The value of case studies for evaluating initialised decadal climate predictions

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Average skill scores of limited use for decadal prediction:
- Short observational record (=> large sampling uncertainty)
- Non-stationary observing system
- Non-stationary climate
- State dependent predictability

Case studies offer an alternative, complementary, approach to evaluating and improving the performance of a decadal prediction system
Of particular interest is the capability to predict the unexpected, e.g.:
- ‘76 climate “shift”
- Mid 90s warming of the N. Atlantic

Opportunity to take a detailed process-focused approach:
- Why did the event happen?
- To what extent was it predictable, and through what mechanisms?
- To what extent does the prediction system capture these mechanisms (and if not why not)?
Causes of the rapid warming of the North Atlantic in the mid 1990s

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Rowan Sutton, Katja Lohmann, Doug Smith and Matt Palmer
Impacts on Greenland glaciers, CO2 uptake, fisheries etc
Role of the North Atlantic Oscillation

**BLACK:** *Inverted NAO*

Temp anomaly of Subtropical gyre (60W-10W, 50N-66N) from Levitus, ECMWF and Met Office
Dynamical response to NAO

- Lagged responses to NAO variability:
  - Gyre circulation
  - AMOC (e.g. Eden and Wilibrand, 2001)

- Associated changes in heat transport influence energy budget of subpolar gyre.

Lohmann et al, 2009:

Overturning index  Mixed Layer Temp  Gyre Index
Hypotheses for the warming

A. Direct response to the decline in the NAO (esp 95/96):
   - Thermodynamic response to surface buoyancy fluxes
   - Dynamic response?

B. Dynamic response to the persistent high NAO conditions that preceded the warming

B best for predictability
Experimental design

- MICOM 2.4° resolution, ~150km in the Atlantic

Experiments:
- Ocean forced with daily fluxes from NCEP reanalysis (CONTROL) from 1948-2006
- Two extra experiments started in 1980 from CONTROL:
  - CLIM WIND – climatological wind stress - buoyancy fluxes vary
  - CLIM BUOY – climatological buoyancy fluxes – wind stress varies

Ocean analysis:
- Comparison with Met Office ocean analysis, and raw EN3
Evolution of heat content anomalies in the Control

- Captures major characteristics of rapid warming
- All anomalies are relative to the 1961-1990 climatology
Sub surface temperature evolution

0-500m anomalies          1000-2500m anomalies
Response to buoyancy flux or wind stress forcings

- 0-500m temperature anomalies
What is the relative importance of local surface heat fluxes versus changes in ocean heat transport?
Energy budget of the subpolar gyre

- Solid = ocean heat transport convergence ($H_O$)
- Dashed = energy lost to atmosphere ($H_A$)

- Solid = difference in $H_O$ and $H_A$
- Dashed = delta E calculated from the models T

What is the reason for the increase in the ocean heat transport convergence?
Changes in the AMOC

- CONTROL shows an increase in the AMOC and an increase in MHT.
- Low frequency strengthening of the AMOC is due to the buoyancy forcing.
- Wind forces higher frequency variability which modulates the AMOC and MHT.
The role of the NAO

- The experiments show that the buoyancy forced variability was key for the warming of the SPG in the mid 1990s, particularly the forcing that preceded the warming which spun up the ocean circulation & increased ocean heat transport.

- But, how important was the negative NAO?

- Idealized NAO forcing runs
  - Model is forced with persistent positive NAO forcing for 40 years.
Can we recreate the warming with just NAO + forcing?

- Forcing the ocean with persistent positive NAO also recreates the warming of the North Atlantic.
- However, the warming of the subpolar gyre is not as rapid.

Subpolar gyre 0-500m T
The North Atlantic Subpolar gyre underwent a large and rapid warming in the mid-1990s.

The warming was primarily due to a surge in the northward ocean heat transport, associated with an acceleration of the MOC and significant changes in the gyre circulation.

The surge in heat transport and acceleration of the MOC were caused by anomalous buoyancy forcing over the subpolar gyre associated with the prolonged positive phase of the NAO during the 1980s and early 1990s.

The negative NAO winter of 95/95 contributed to the rapidity of the warming, but was not the primary cause.

Potential predictability arising from the delayed, and integrated, ocean circulation response to the positive NAO forcing.
Performance of the Met Office Decadal Prediction System for the rapid warming of the North Atlantic in the mid 1990s

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Performance of Met Office DePreSys system for the rapid warming of the North Atlantic in the mid 90s

Subpolar gyre 500m heat content

June 1995

Sept 1995

June 1995

DePreSys

obs
Questions

- When the hindcasts look good:
  - Is the system doing the right thing for the right reasons?

- When the hindcasts look bad:
  - What went wrong?
Anomaly assimilation method is based around a model climatology

**Hypotheses**

1. Problem with the model climatology
2. Errors in assimilated density anomalies arising from non-linearities in the equation of state

\[
\rho' = \rho(\bar{T} + T', \bar{S} + S', P) - \bar{\rho}
\]
The effect of correcting density errors: 1991 start

Subpolar gyre 0-500m Temp

Observations

Unperturbed

Perturbed salinity

2\textsuperscript{nd} year SST forecast difference control – perturbed Salinity.

Control – Perturbed Salinity

overturning stream function

Nortward HEAT Transport diff between control and pert S

Latitude

Time (years)
Original climatology was imbalanced, with very high MOC which declined rapidly.

- High MOC => excess northward heat transport => excess warming

- Correcting climatology reduces MOC and heat transport, and improves prediction of the warming
The effect of a new climatology: 1991 start

Subpolar gyre 0-500m Temp

MOI at 50N

2nd year SST forecast difference control – new clim.

Nortward HEAT Transport diff between control and New_Clim
The effect of a new climatology: 1991 start

Maps showing climate patterns for years 1 to 4.
Questions

When the hindcasts look good:
- Is the prediction system doing the right thing for the right reasons?

When the hindcasts look bad:
- What went wrong?
Compare 91 and 95 starts

MOC at 40N

MOC initialised
~2SV higher for 95 start

Initialised acceleration of the MOC

MOC at 50N
Northward heat transport for ‘95 start anomalies relative to model climatology.
Northward heat transport for ‘95 start

\( \mathbf{v}'T \) dominates heat transport variation in DePreSys: initialisation of ocean dynamics critical for prediction of the warming
Heat budget of the subpolar gyre

1995 starts - 1991 starts

- Warming attributable to changes in overturning component of ocean heat transport convergence

- Anomalous air sea fluxes act to damp the warming
Timing of the warming

95 start appears to predict warming later than observed

But!...
When initialised using a balanced climatology, DePreSys does a pretty good job of predicting the rapid warming event:

- Magnitude and timing consistent with observations
- Warming is attributable to a surge in the northward ocean heat transport, associated with an acceleration of the MOC
- Exact timing and rapidity is sensitive to interannual fluctuations in the NAO

Some room for improvement, e.g. $v'T'$
Conclusions 2: Metrics for case studies

- Generic metrics:
  - Time series of key indices (SST, heat content etc)
  - Do the observations fall within the spread of the ensemble ("reliability")
  - Needs large ensembles to capture non-Gaussian behaviour

- Key process-based metrics for the specific event, e.g.:
  - Northward heat transport
  - MOC
  - NAO

Is the prediction system doing the right thing for the right reasons?
The role of initialisation in decadal climate prediction

- Initialisation usually motivated by the need/opportunity to predict aspects of internal variability.
- Arguably it will prove *more important* as a tool to identify and understand model errors.
- Analysis of error growth provides a powerful new way to test climate models and prediction systems *at a process level*, and thereby improve them.
- Long used in NWP; a big opportunity in climate prediction.

See also Ed’s talk
What is the value of the RAPID array observations for:
- Evaluating predictions?
- Initialising predictions?

- Reading, NOC, Met Office, ECMWF
- DePreSys & NEMO workstreams
VALOR Aims

1. To use the RAPID observations as independent data to evaluate the representation of the AMOC in ocean analyses, and to assess the skill of AMOC predictions.

2. To develop and evaluate strategies for including RAPID observations in ocean syntheses, thereby generating new, improved, ocean analyses.

3. To determine the impact of assimilating RAPID and other ocean observations on predictions of the AMOC and climate.

4. To develop and evaluate strategies for sampling the initial condition and model-related uncertainty in ensemble predictions of the AMOC and its impacts of climate.
Model uncertainty: sensitivity to resolution

Density Integrated 1500-3000m

HiGEM

MOC Boundary Density

HadGEM
AMOC in DePreSys

DePreSys MOI at 50N

800-3000m mean hindcast
Drifts present in DePreSys

800-3000m mean hindcast
Changes in the AMOC

- CONTROL shows an increase in the AMOC and an increase in MHT.
- Low frequency strengthening of the AMOC is due to the buoyancy forcing.
- Wind forces higher frequency variability which modulates the AMOC and MHT.
Chain of events

- Positive NAO, cools surface of subpolar gyre, increase in southerly Ekman → increased convection
- Wind stress and deep water formation strengthens gyre circulation and AMOC
- Strengthening of ocean circulation (in particular AMOC) → increased northward heat transport
- Increase in northward heat transport initially offset by strong southerly Ekman and strong surface heat loss
- Negative NAO, sudden relaxation in southerly Ekman → sudden increase in northward heat transport, and reduction of surface heat flux
- Warming of the subpolar gyre → decreases doming of isopycnals → sudden weakening and contraction of the gyre → increased intrusion of subtropical waters
- Decrease in deep convection → weakening of the AMOC → reduction in northward heat transport