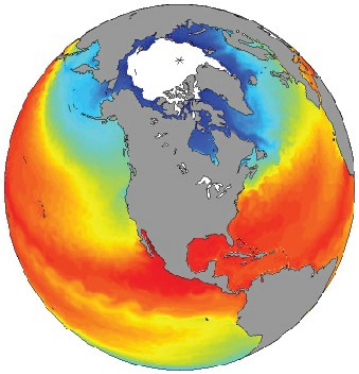
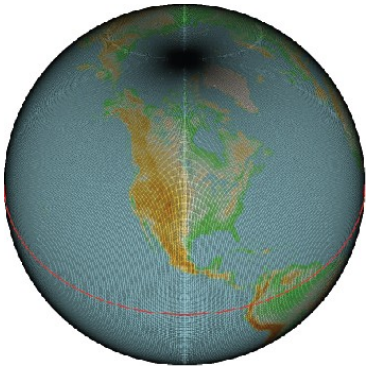


GOAPP

Global Ocean-Atmosphere Prediction and Predictability



Progress and Plans, Issues and Opportunities

Keith Thompson and Hal Ritchie
Bill Merryfield and Dan Wright

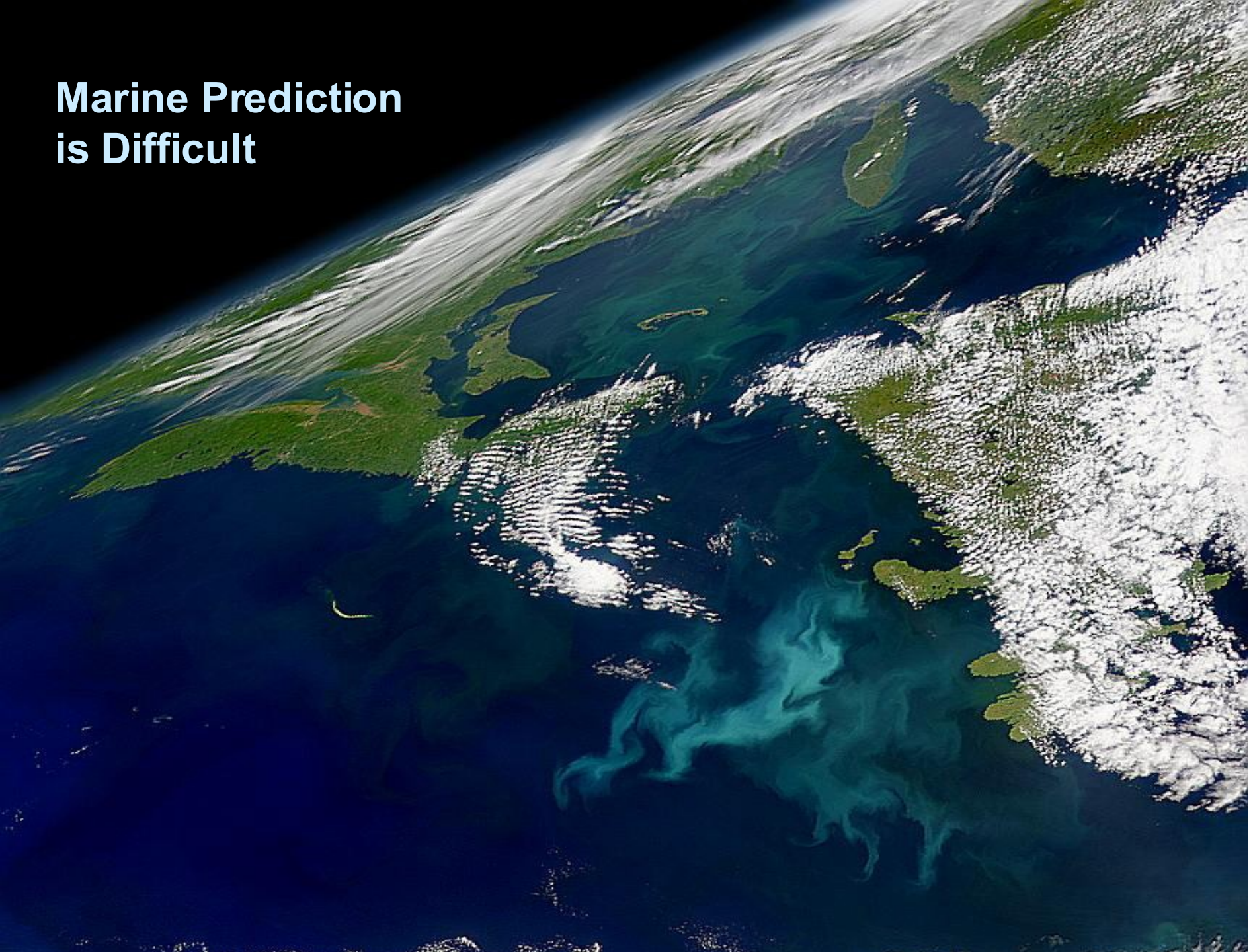
Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)

Fondation canadienne pour les sciences du climat et de l'atmosphère (FCSCA)

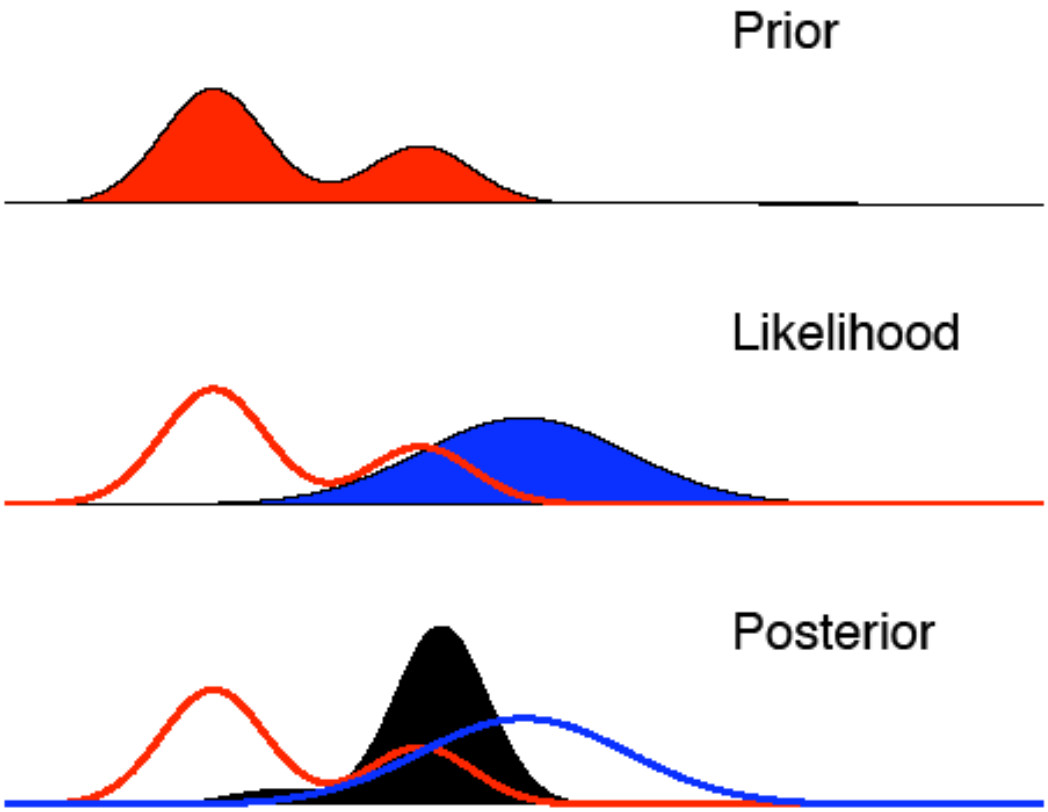
Applications of a Coupled Atmosphere-Ocean Forecast System

- Sustaining a healthy and productive marine environment through ecosystem modeling and informed fisheries management
- Short term forecasting of currents and sea ice for search and rescue, navigation, ship routing and pollution containment
- Short term forecasting of maritime weather such as hurricanes and “bomb” storms, and accompanying storm surges and flooding
- Assist Canadian exercises and operations in regions of strategic interest (e.g., the Arctic Archipelago)
- Providing multi-season and multi-year climate predictions to assist with planning of seasonally dependent economic activities such as agriculture, oil refining, hydro-electric generation and transportation

Marine Prediction is Difficult



Managing Uncertainty: The Need for Data Assimilation



GOAPP in a Nutshell

- CFCAS research network, close to $3 Million from CFCAS
- In-kind (EC, DFO, DND) ~ $975 k/yr over 4 years
- Objective: Improve forecasts of the coupled atmosphere-ocean system on time-scales of days to decades, and space scales of tens of kilometers to global
- Outcomes: Better models and assimilation schemes, a deeper understanding of contributors and limits to predictability
- Complements the EC-DFO-DND Canadian Operational Network of Coupled Environmental PredicTion Systems (CONCEPTS) and EC's operational seasonal forecast activity

Structure of the Research

Two themes distinguished by time-scale:

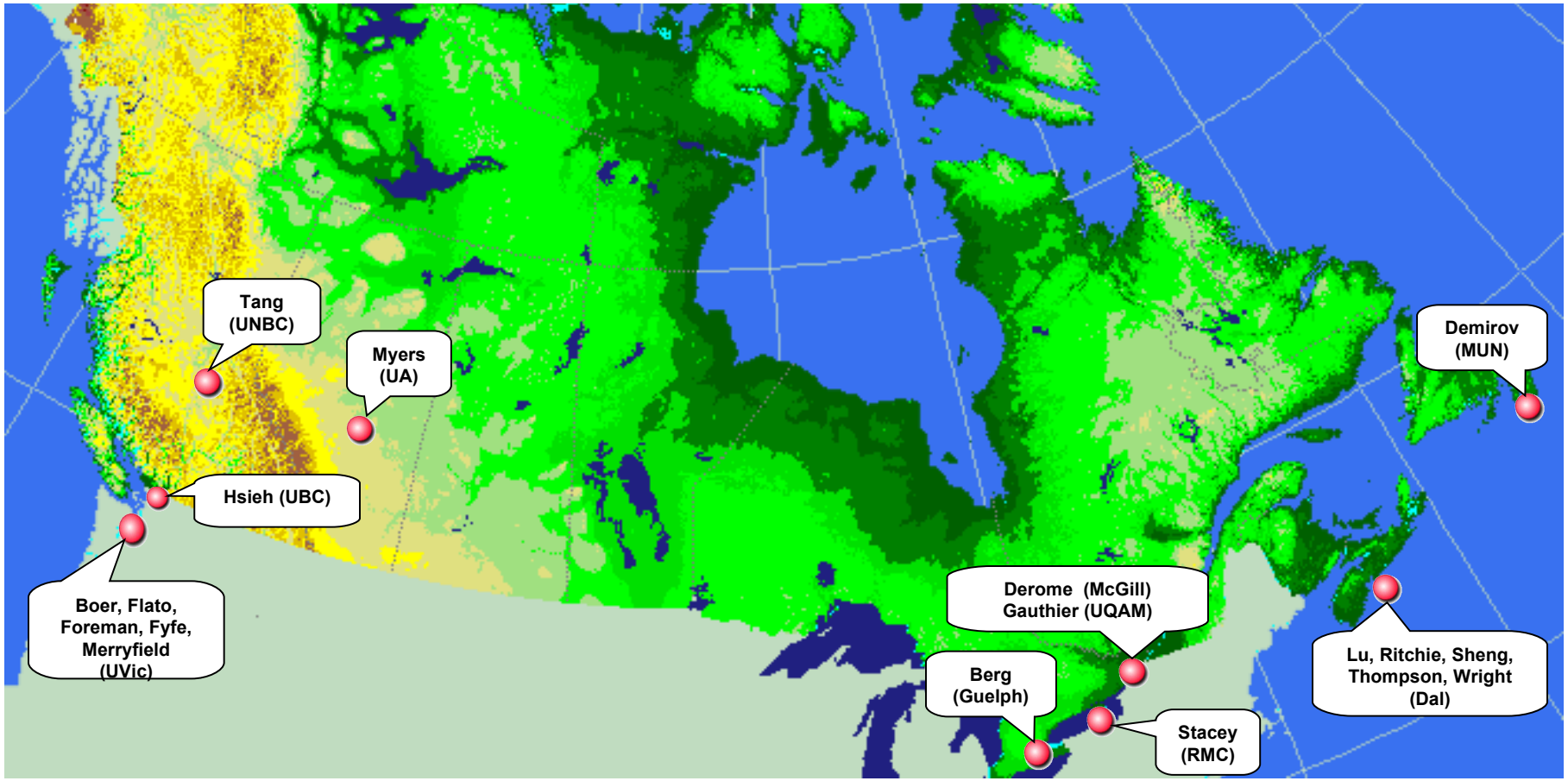
Theme I: Days to Seasons
Theme II: Seasons to Decades

These two themes reflect:

- ❑ **Present expertise in weather and climate modelling and prediction in Canada**
- ❑ **Potential advantages of a multi-model approach**

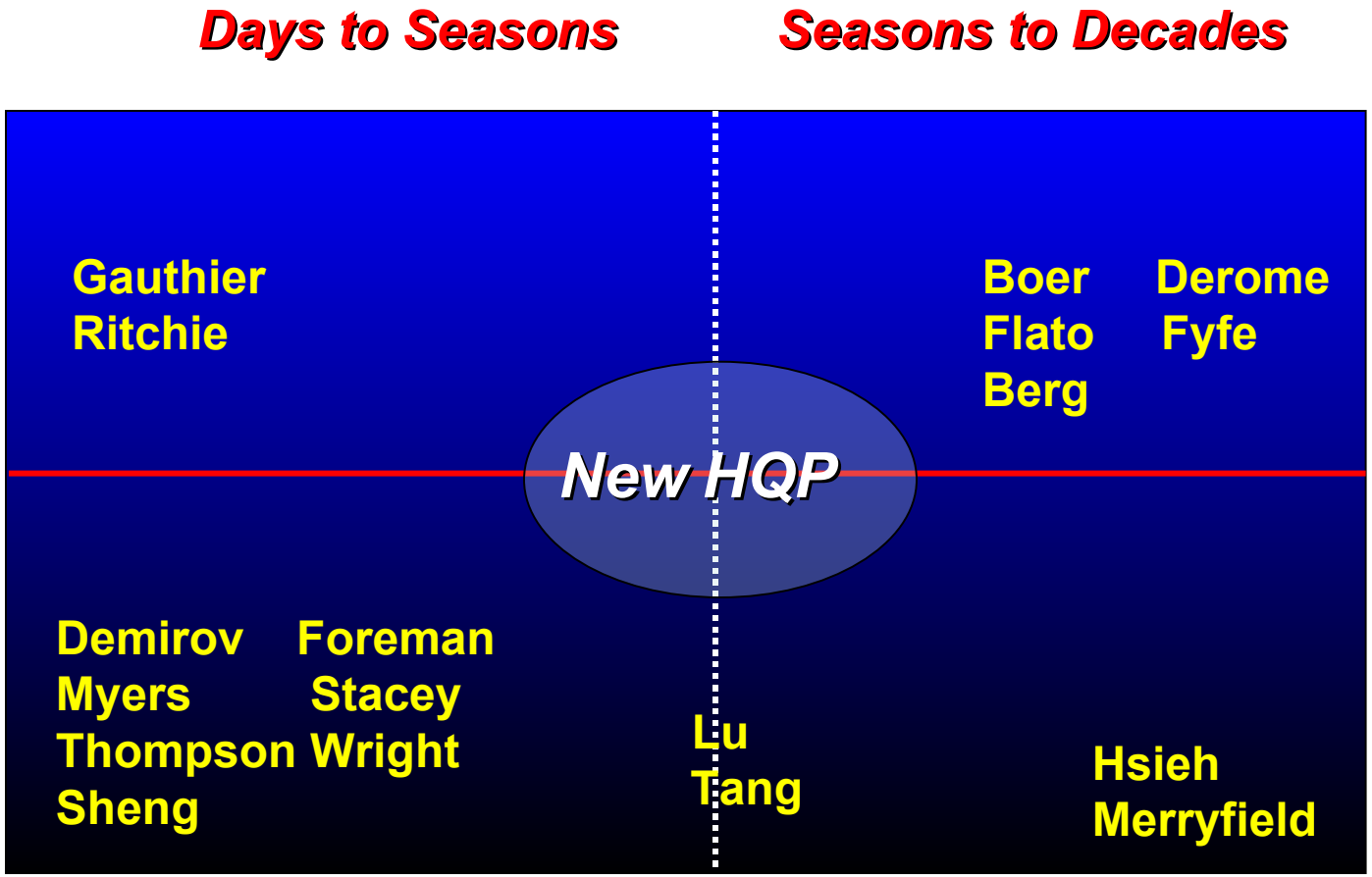
Working toward a *seamless prediction capability* that bridges these time-scales (consistent with developing international activities e.g. THORPEX, WCRP)

Geographical Distribution of the 18 GOAPP Co-Investigators



20 Collaborators from EC and DFO

The GOAPP Researchers



Highly Qualified Personnel

Trainees	**2009**	**Anticipated Total**
Research Associates	7	8
Post Doctoral Fellows	5	6
PhD	6	12
Masters	9	17
Undergraduates	2	7
Total	**29**	**50**

Theme I Projects: Days to Seasons

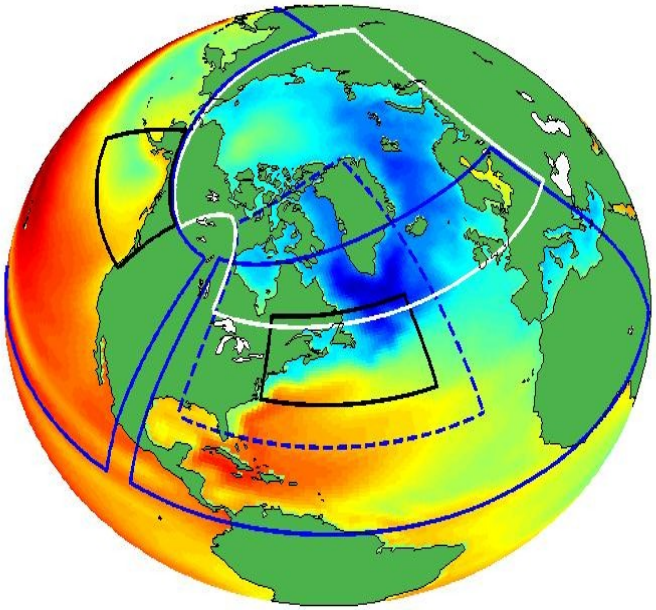
Ocean Modeling and Data Assimilation

- Suppression of bias and drift in ocean model components
- Statistics of observed variability for model testing and improvement
- Multivariate assimilation of altimeter and Argo data
- Ocean reanalysis and forecasting
- Modelling and assimilation of sea ice
- Assessing the capability of a nested-grid shelf circulation model for the Eastern Canadian Shelf

Coupled AO Modeling and Data Assimilation

- Assimilation into coupled atmosphere-ocean models
- Studies on joint assimilation into coupled models

Theme I: Ocean Modelling and Assimilation



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- Statistics of observed variability for model testing and improvement
- Multivariate assimilation of altimeter and Argo data
- Ocean reanalysis and forecasting
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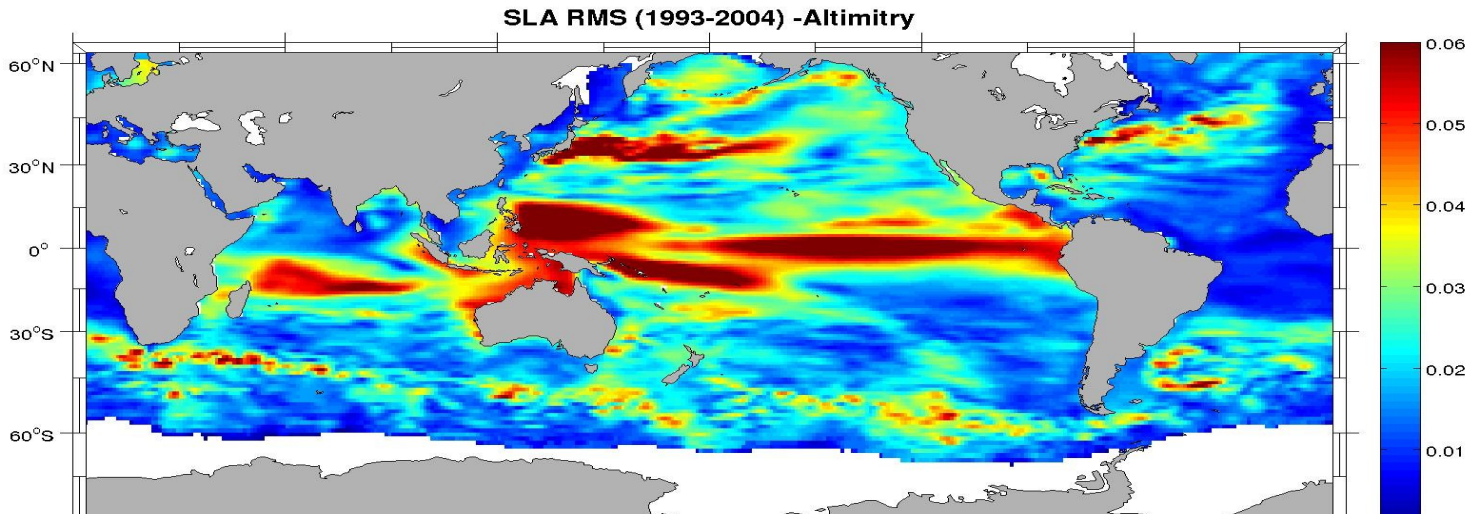
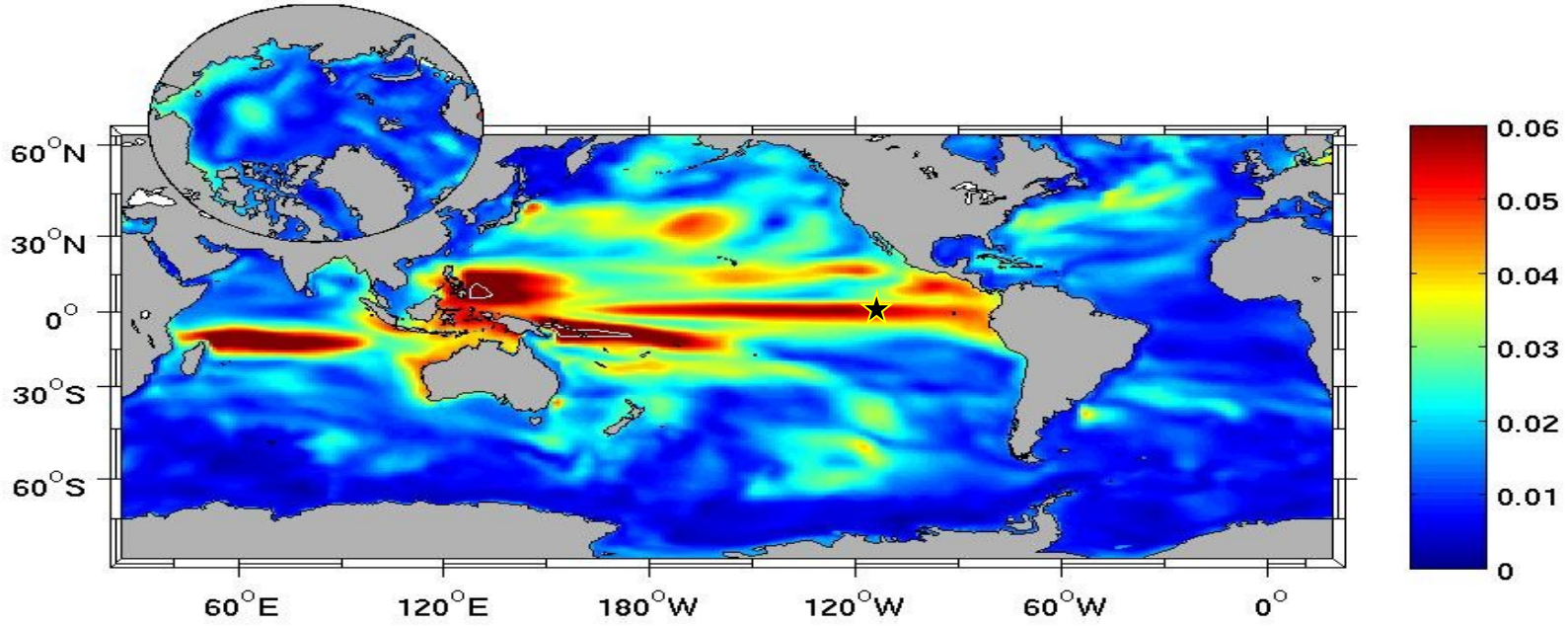
Inter-Annual Sea-Level RMS 1993-2004 (m)

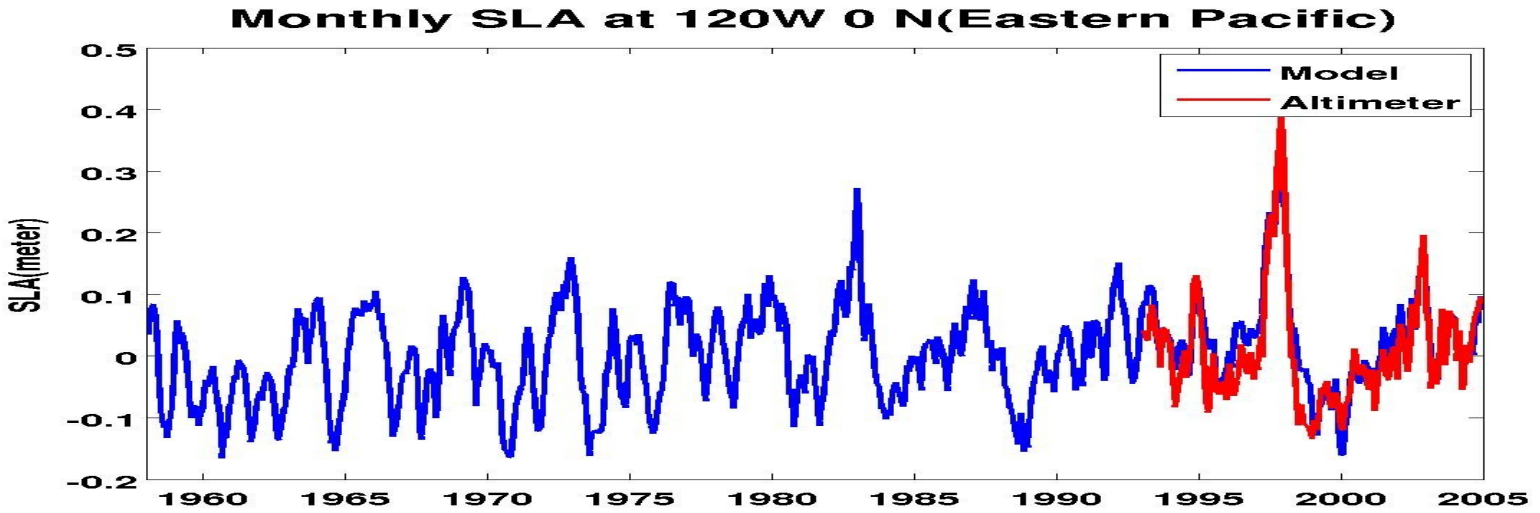
Obs

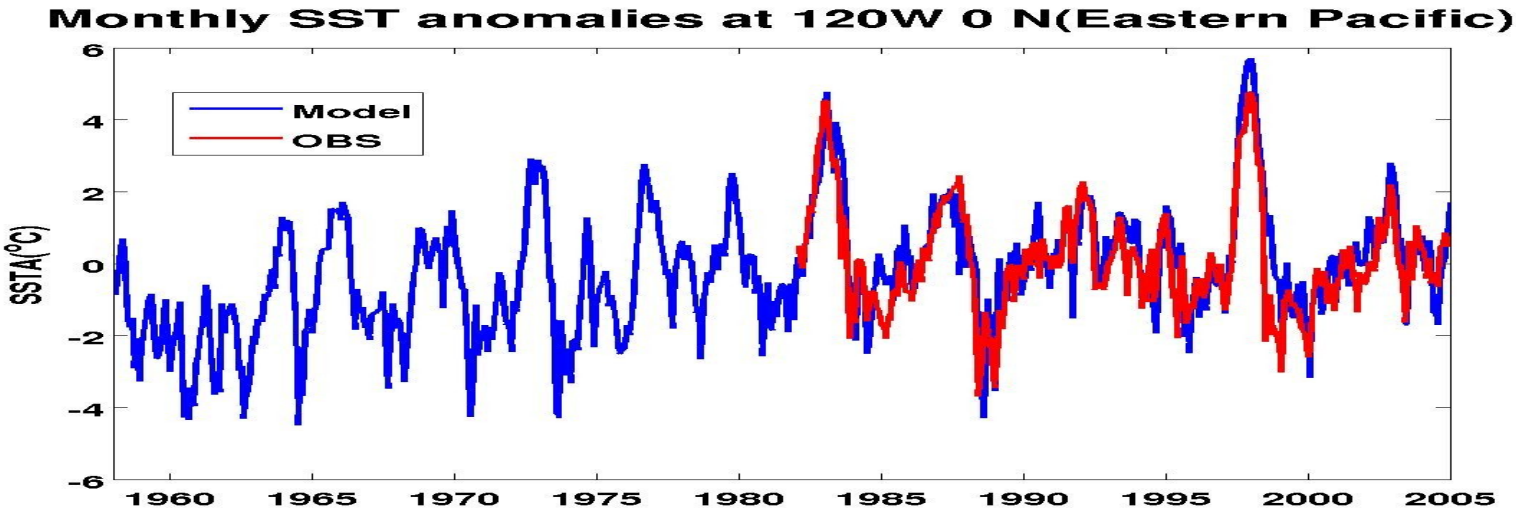


Model



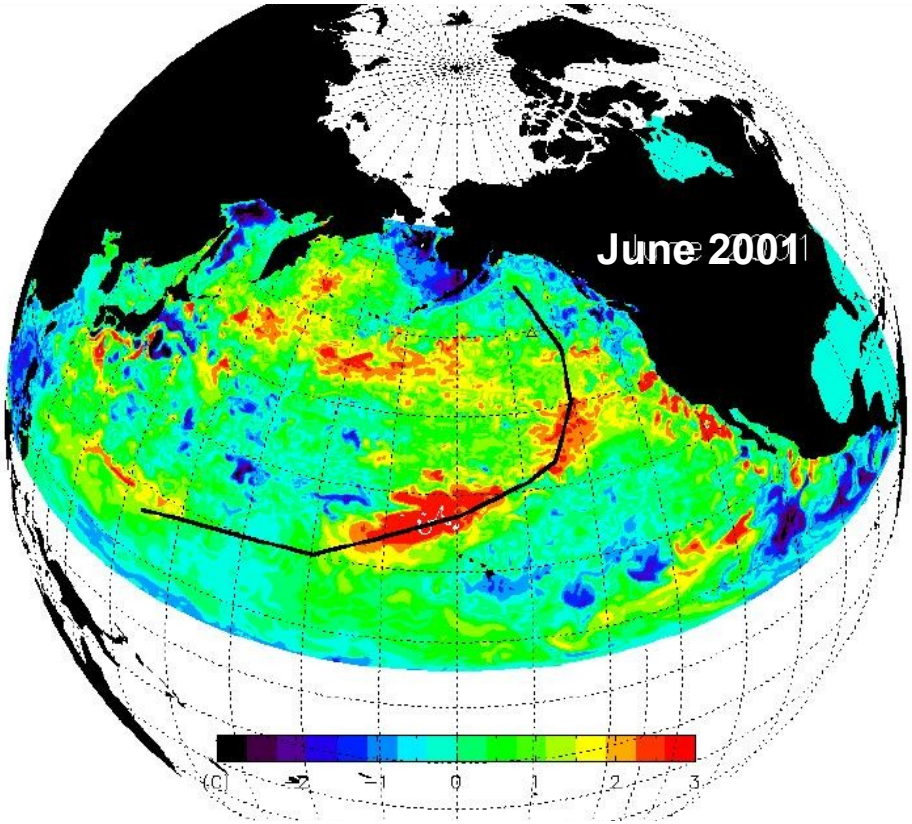
Tropical Pacific Variability





SSH and SST in the equatorial Pacific are well simulated WITH REANALYSIS ATMOSPHERIC FORCING.

Potential Predictability in North Pacific SST

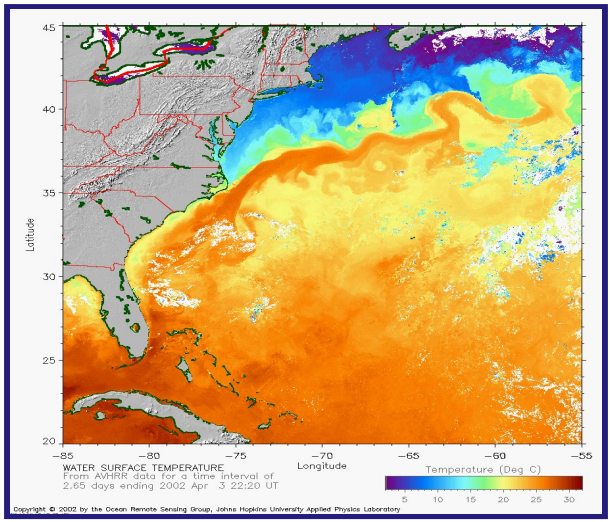


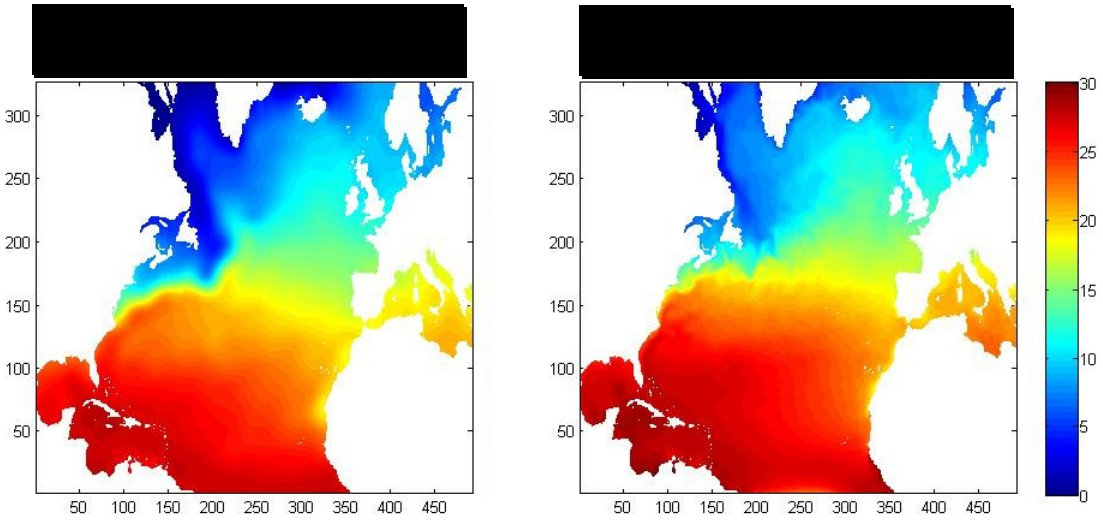
Black line shows theoretical position of Rossby wave front, generated at the coast 3y earlier by ENSO event.

Note correspondence of the black line with maxima in the simulated SST anomaly.

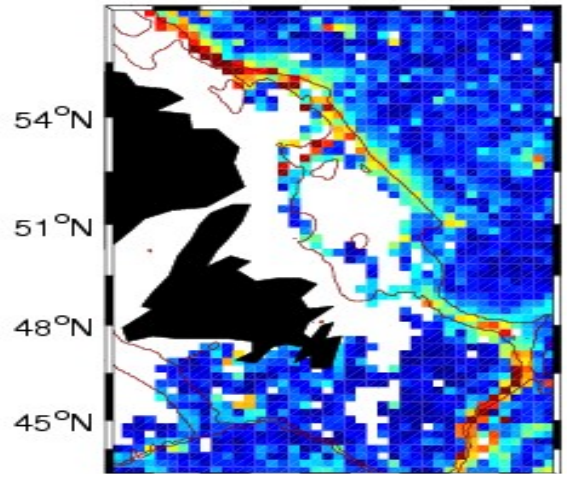
For example, Rossby waves take 3-5y to propagate from coast to OWSP, implying predictability in the northeast Pacific.

Gulf Stream separation problems

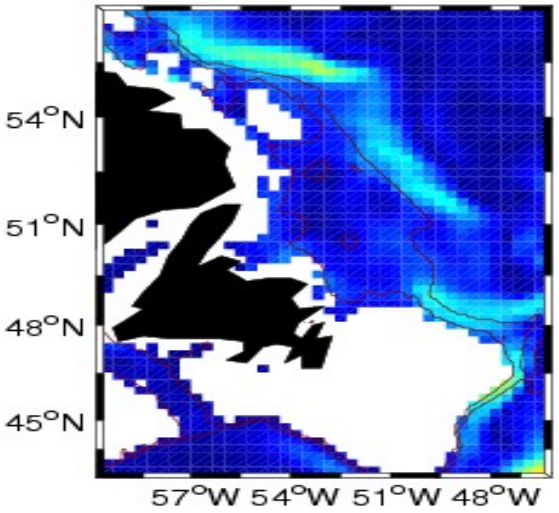




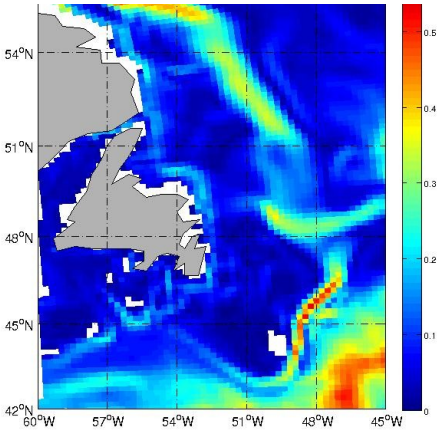
Drifters: the benchmark



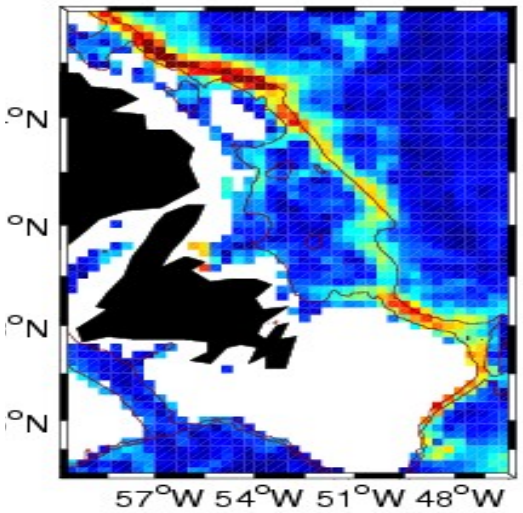
Old nudged model result



New nudged model result



$MSST_{G1}$

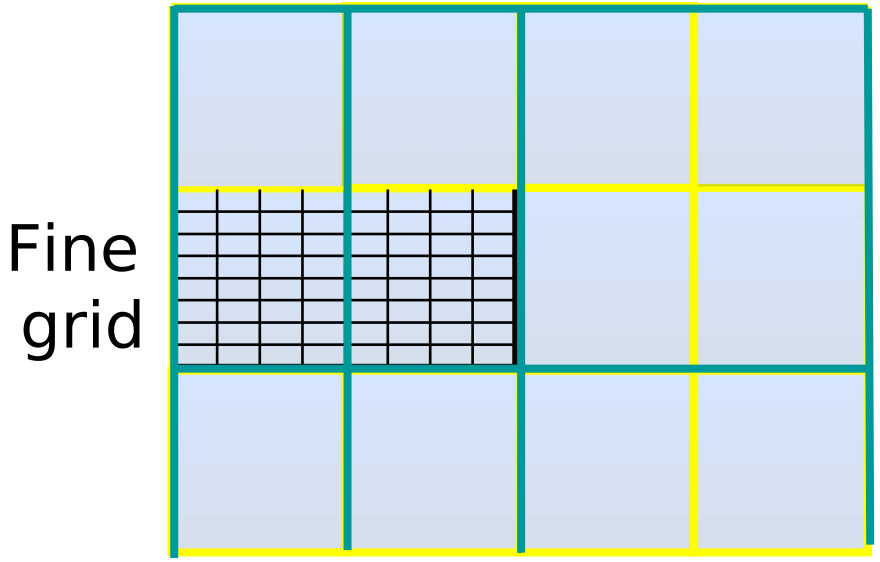


Satellite-based result

The old nudged model results have currents significantly too weak in the sub-polar gyre. The new result is significantly improved in spite of greatly reduced nudging.

2-way nesting using AGRIF

A regional modelling strategy

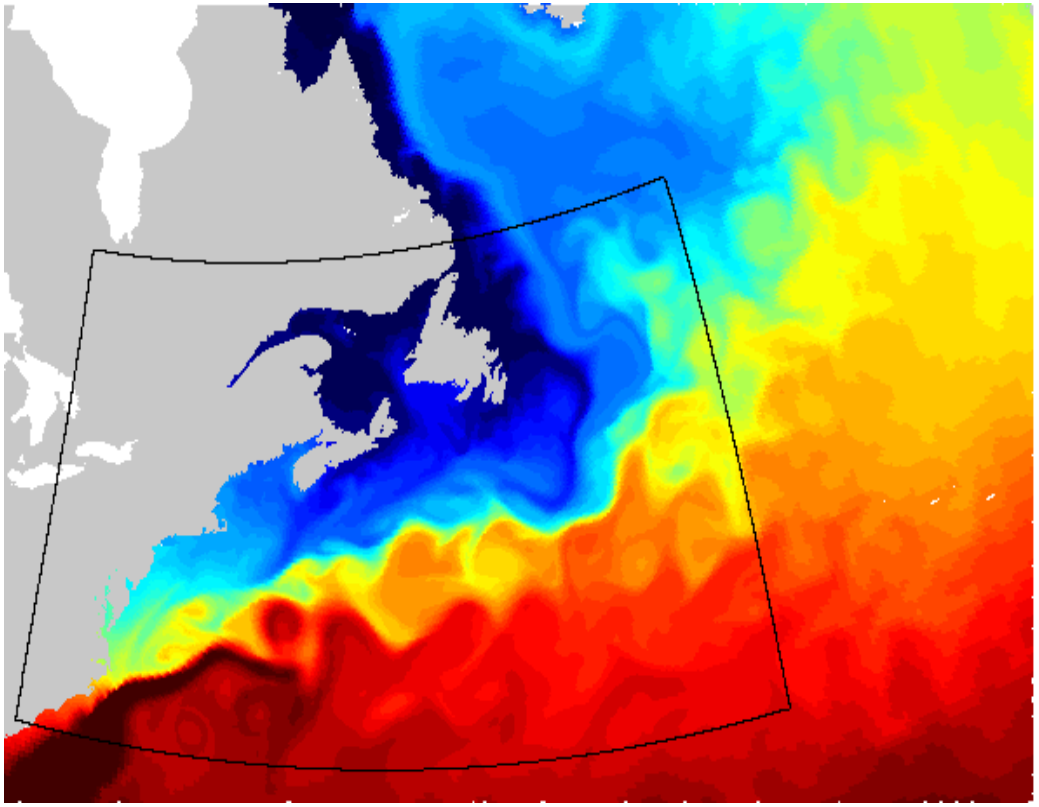


Coarse resolution large-scale model

Interpolate to provide initial and boundary condition control

Finer resolution regional model

AGRIF test of ¼ degree NA with a 1/12 degree embedded “Gulf Stream region”



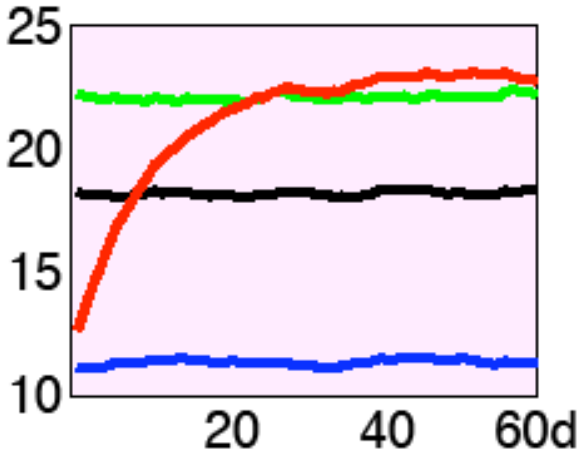
This surface temperature Illustrates results after 9 years of prognostic Integration with no nudging. Major problems Commonly occur within The first 5 years.

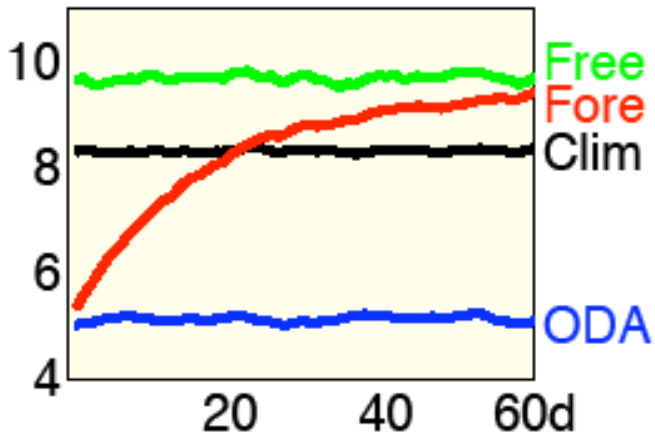
More work is needed but this is a major step forward.

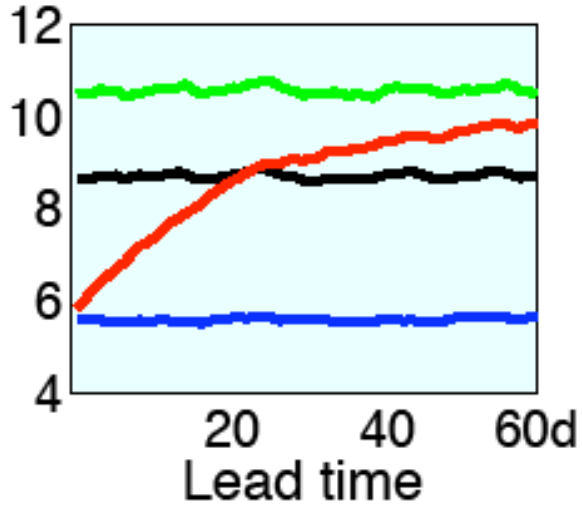
Assimilating Altimeter and ARGO Data: North Atlantic Example

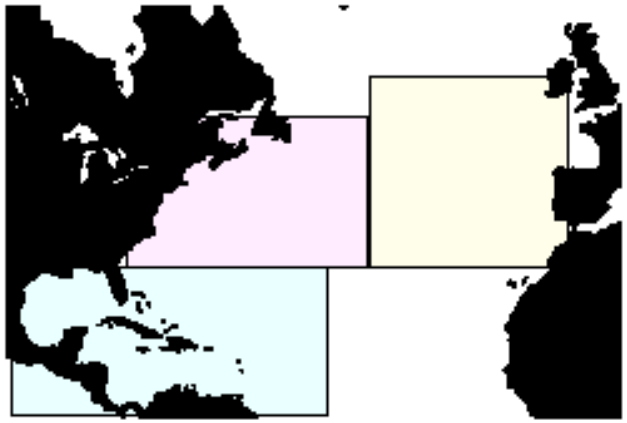
- 1/3 degree ocean model with 23 levels.
- Daily atmospheric forcing from NCEP reanalysis.
- Assimilate Argo and altimeter data, 2003-5.
- 3D-Var extension of Cooper-Haines method.
- The DA scheme is both evolutive and efficient.

Forecast Skill For Sea Level

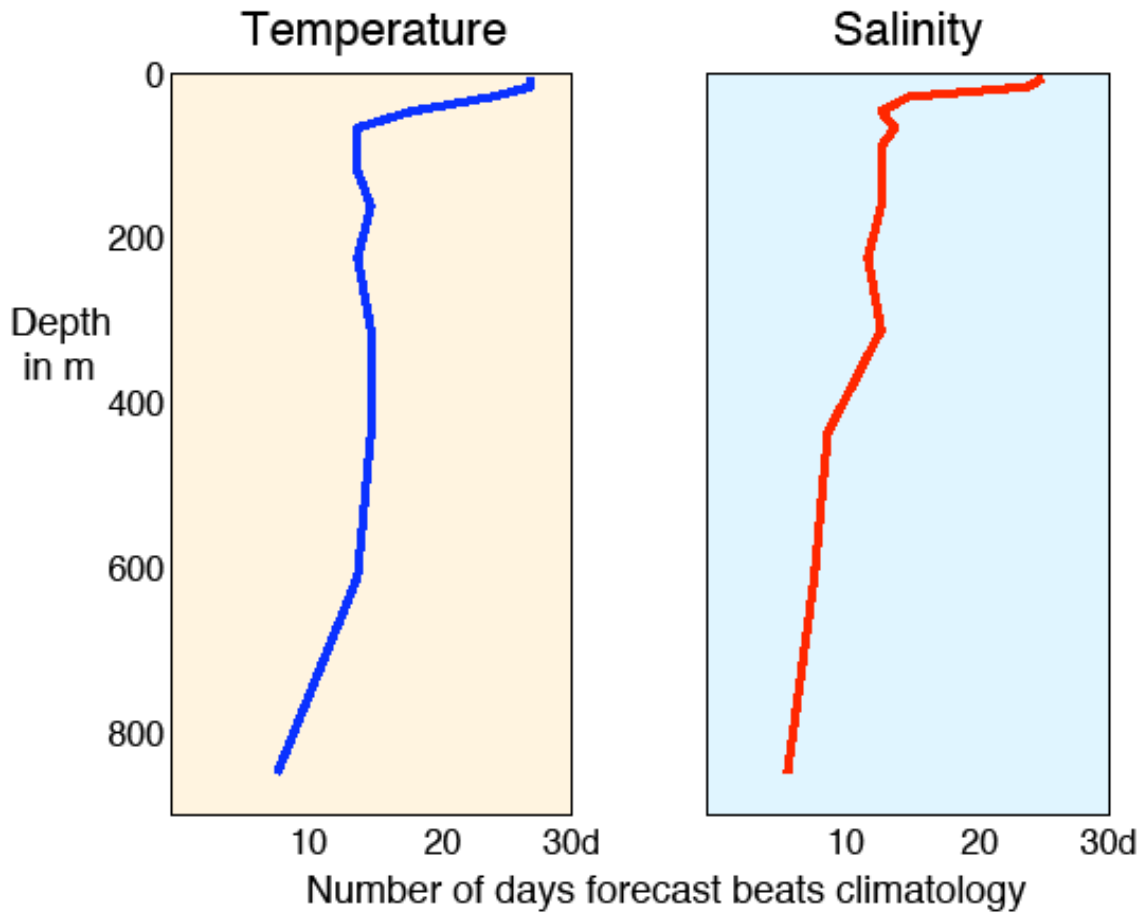








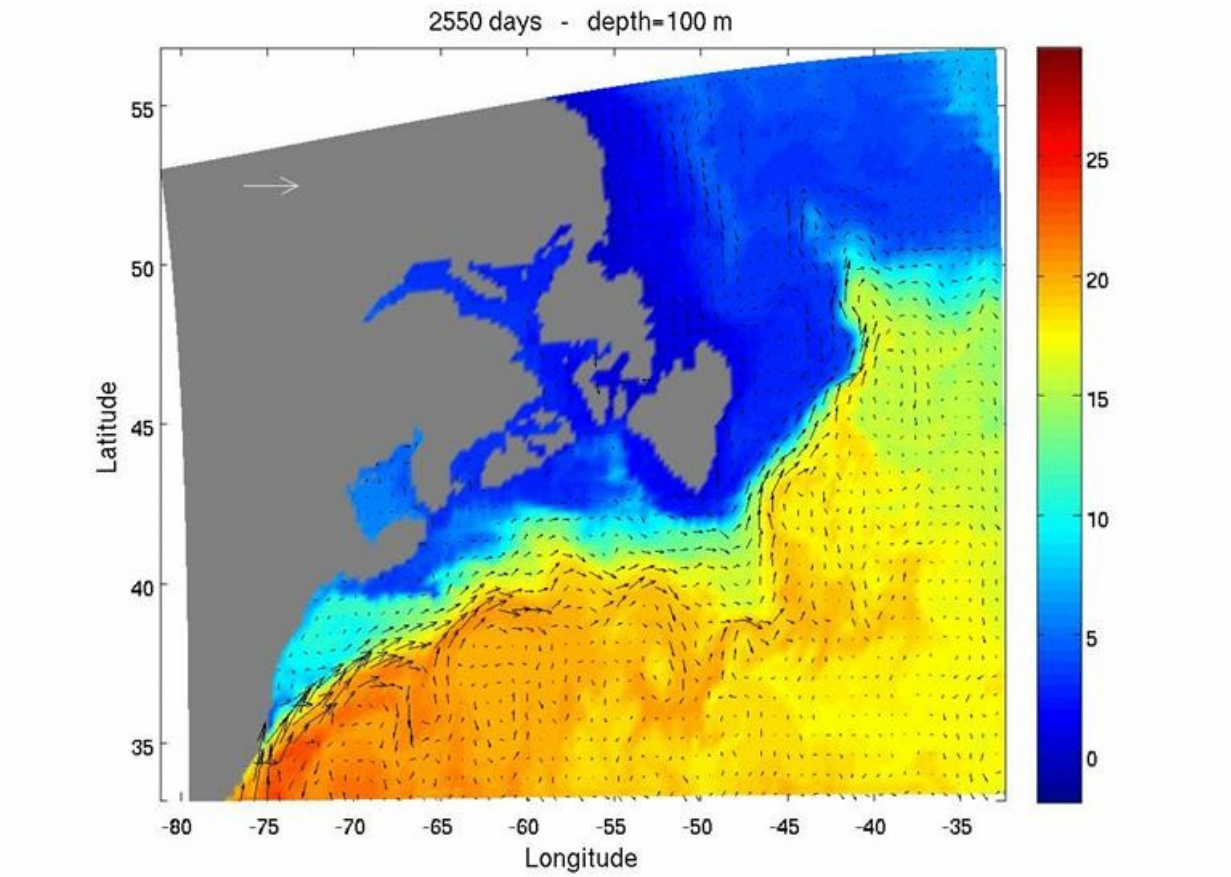
Forecast Skill for Temperature and Salinity



Downscaling from Ocean to Shelf

Objective: to develop a high-resolution (1/12 degree), 3D shelf circulation model for the eastern Canadian shelf to be embedded within a larger-scale (1/4 degree) model of the North Atlantic Ocean.

Subsurface (100 m) temperatures from 1997 to 1999 produced by the outer sub-model of the nested-grid shelf circulation system for the eastern Canadian shelf



Independent Assimilation into Coupled Atmosphere Ocean Models

- ✓ **Data assimilation into a coupled model raises new issues.**
- ✓ **Recent work focused on parameter estimation to improve heat, momentum and moisture exchange between atmosphere and the ocean. Anticipate significant improvements in quality of the analyses.**
- ✓ **EC is coupling GEM to Mercator's NEMO ocean system.**
- ✓ **Incremental formulation being developed by GOAPP: independent assimilation for ocean and atmosphere observations in an "inner loop" but full coupled model integration.**

Joint Assimilation into Coupled Atmosphere Ocean Models

Using observations from either the atmosphere or ocean to simultaneously update both

Initial work focused on covariance between atmosphere and ocean state variables – in CCCma coupled model and NCEP reanalyses.

Interesting results from Redundancy Analysis:

- Clearer, more robust patterns of co-variability
- Identification of causal relationships to guide joint data assimilation.

Simplified coupled state space model being used to test innovative strategies for joint data assimilation

GOAPP Theme II Projects: Seasons to Decades

Analysis and Mechanisms

What are the origins of predictability?

- Pacific Decadal Oscillation
- Southern and Northern Annular Modes

Predictability of the Coupled System

What are the limits of predictability?

- Potential Predictability Of Current And Future Climates
- Prognostic predictability from ensembles of coupled model simulations

Prediction

"Climate forecasting"

How well can we predict in practice?

- Coupled Model Initialization
- The Coupled Model Historical Forecasting Project
- Forecast Combination, Calibration and Verification
- Sensitivity of Climate Forecasts to Initialization of Land Surface

Theme I ⇨ Ocean bias correction for climate forecasts

Climate forecast horizons

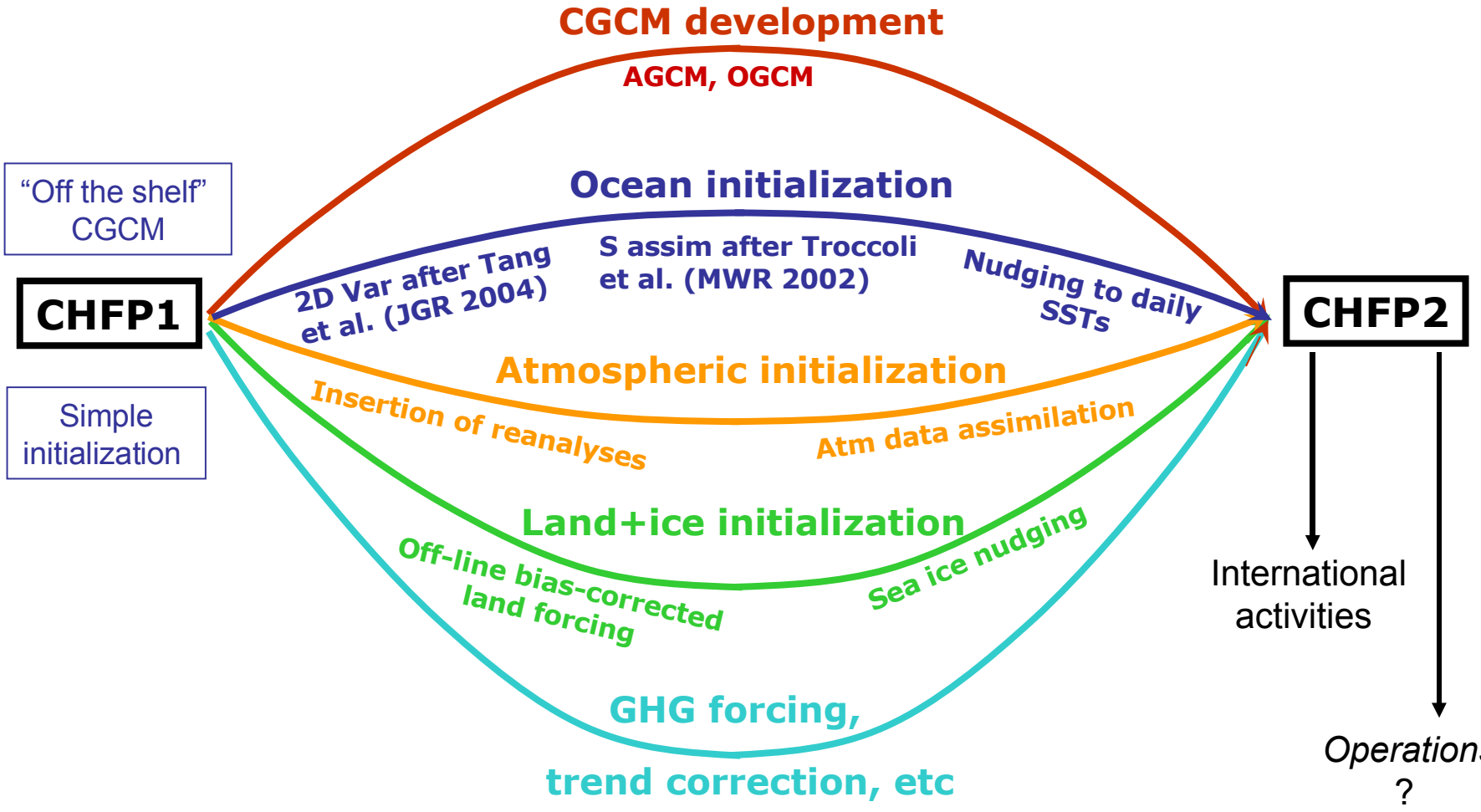
timescale	sources of predictability
Subseasonal ~15-60 days	Madden-Julian Oscillation Land surface “memory”
Seasonal to interannual ~2 months-2 years	El Niño-Southern Oscillation (ENSO)
Interannual to Multidecadal ~2-20 years	Atlantic Multidecadal Oscillation
Multidecadal to Centennial ~20-100 years	Anthropogenic forcing trends

Climate forecasting in Canada

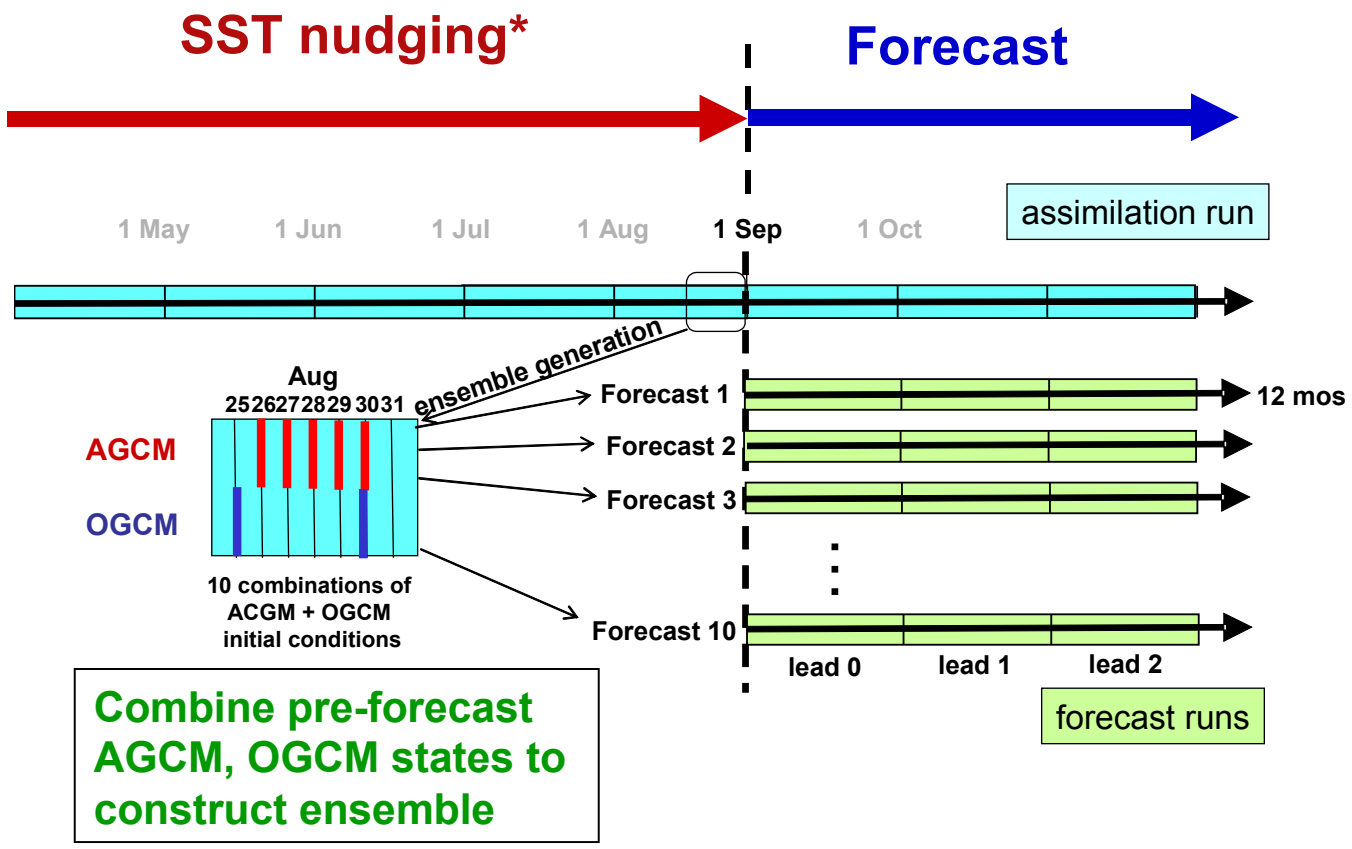
- **Current operational system** based on HFP2:
  - 4 AGCMs (AGCM2, AGCM3, SEF, GEM)
  - ensemble size 4×10
  - Two-tier: persisted SSTA
  - 4 month forecasts
  - statistical model used at longer leads

- **GOAPP→ develop one-tier forecast system**
  - Future SSTs *predicted* as part of forecast → *potential for skill at much longer leads*
  - Requires coupled climate model

The Coupled Model Historical Forecasting Project (CHFP)



CHFP1 initialization

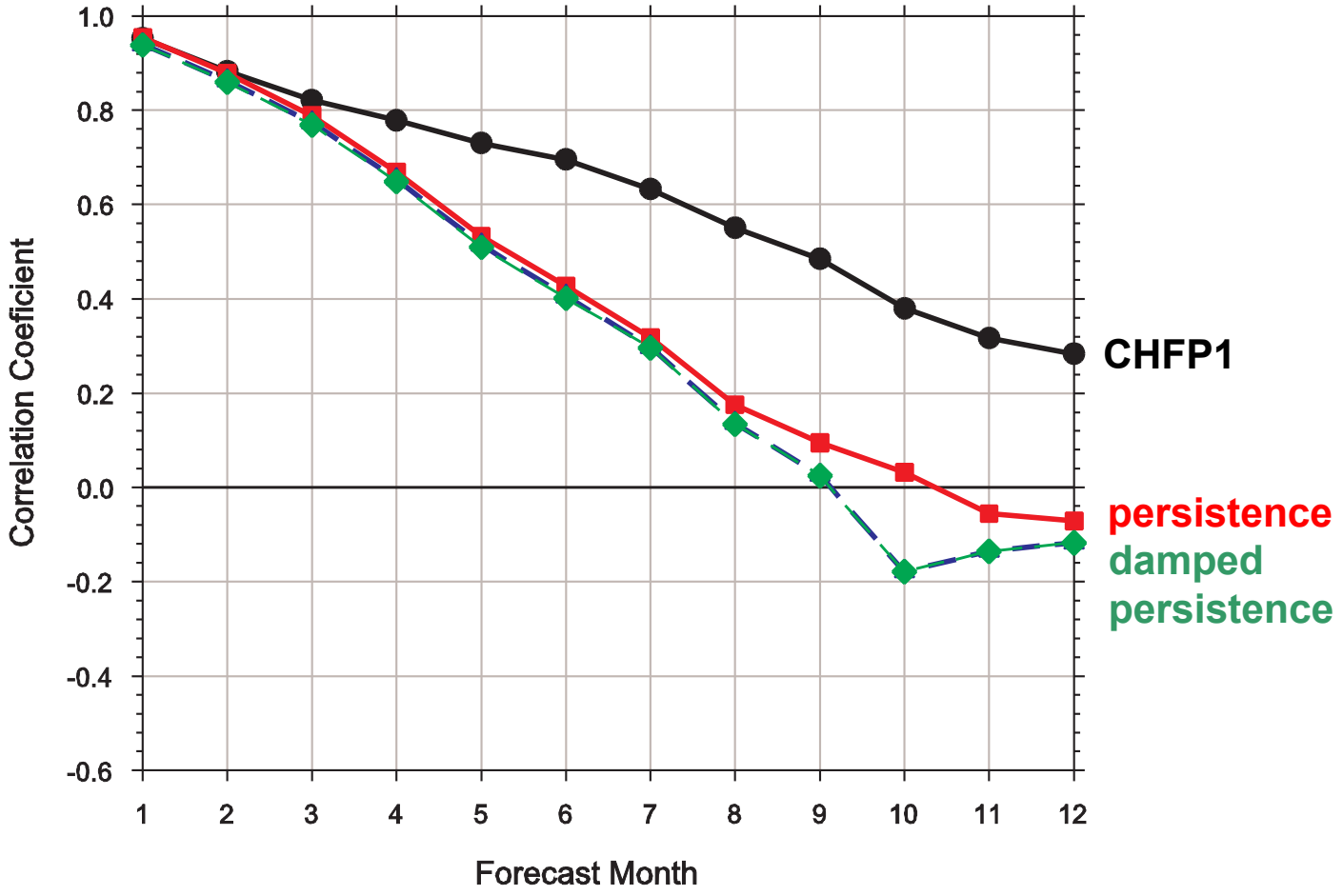


simplest procedure demonstrated to have much skill

CHFP1 results

Anomaly correlation skill score: Nino3.4 index

All seasons 1972-2001



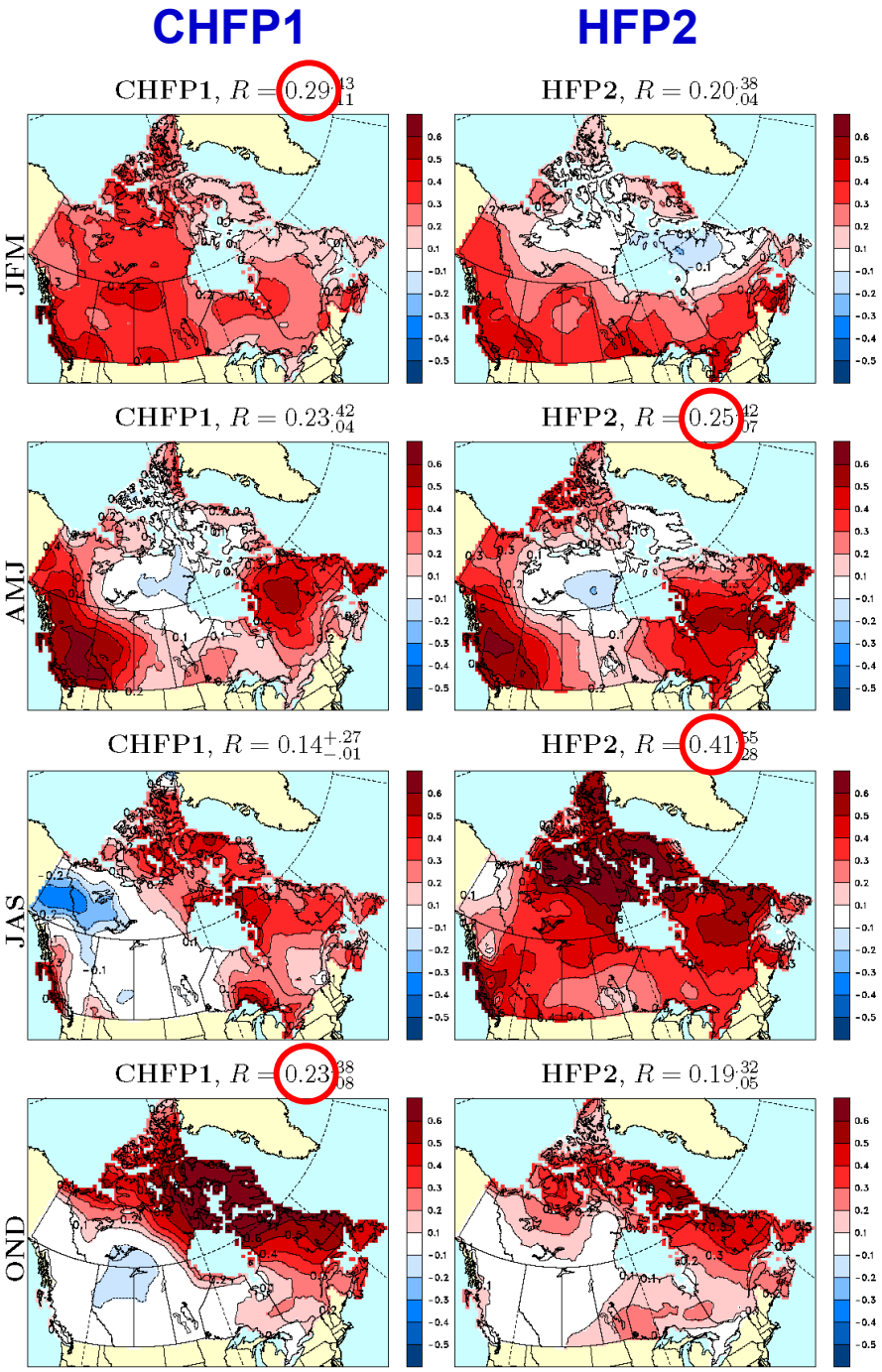
CHFP1 vs HFP2

Correlation skill

Surface air temperature over Canada

1-month lead

→ **CHFP1 competitive with two-tier HFP2 despite smaller ensemble size**

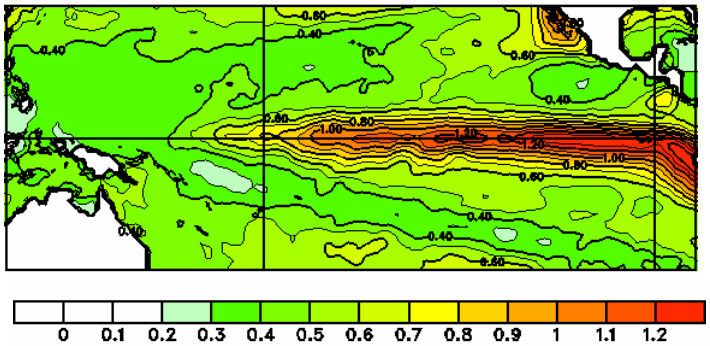


Merryfield, W. J., W.-S. Lee, G. J. Boer, V. V. Kharin, B. Pal, J. F. Scinocca and G. M. Flato, 2009: The first Coupled Historical Forecasting Project (CHFP1). *Atmosphere-Ocean*, submitted.

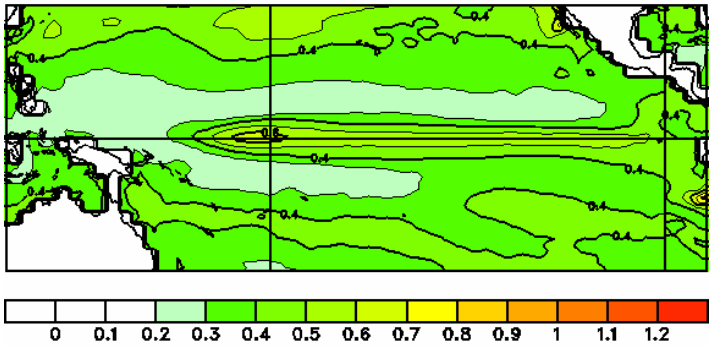
Model improvements: ENSO

Monthly SSTA standard deviation

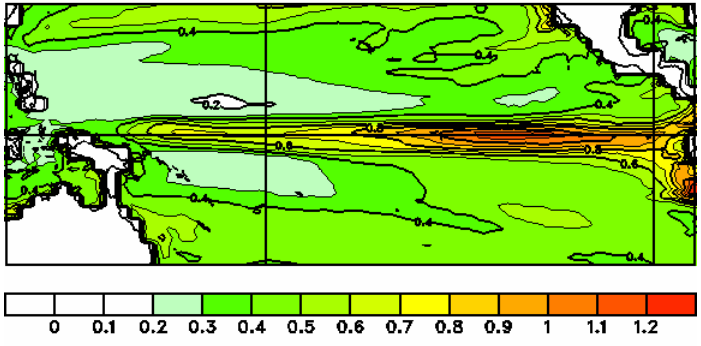
Observations:
HadISST 1970-99



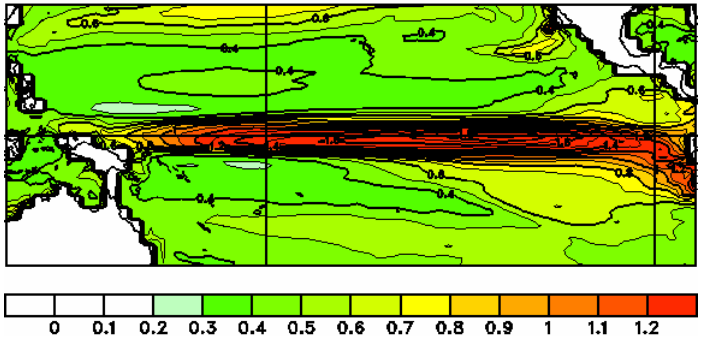
AGCM3+OGCM3
CHFP1



AGCM3+OGCM4
CHFP2$_1$



AGCM4+OGCM4
CHFP2$_2$

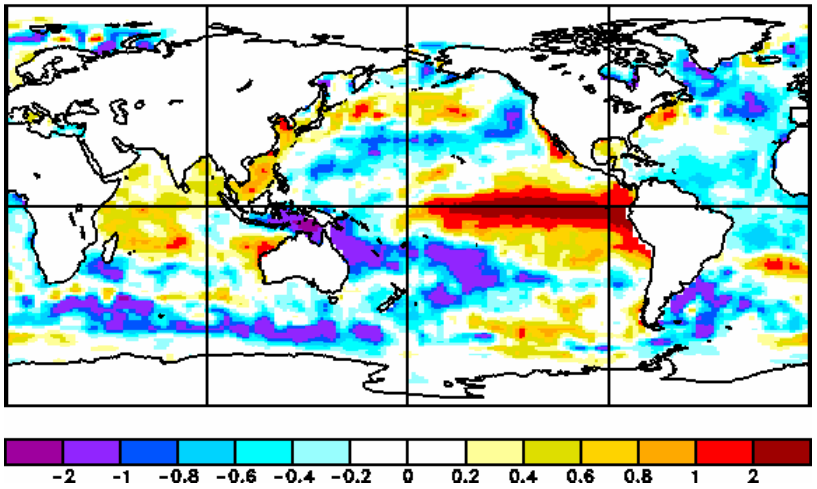


*

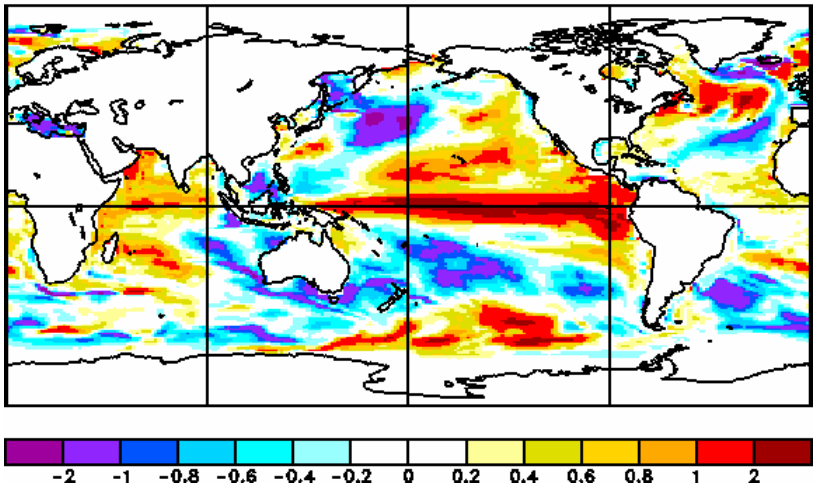
Impact of model improvements

- Illustration: 1982/83 El Niño, 11 month lead

Obs SSTA Nov 1982



Forecast SSTA Nov 1982
AGCM4 + OGCM4 Lead=11 mo



- While such "hits" not always possible (even in theory), a *strong El Niño is now within the range of possibilities that can be forecast*

Impact of Model improvements on ENSO Prediction

	OGCM AGCM	Ens size	Avg skill
CHFP2	OGCM4 + AGCM3	1	0.55
CHFP2	OGCM4 + AGCM4	1	0.64
CHFP1	OGCM3 + AGCM3	1	0.48
CHFP1	OGCM3 + AGCM3	**10**	**0.60**

Mean NINO3.4 correlation skill of rolling 3-month forecasts

Dec → Nov Mar → Feb Jun → May Sep → Aug

SST nudging only 1972-2001

Impact of Model improvements on ENSO Prediction

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N=1 CHFP2 skill exceeds N=10 CHFP1 skill

Mean NINO3.4 correlation skill of rolling 3-month forecasts

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Impact of Model improvements on ENSO Prediction

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CHFP1	OGCM3 + AGCM3	1	0.48
CHFP1	OGCM3 + AGCM3	**10**	**0.60**

N=1 CHFP2 skill exceeds N=10 CHFP1 skill

→ much room for further improvement through ensembles & better initialization

Mean NINO3.4 correlation skill of rolling 3-month forecasts

Dec → Nov Mar → Feb Jun → May Sep → Aug

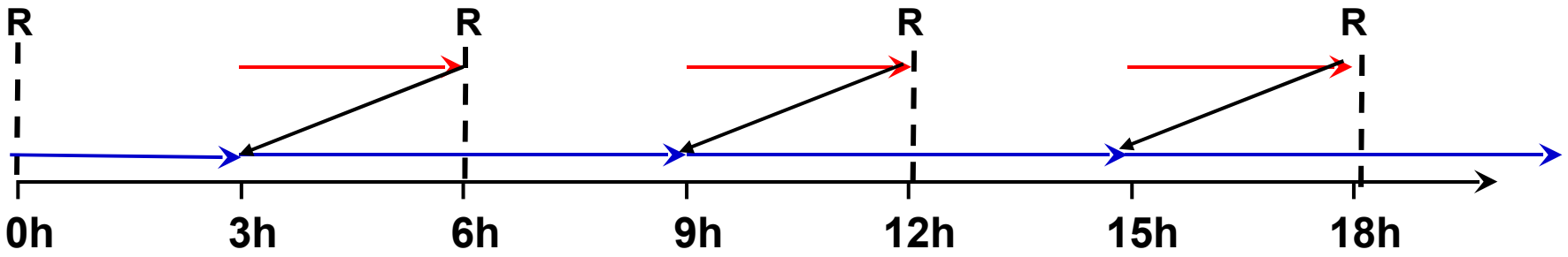
SST nudging only 1972-2001

Atmospheric Data Assimilation

Incremental Reanalysis Update (IRU) assimilation:

- run model freely for 3h ("forecast") to reanalysis time R
- difference with reanalysis $\rightarrow$ "centered" increments $\Delta\mathbf{x}^a$
- rewind
- rerun for 6h adding analysis increments as forcing to model equations:

$$\frac{d\mathbf{x}}{dt} = M(\mathbf{x}) + h(t)\Delta\mathbf{x}^{\mathbf{a}}$$

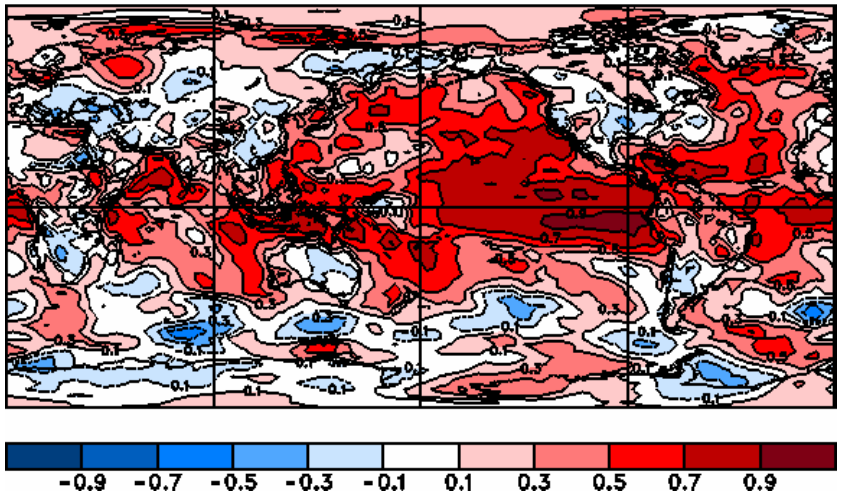


Impacts of AGCM assimilation: Improved 1st month skill

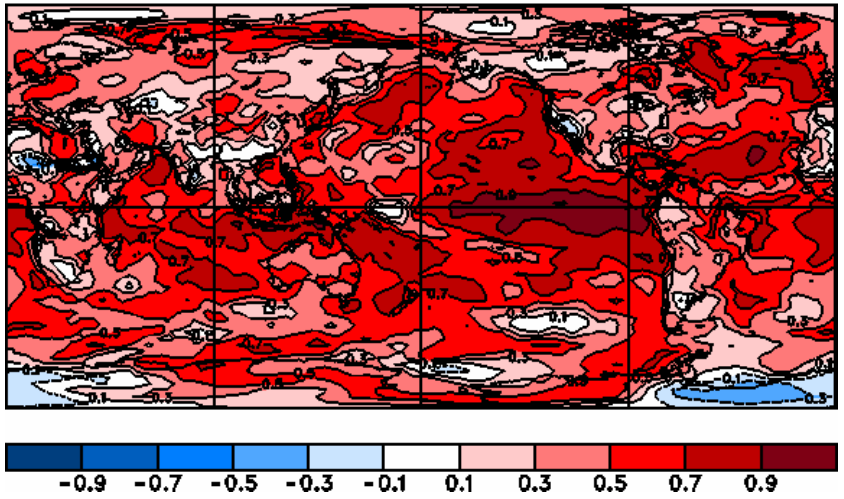
Surface temperature correlation skill

First forecast month from 1 Sep 1980-2001

SST nudging only



SST nudging + AGCM assimilation



GLOBAL: 0.29
LAND: 0.09
OCEAN: 0.37

GLOBAL: 0.51
LAND: 0.33
OCEAN: 0.58

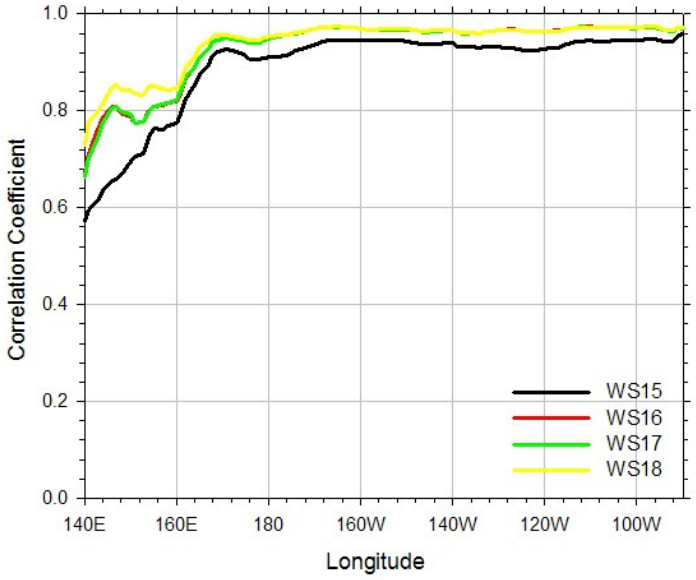
Impacts of AGCM assimilation: Improved ocean initialization

Correlation coefficients vs obs: equatorial Pacific (5S-5N)

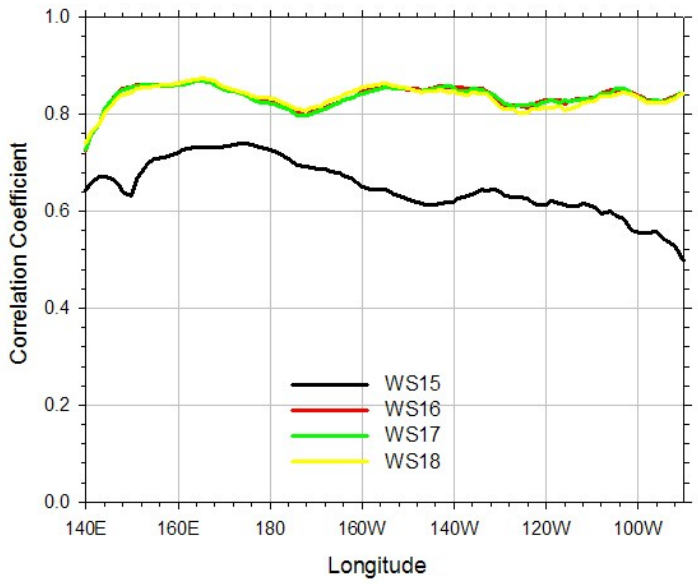
colours: SST nudging + AGCM assimilation

black: SST nudging only

SST



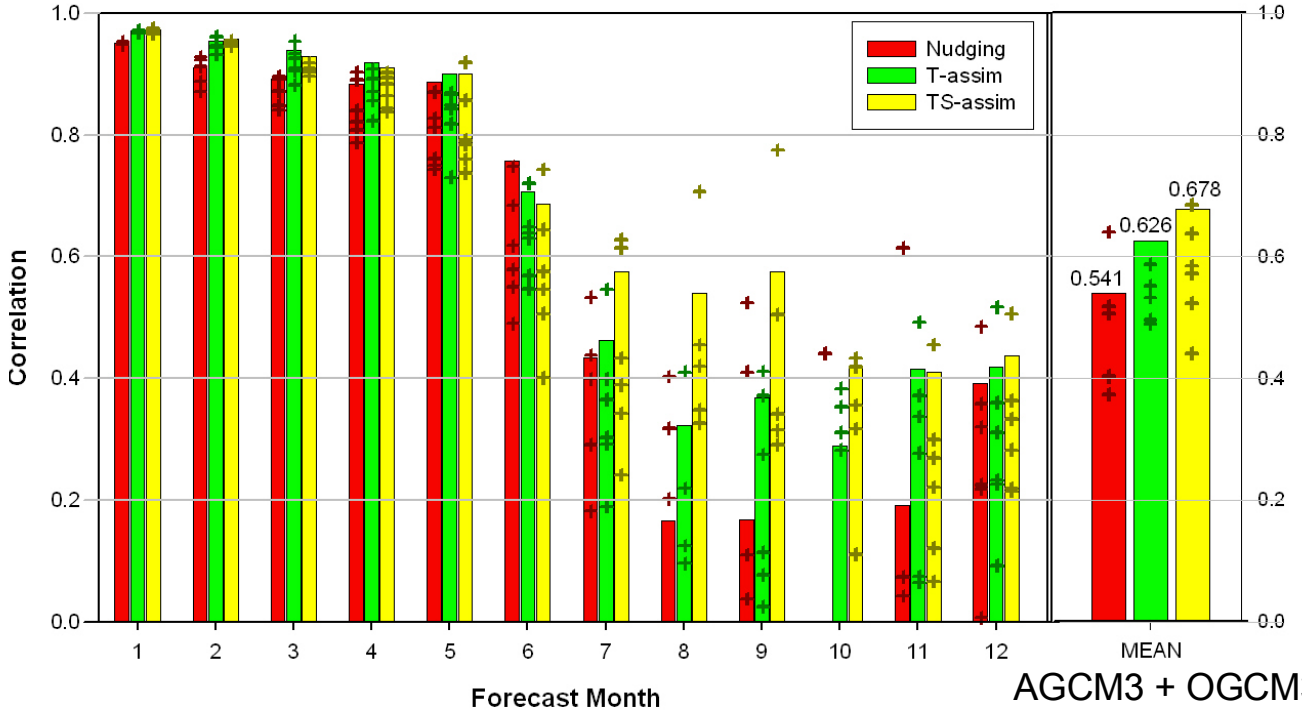
thermocline depth



Ocean Data Assimilation

- **T assimilation**
  - procedure of Tang et al. *JGR* 2004
  - off-line variational assimilation of 3D gridded analyses
- **S assimilation**
  - procedure of Troccoli et al. *MWR* 2002
  - preservation of T-S relationship: prevents spurious convection, etc.

Nino3.4 anomaly correlation: from 1 Sep 1980-2001 (6 ensemble members)



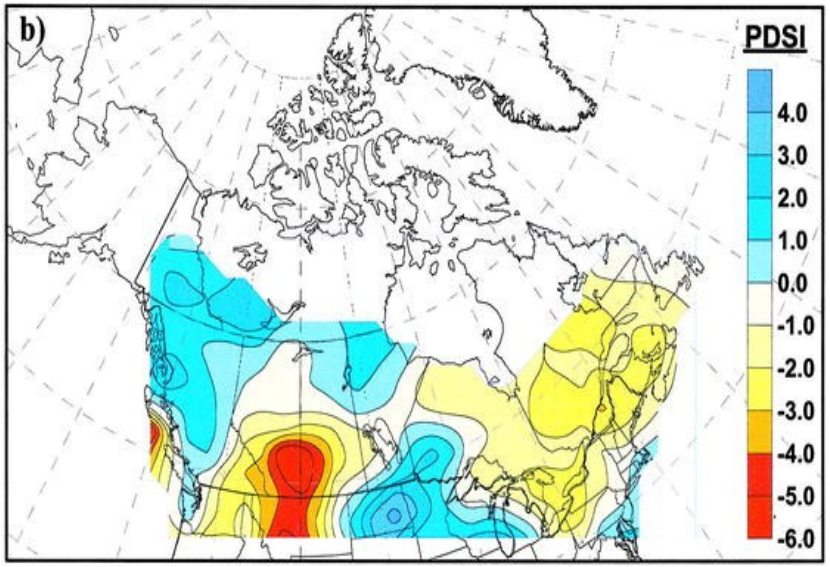
AGCM3 + OGCM3.6

Land surface initialization

- CCCma collaboration with U Guelph
- Strategy: drive CLASS land surface model used in CGCM off-line with *bias-corrected* reanalysis

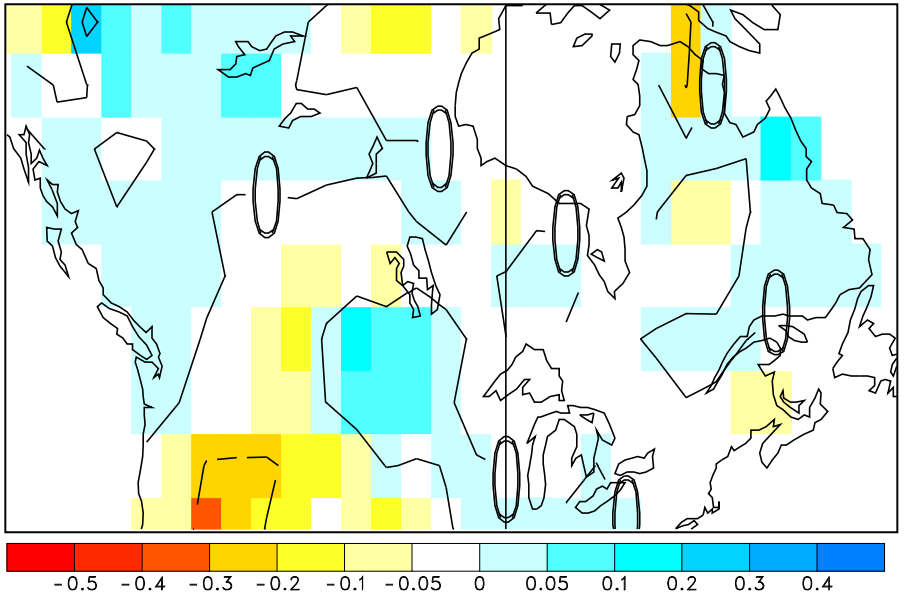
Case study: 2001 drought

Observed Palmer Drought Severity Index: JJA 2001



(Shabbar & Skinner 2004)

Soil moisture forecast initialization



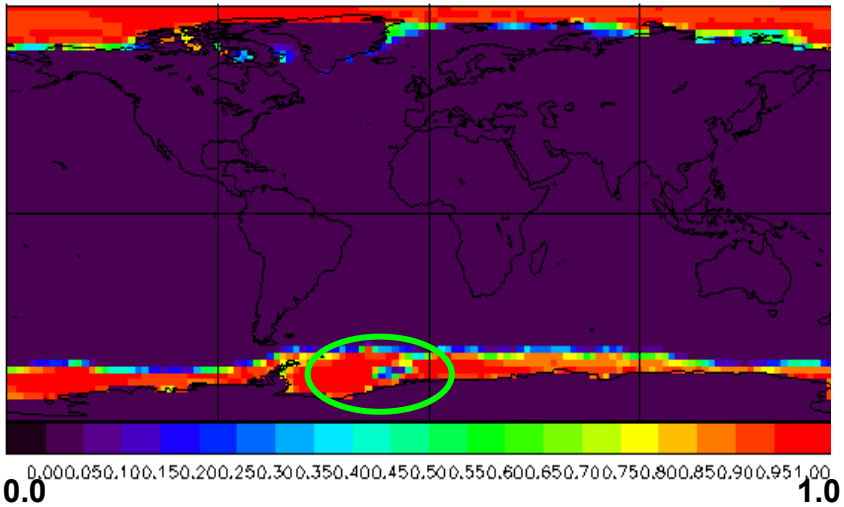
Fractional soil moisture anomaly

Sea ice initialization

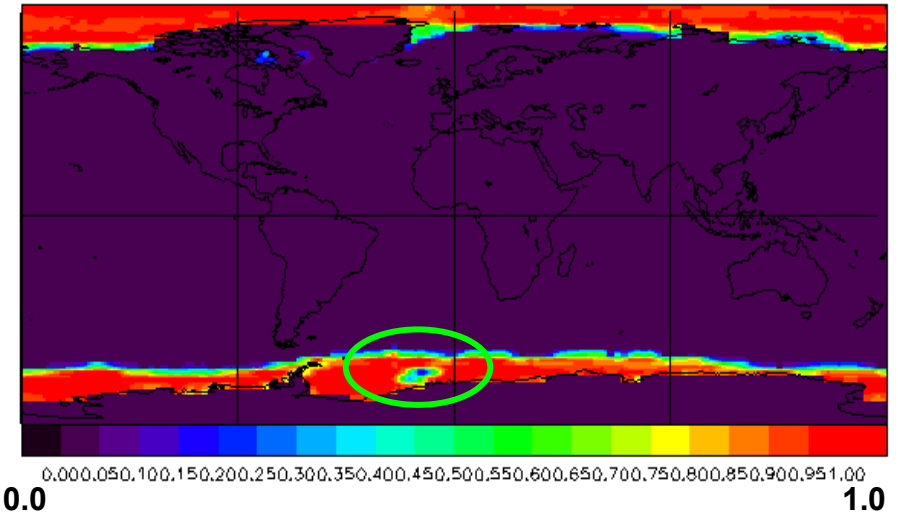
- Nudge to Hadisst observations

Sea ice concentration: August 1976

Hadisst



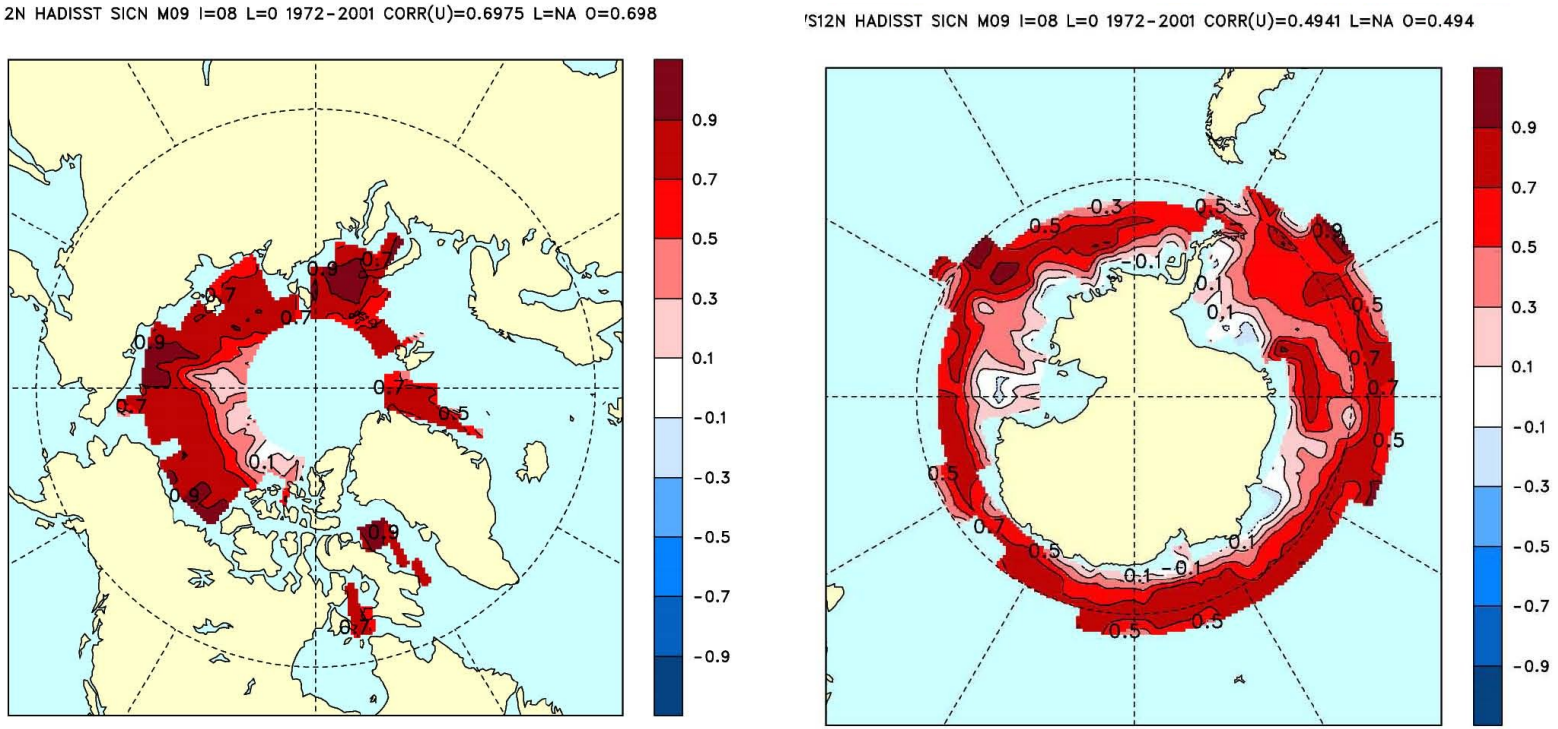
Forecast initial conditons



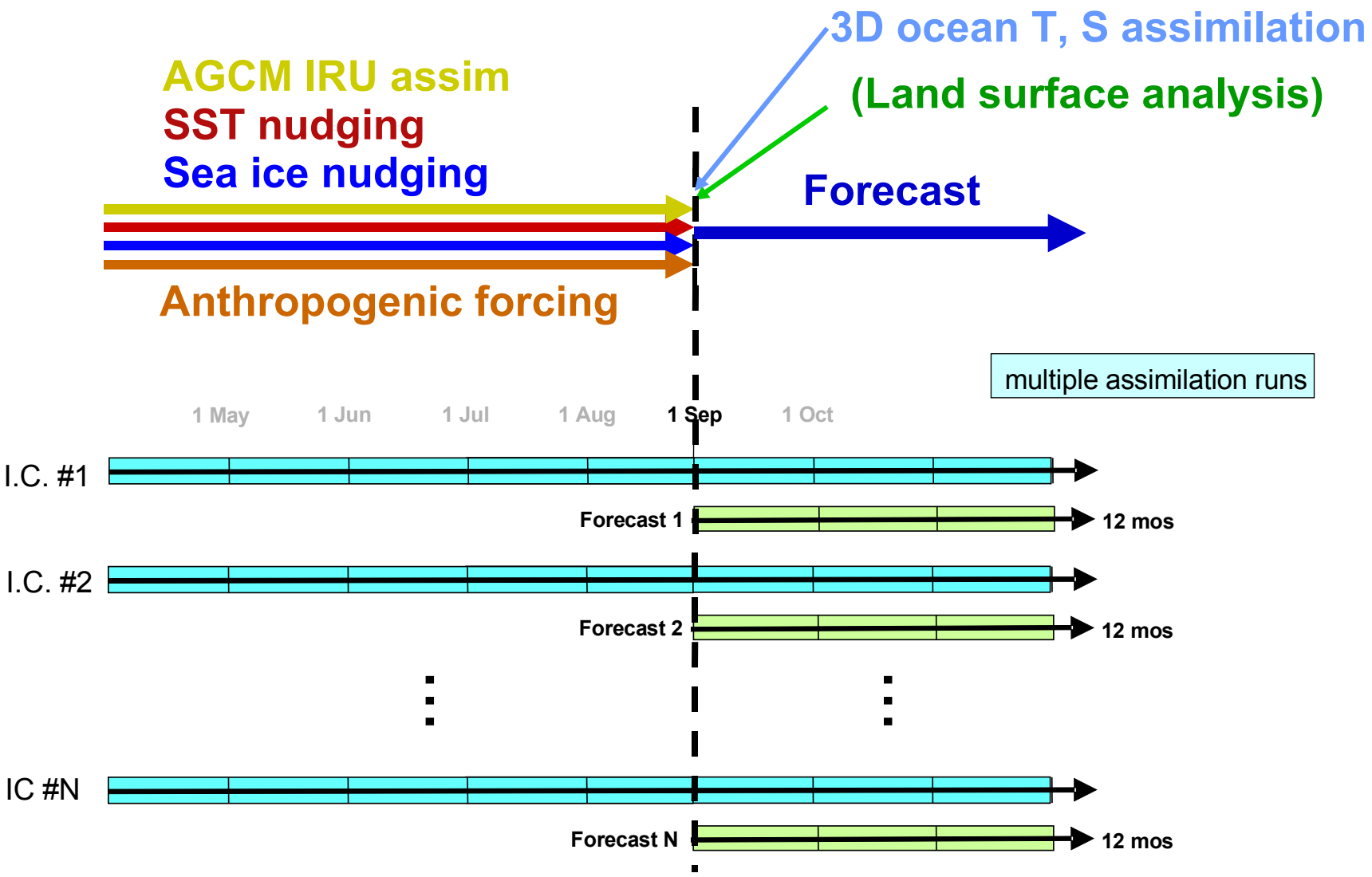
Sea ice concentration

Anomaly correlation skill score

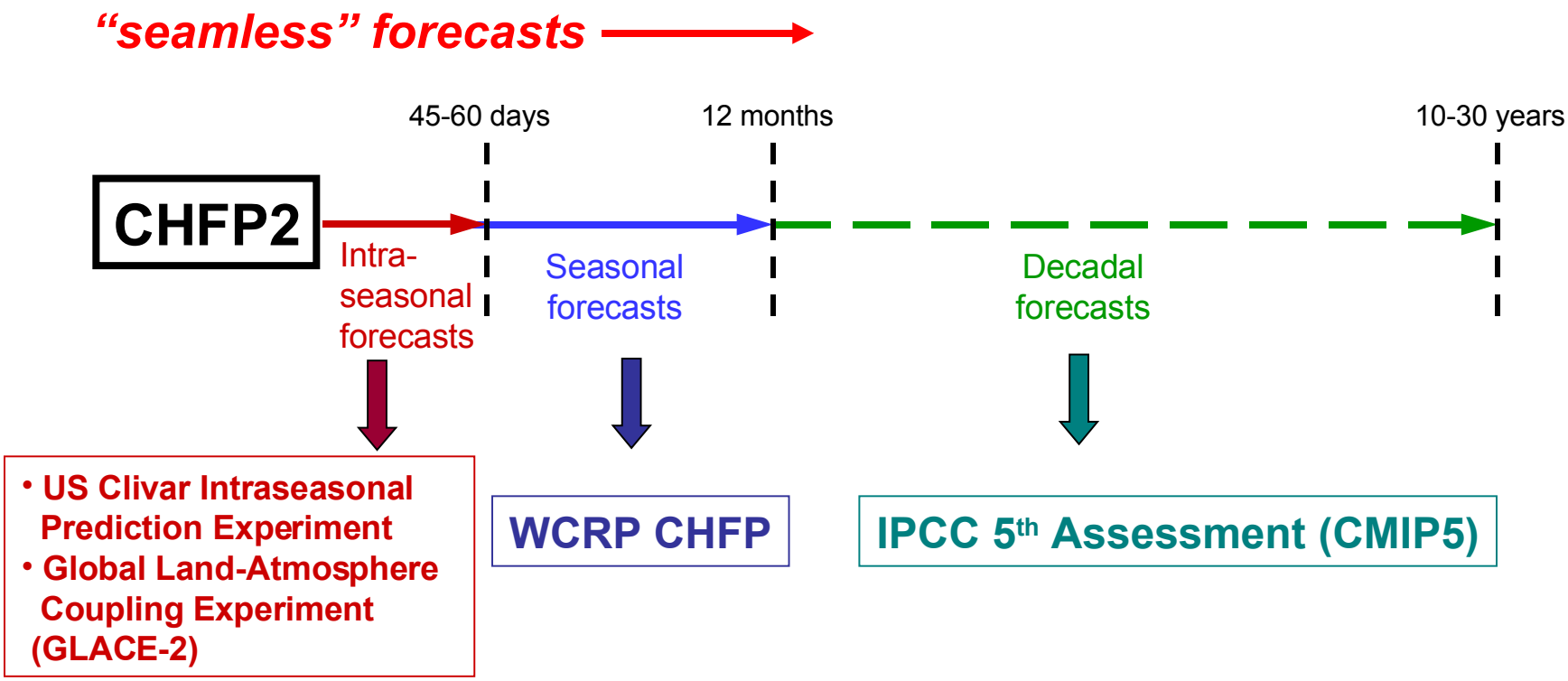
Sep, lead=0, WS12N



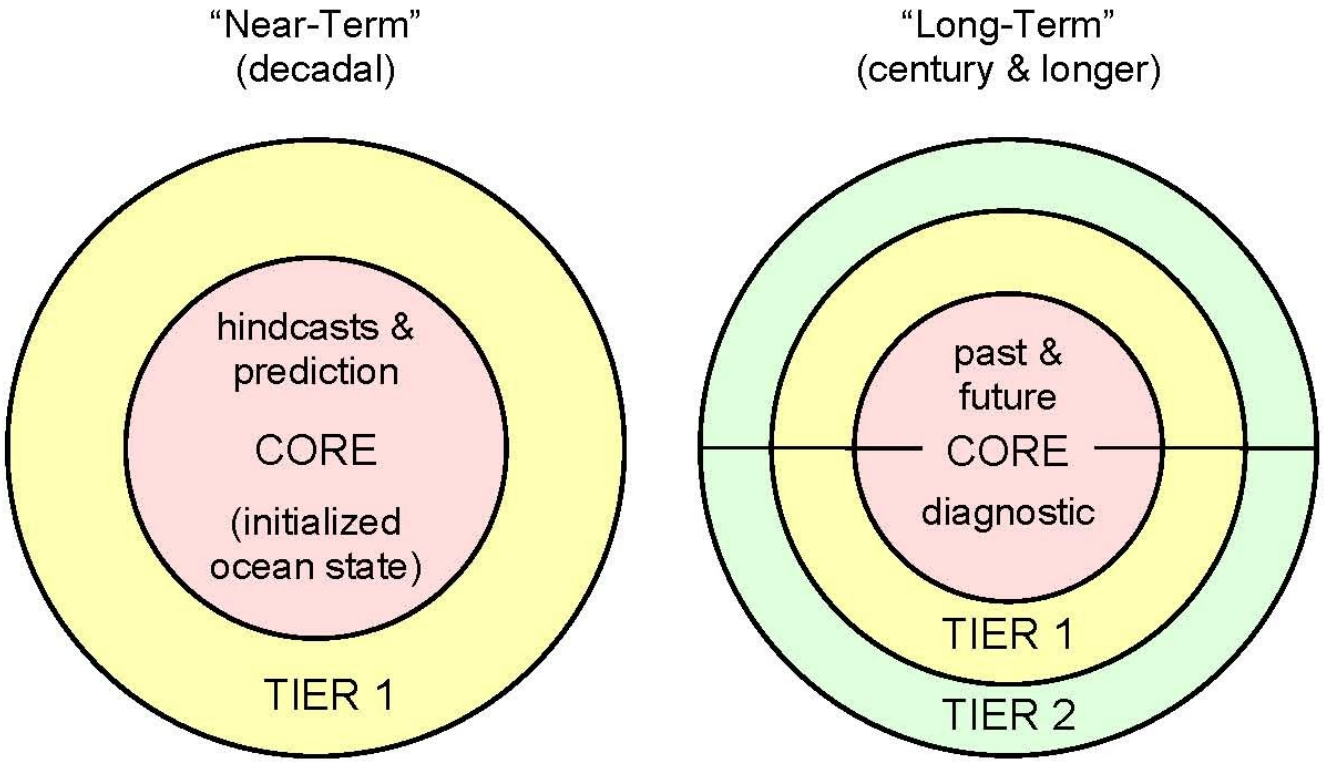
CHFP2 initialization



Contributions to international activities



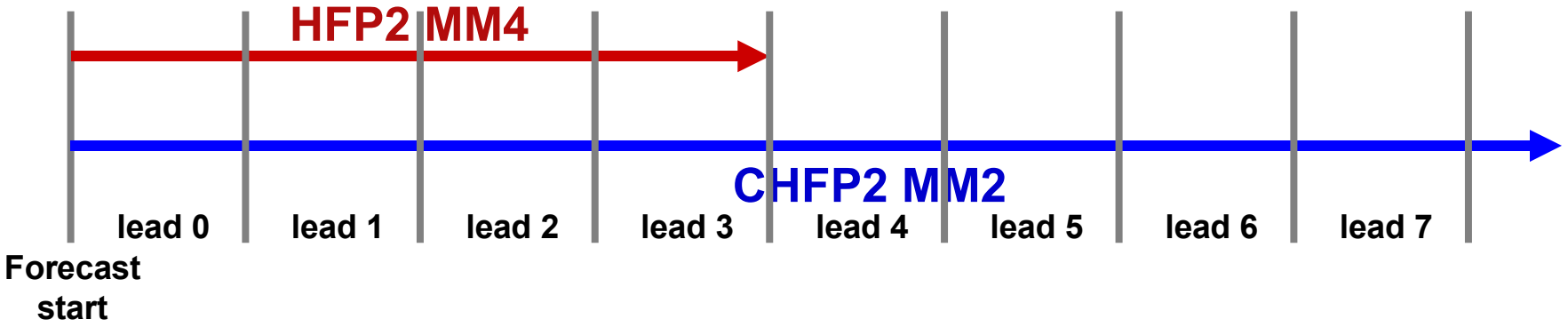
IPCC: From projection to prediction



Schematic of the two focus areas of CMIP5

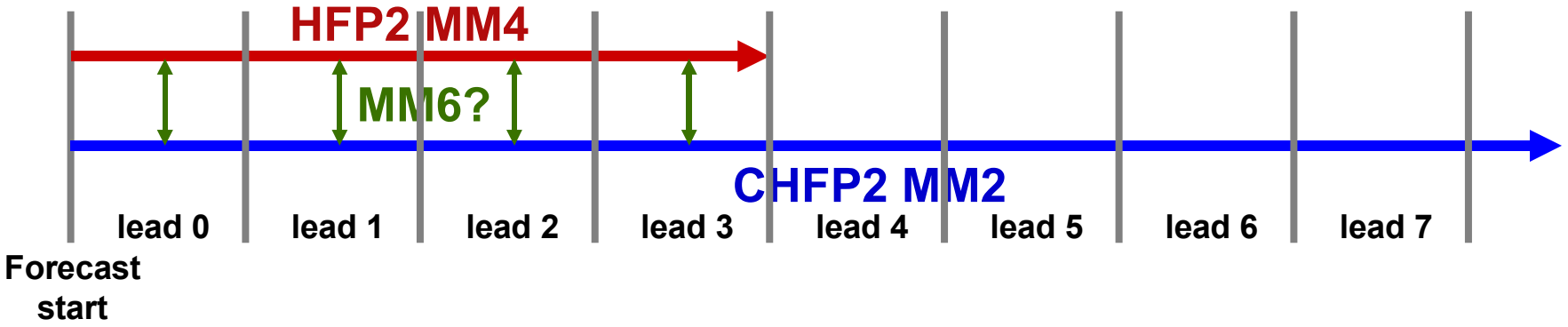
Taylor et al.: CMIP5 Experiment Design

Future CMC Seasonal forecasts?



- GOAPP ends in 2010
- CHFP2 intended to be transitionable to operations
  → planning, resource allocation needed
- CCCma well situated to contribute to CMIP5 *predictions*
  → interannual-decadal predictions also could potentially become operational

Future CMC Seasonal forecasts?



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What has GOAPP Delivered?

Expertise in Critical Areas

- Ocean, coupled and coastal data assimilation
- Seasonal forecasting
- Land surface processes modelling and validation
- Adding value to forecasts (downscaling, statistical enhancement of forecasts)

Ocean Hindcasts

- Reconstructions for the North Atlantic and North Pacific

Access of Government Researchers to the University Environment

- Interaction with students and university faculty
- Helping shape the next generation of HQP
- Improving connections among departments (e.g., EC, DFO, DND)

Funding

- Cost-sharing to support key positions
- Access to university infrastructure, computers, support staff

Development of Operational Systems

- Pre-operational forecast system for ocean weather (CFCAS supplementary funding)
- Seasonal Forecasts Using Coupled Models (CCCma)

Multiple agency (EC, DFO, DND) interest in coupled atmosphere-ice-ocean prediction has led to the establishment of

CONCEPTS: Canadian Operational Network of Coupled Environmental PredicTion Systems

To coordinate the national development and implementation of ocean models, DFO has established

COMDA: Centre for Ocean Model Development and Application

Theme I of GOAPP contributes to, and benefits from, CONCEPTS.

After CHFP2

- **Transition to EC operations?**
  - will need expanded set of retrospective forecasts
  - retention of HQP crucial

- **Ongoing R & D**
  - Theme I & II research providing innovative bases for further forecast system improvements
  - Bias removal through spectral nudging (Theme I)
  - Data assimilation (Tang UNBC)
  - Nonlinear forecast post-processing (Hsieh UBC)

Issues and Opportunities

- GOAPP finishes December 2010
- Delivering products hinges on retention of GOAPP's newly trained HQP
- Need to better coordinate research in the government and academic sectors in order to maximize use of future funding
  - ? Resurrect and expand the subvention programs for funding targeted research in universities
  - ? Enable academia to play more active role in CONCEPTS and seasonal to decadal prediction