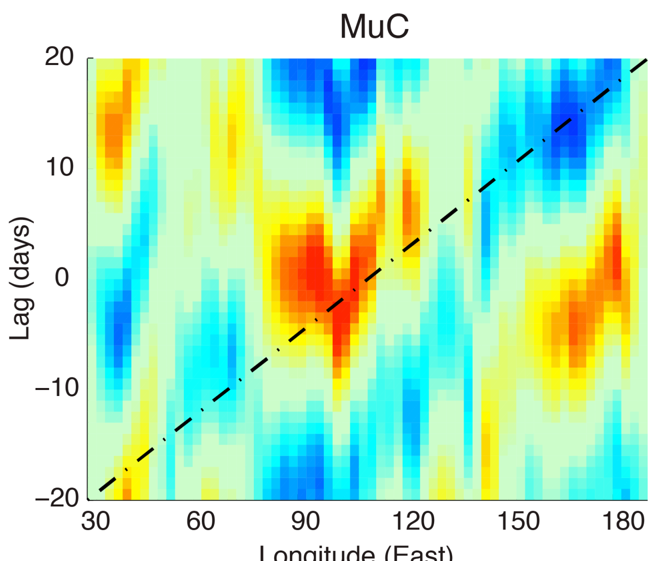
Key Features

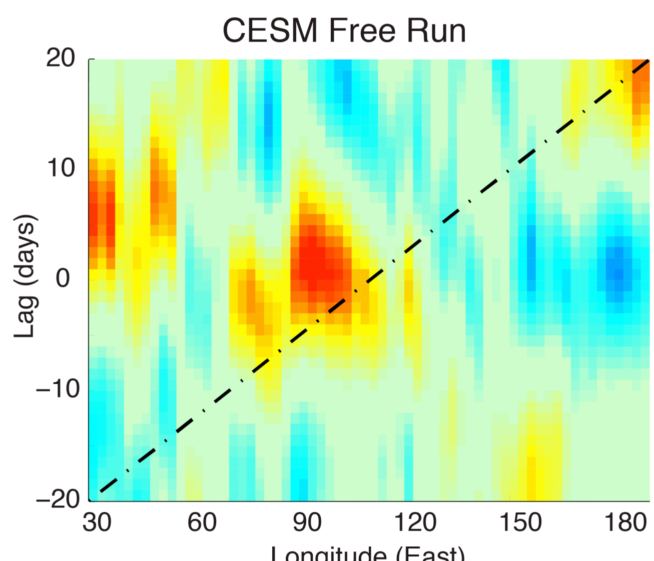
- Dominant mode of Tropical variability at intra-seasonal time scales
- 30-60 day period
- Eastward propagation of large scale convective precipitation
- **See Zhang [2013] BAMS for a thorough review**

Precipitation Lead-Lag Correlation Patterns

- Lead-lag correlation coeff. of 20-90 day band-pass filtered precipitation
- 10N-10S averages over DJFM
- IO reference point (75-100 E)

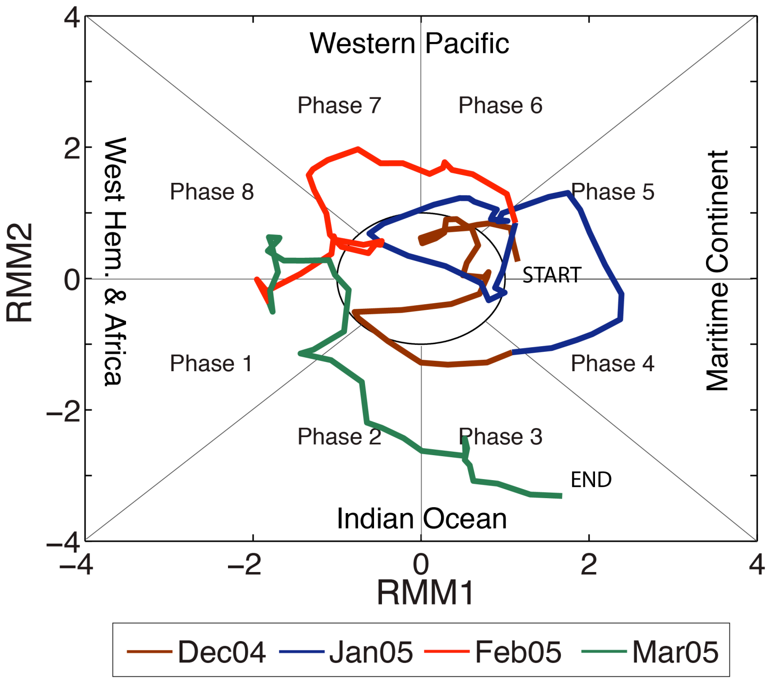






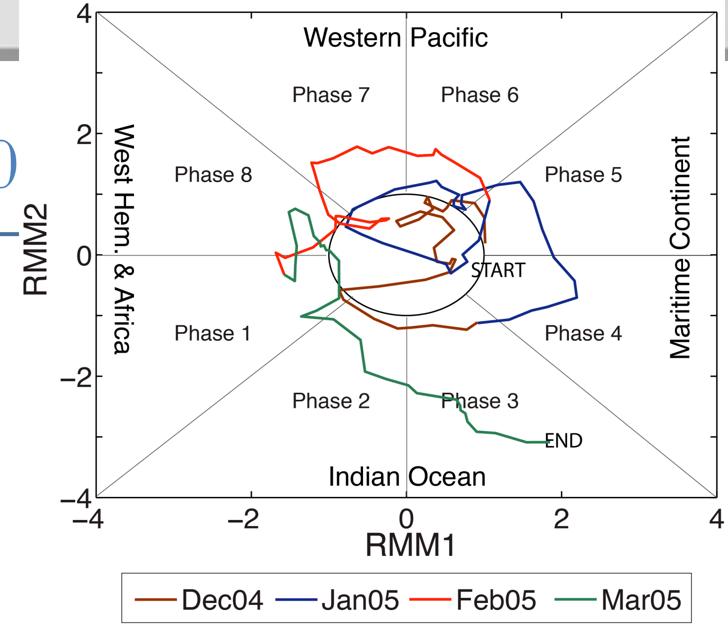
MJO State during Boreal Winter 200

MuC CDA (Boreal Winter 04-05)



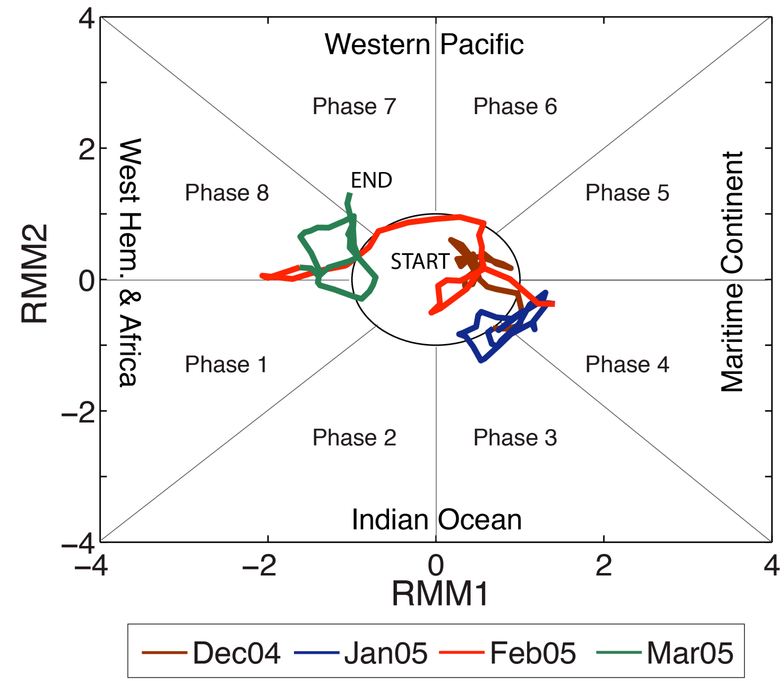
Corr. = 0.96
RMSE = 0.47
Amp. Err = 0.21
Phase Err = -1 day

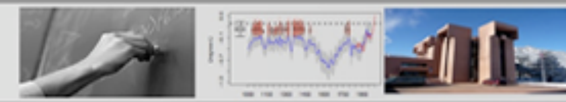
Observed (Boreal Winter 04-05)



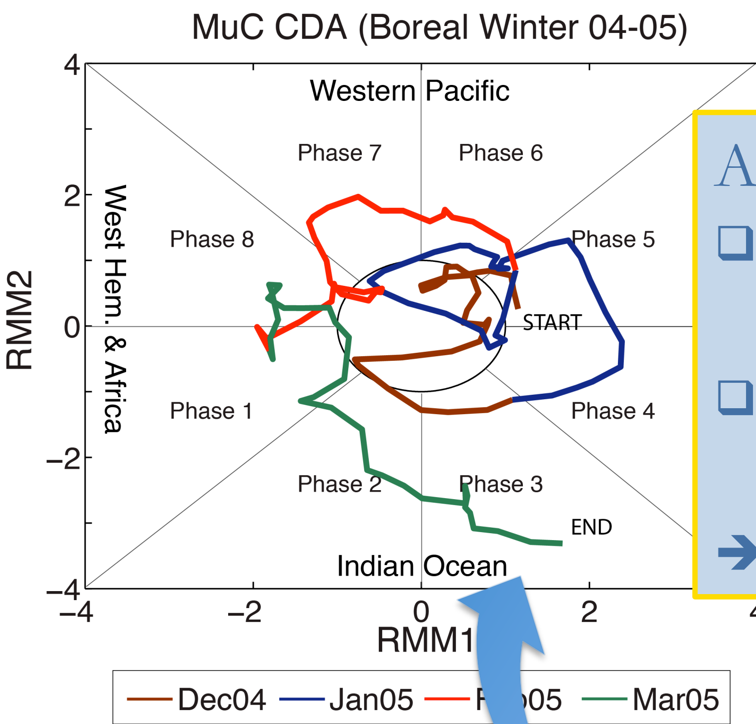
Corr. = 0.22
RMSE = 1.60
Amp. Err = -0.28
Phase Err = -10 days

CESM Free Run (Boreal Winter 04-05)





MJO State during Boreal Winter 2004

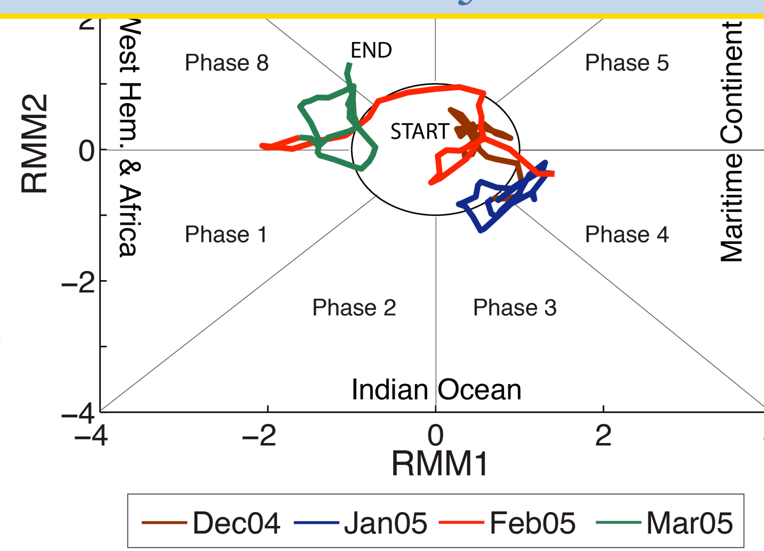


Assimilation in the coupled model

- impacts atmospheric forcing (westerly wind-bursts)
- impacts air-sea coupling (SST – convection relationship)

➔ improves simulation of the MJO

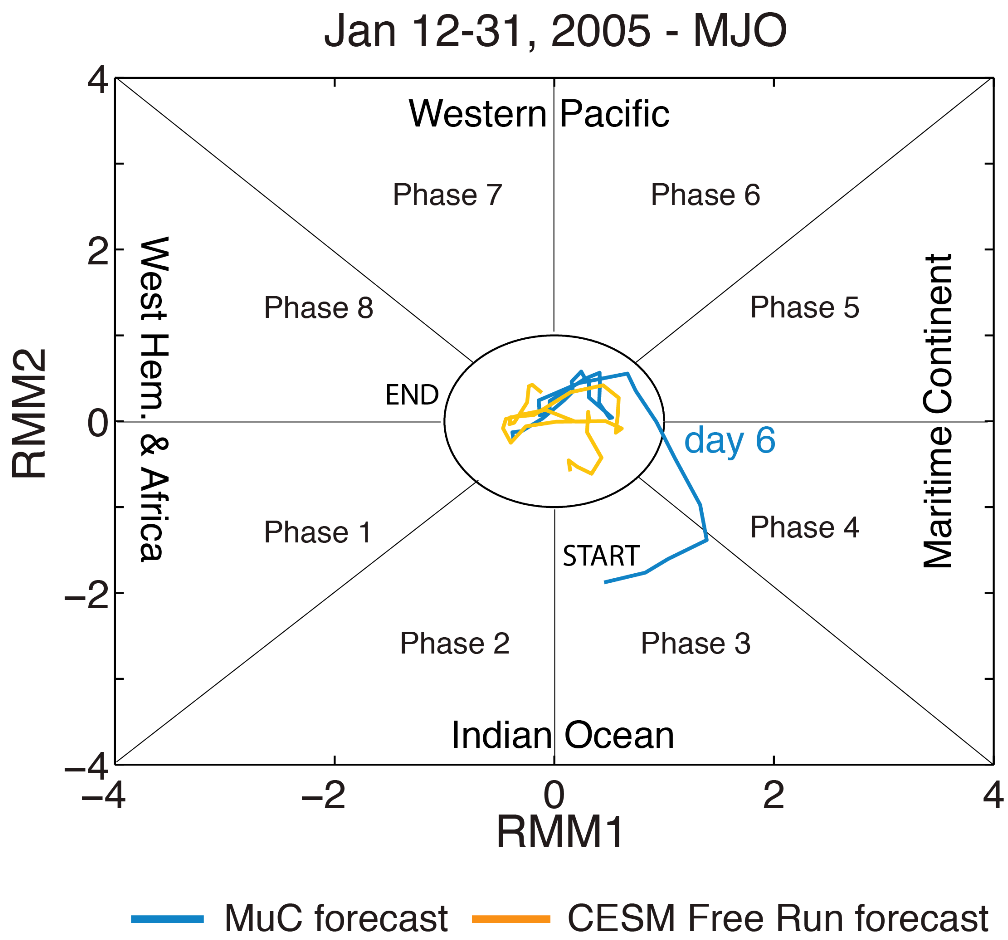
Corr. = 0.22
RMSE = 1.60
Amp. Err = -0.28
Phase Err = -10 days



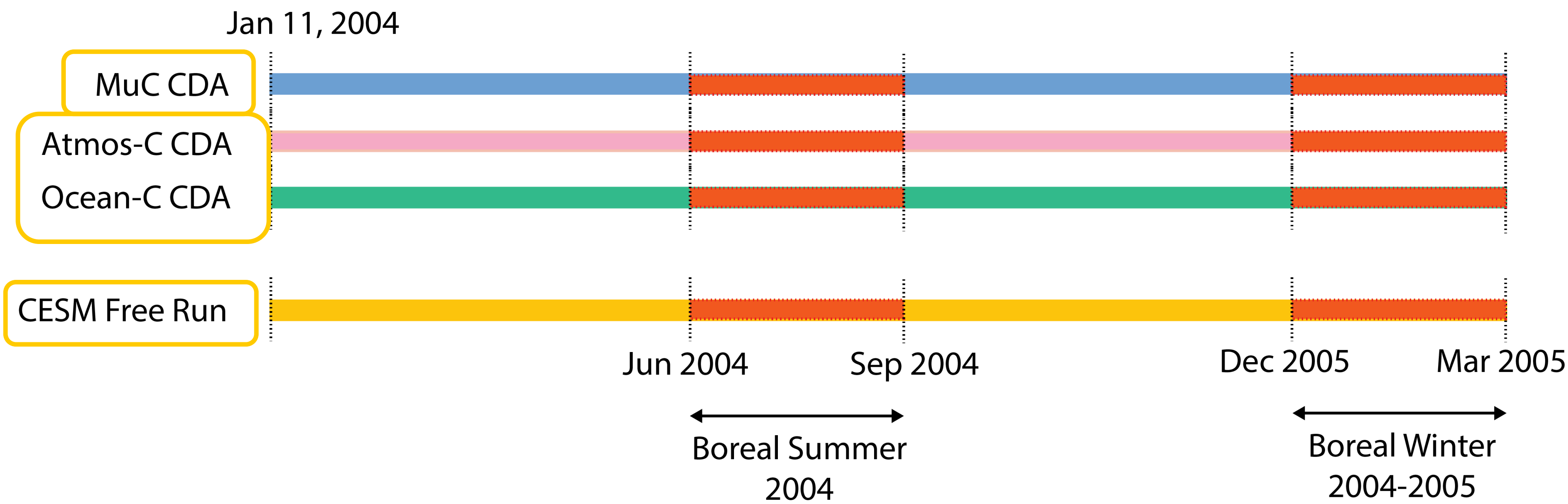
MJO Prediction Skill

- ❑ After 1 year of assimilation, a 3-week prediction is started
- ❑ Caveat: *only one event*

- Only ens mean shown
- MuC retains the MJO signal for ~3-5 days
- Drift towards model climatology after day 6



Impact of DA in a single-component vs. MuC

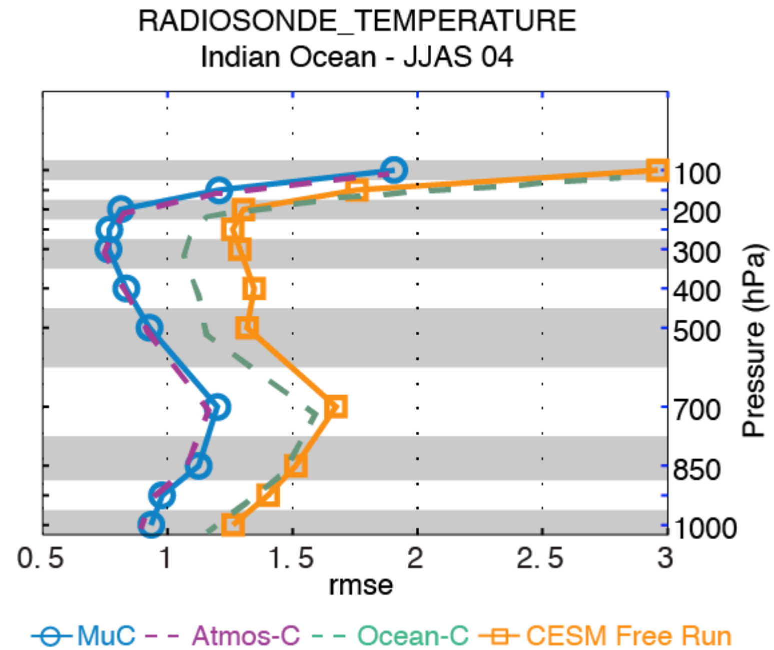


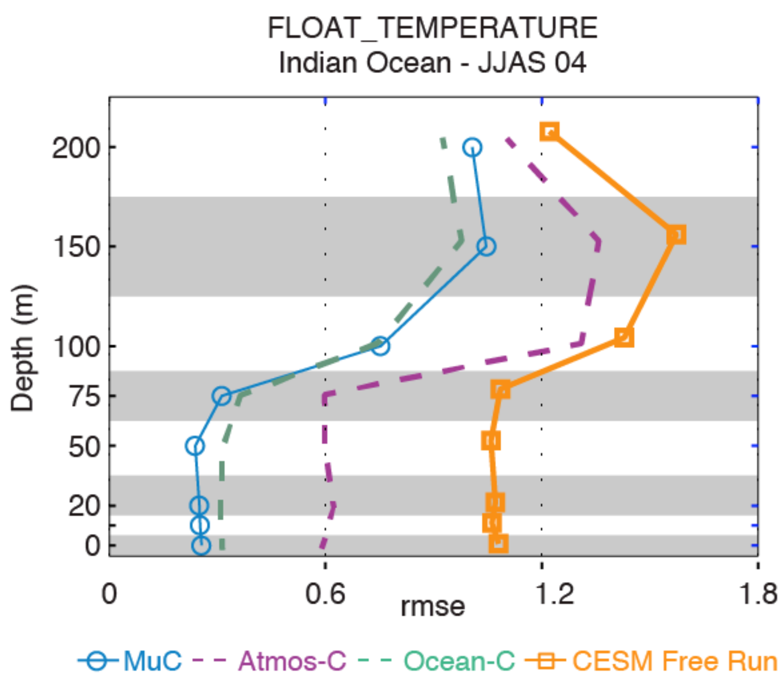
What are the differences due to assimilation of observations in a single-component vs. multiple-components?

Impact of DA in a single-component vs. MuC

Atmos-C Experiment

- Comparable to MuC in terms of estimating atmospheric states
- Small reduction in SST bias and/or biases in other oceanic states





Ocean-C Experiment

- Comparable to MuC in terms of estimating oceanic states
- Poor job in simulating MJO or reducing biases in atmospheric states

Impact of DA in a single-component vs. MuC

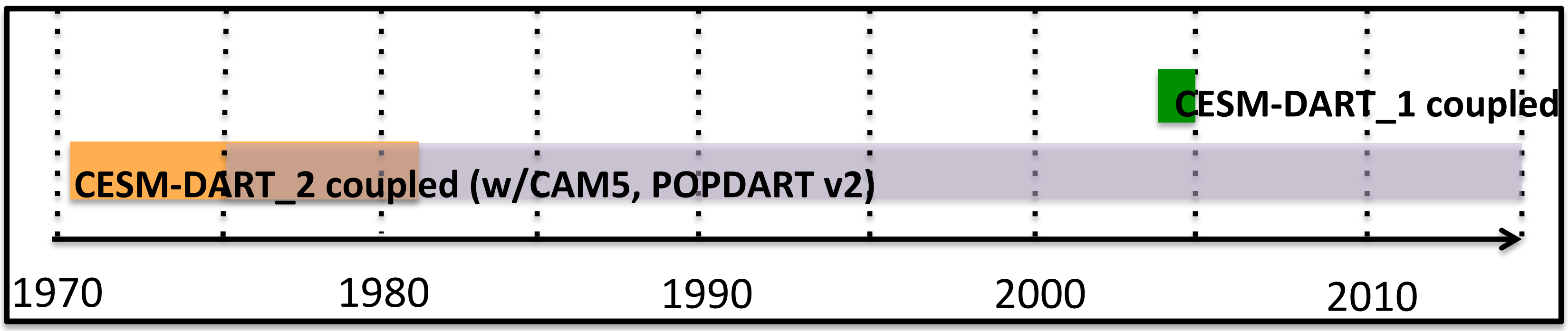
- What are the differences due to assimilation of observations in a single-component vs. multiple-components?
  - single component assimilation limits the 'full' impact of observations across the air-sea interface, even though forecast step may be coupled
  - Ocean-C (Atmos-C) provide limited improvement in atmospheric (oceanic) states

	Atmosphere	Ocean
MuC	☑	☑
Atmos-C	☑	--
Ocean-C	--	☑
CESM Free Run (baseline)	---	---

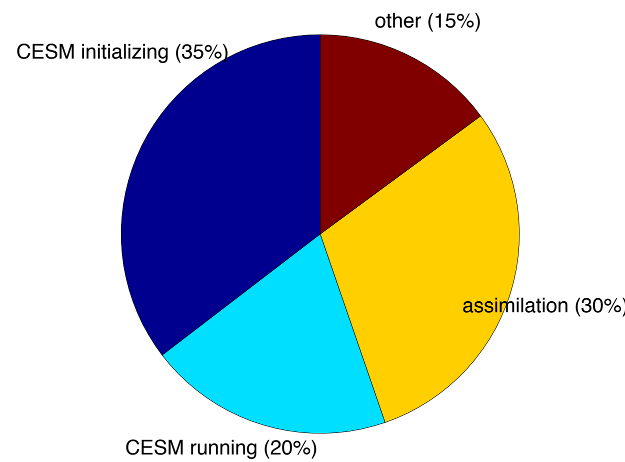
Source: A. Karspeck (NCAR)

Towards an Experimental Climate Reanalyses

- Primarily motivated by the need for a more self-consistent initial conditions for decadal prediction
- Uses a 'similar' setup as MuC CDA, no assimilation in land

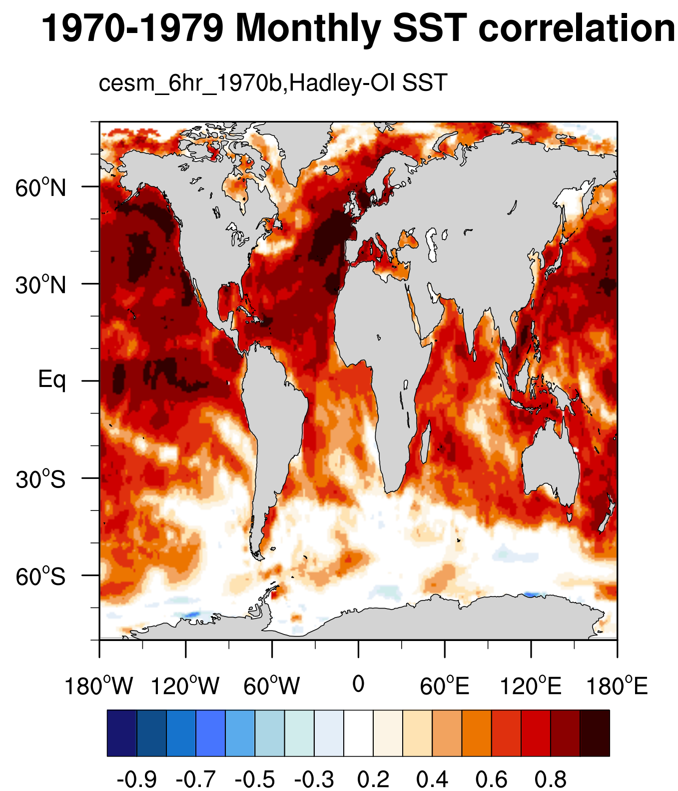


- Main challenge: computational time, for e.g., 2 sim-years per wallclock month on NCAR HPC
  - CESM stops and starts every 6 hours,
  - Lots of IO
    (CESM model components -> DART)

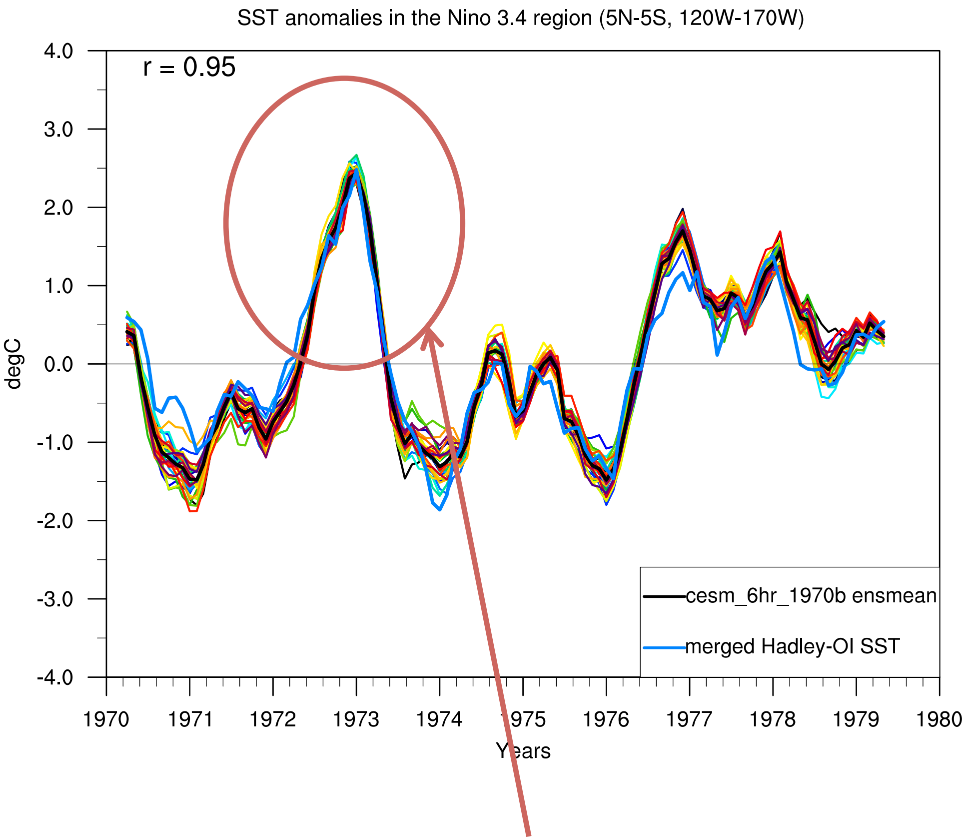


Source: A. Karspeck, S. Karol (NCAR)

Ocean results: SST variability



Overall high +ve correlation with HADISST



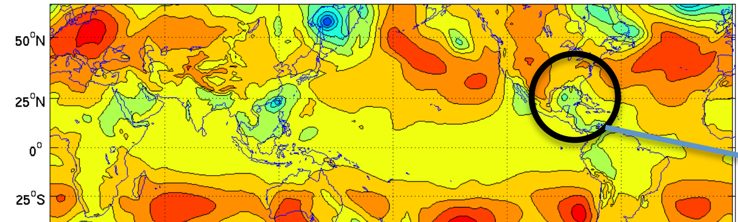
1972-73 El Nino event simulated

Source: A. Karspeck, S. Karol (NCAR)

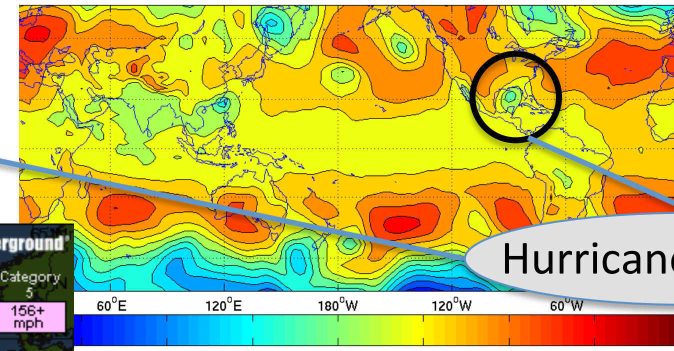
Atmosphere results: Tropical Cyclones

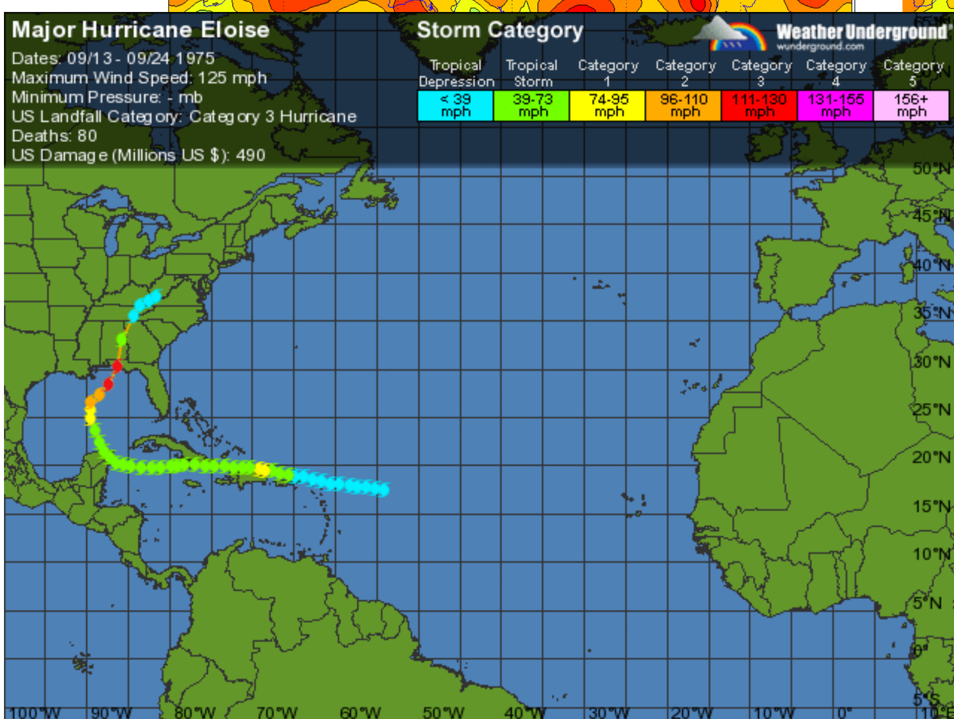
6hr snapshots of sea level pressure from CAM5

NCAR CESM-DART
SLP (dynes/cm^2); ENS mean
1975-09-23-00000



NCEP
SLP(dynes/cm^2)
1975-09-23-00000





A case for CDA for hurricane forecasting?

Summary (1)

- Implementation of CESM-DART
  - multi-component coupled model framework -- test-bed for transitioning to cross-component coupled model scheme

- What are the impacts due to assimilation of observations in multiple-components in CESM?
  - reductions in model biases, improvements in model fidelity and forecasting skill

- What are the impacts on the modes of tropical intraseasonal variability, for e.g., MJO?
  - MuC improves the simulation of MJO state in terms of the amplitude (larger), seasonality (stronger), phase speed (faster)

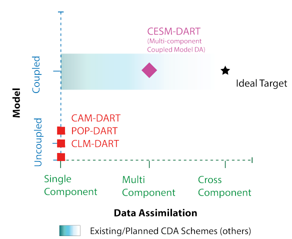
Summary (2)

- Ongoing reanalyses from 1970-onwards
  - Early results (1970-1980+) are promising
  - Interested in looking at preliminary results from ocean/atmosphere/land/ice components? – **contact Alicia (aliciak@ucar.edu)**

Outline

Coupled Data Assimilation – general issues

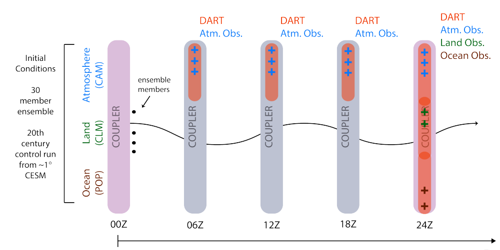
Whys, whats and hows of CDA?

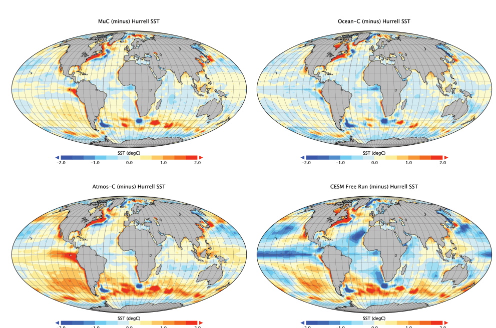


Illustrative Examples

CESM-DART

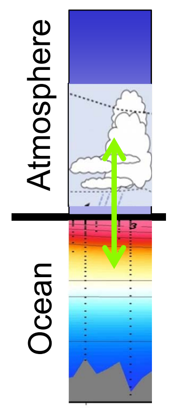
Implementation -> Results





Known unknowns + *Unknown* unknowns

Scientific & Practical Challenges



Scientific & Practical Challenges

- All the usual challenges with atm/ocn/land DA remain; for e.g., a few common ones -
  - Model imperfections, biases – DA corrects for random errors
  - Observations – inhomogeneous, sparse for certain components
  - Representativeness error
  - Specification of background error variances
  - Related to DA tool – ensemble (sampling error) vs. variational (adjoint, Jacobians, etc.)

- In addition, we have brought into play exchange across the boundaries – atm/ocean, atm/land → increased complexity

Questions remain…

"Known" Unknowns	"Unknown" Unknowns
(1) Practical Considerations – especially for ESMs **(2) Specifying Cross-Covariances across model components, e.g.** Ocean -> Atmosphere • How strong is the influence of the ocean on the atmosphere? Model dependent, resolution dependent, others? • How large of an ensemble size do you need to capture the signal from the atmosphere? With small ensemble size, sampling error dominates the 'small' signal from ocean to atm. Atmosphere -> Ocean • Do we really need coupled covariances or is the coupling between model components enough to propagate the information? • Interacting slow (ocean) & fast (atmosphere) components – and the fast component is noisy! How to reconcile differences in timescales?	**(1) Benefit of CDA** (vs. uncoupled DA) – contribution of CDA in generating accurate initial condition for near-term climate prediction **remains to be established at a fundamental level**

Summary

Coupled Data Assimilation – general issues

- CDA is expected to produce self-consistent estimates
- Big push, especially in operational centers towards cross-component coupled model DA

CESM-DART

- CESM-DART – currently setup as a multi-component coupled model DA
- Initial runs designed to test the feasibility of the framework, benefits for sub-seasonal prediction
- Ongoing runs designed to improve decadal prediction skill

Known unknowns + *Unknown* unknowns

- Usual challenges with atm/ocean/land DA are applicable
- Fundamental “mathematical”/”methodological” development required on specifying cross-component covariances
- **Big big…big** unknown – how much benefit will coupled DA really provide?

QUESTIONS?

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