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Atlantic Predictability

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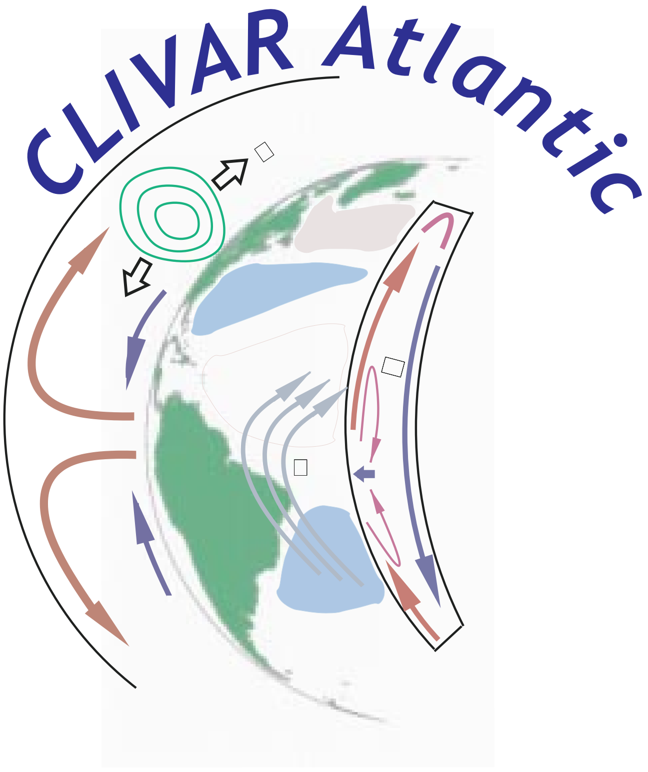

Papers from the CLIVAR Workshop on Atlantic Predictability 19-22 April 2004

Call for Contributions

We would like to invite the CLIVAR community to submit papers to CLIVAR Exchanges for issue 33 . The overarching topic will be on **science related to Asian Monsoon.** The deadline for this issue will be January 31st 2005.

Guidelines for the submission of papers for CLIVAR Exchanges can be found un-

Editorial

It is now over 3 months since the 1st International CLIVAR Science Conference in which many of you will have participated. The Conference, held in Baltimore USA from June 21-25 2004, was, by any measure, an enormously informative, enjoyable and successful event. It provided a comprehensive overview of progress with CLIVAR science over the past 5 years, a host of new results expressed in a wide variety of talks and posters, and directional pointers for the future progress of our science. The Conference attracted over 640 registered attendees from 56 countries. More than 650 posters were displayed on all aspects of CLIVAR science and we were pleased to present 16 awards for student posters at 2 "breakfast" events. 35 multi-author oral presentations were made and 9 individuals led end of day discussions. In addition 4 press briefings involving 17 panelists and 4 moderators were held with several stories going to print. On page 18 you can see a few of the photographs taken over the five days.

Such a conference cannot be organised without a lot of hard work in preparation and behind the scenes effort during the event. CLIVAR is immensely grateful indeed to David Legler, Director of the US CLIVAR Office, who led the Local Organising Committee and who bore the brunt of much of the detailed organisational planning and implementation. Many thanks also to those who so ably supported him, including most notably Cathy Clark from UCAR/JOSS, Cathy Stephens (US CLIVAR Office), Jill Reisdorf (UCAR/JOSS), and Sandy MacCracken of the US Climate Change Science Program office as well as Valery Detemmerman of the Joint Planning Staff for WCRP and the ICPO staff involved. We are most grateful indeed also to Lennart Bengtsson who ably led the formulation of the scientific programme and to the members of the Scientific Organising Committee for their help and input. Finally many thanks to the 14 sponsors of the conference (see www.clivar2004.org) who provided the financial support necessary to hold the event.

The Conference was followed by a meeting of CLIVAR's Scientific Steering Group, the primary business of which was to review and assess the outcomes of a self-assessment of CLIVAR carried out in the months previously and to which the Conference itself formed part of the input. Thanks to our assessors, David Anderson, Mike Manton, Ed Sarachik, Fritz Schott, Neville Smith and Jurgen Willebrand for all their help with this process and well as to those involved in CLIVAR's Panels and Working Groups who provided input. The next edition of Exchanges will include an article providing a summary of outcomes from the Conference and the SSG from the SSG co-chairs Tony Busalacchi and Tim Palmer.

As you will see, this edition of CLIVAR Exchanges is devoted to the topic of Atlantic Predictability, following from the very successful CLIVAR Workshop on that topic held at the University of Reading, UK from 19-22 April 2004. Rowan Sutton acted as chair of the Organising Committee. He outlines the Workshop's rationale, aims and participating bodies below and, in the article following, also summarises the challenges it raised. CLIVAR is indeed thankful to the US National Oceanographic and Atmospheric Administration (NOAA), the UK Natural Environment Research Council (NERC) through its Centres for Atmospheric Science Centre for Global Atmospheric Modelling (NCAS/CGAM) and Coupled Ocean Atmosphere Processes and European Climate (COAPEC) Directed Programme, the Met Office, UK and WCRP for co-sponsoring the Workshop. Thanks also to Rowan and the Organising Committee for organising such a successful and productive programme.

Howard Cattle

Guest Editorial
CLIVAR Workshop on Atlantic Predictability, 19–22 April 2004, University of Reading, UK

Rowan Sutton

Efforts to improve climate prediction are at the heart of CLIVAR. In TOGA, and in the first phase of CLIVAR, much attention was focused on the problem of forecasting ENSO and its climate impacts, particularly those in the Indo-Pacific region. Rather less attention has been addressed to forecasting the climate of the Atlantic region, although a number of centres do now routinely issue seasonal forecasts for various aspects of Atlantic climate. Moreover, significant progress has been made both in identifying potentially predictable phenomena in the Atlantic region, and in developing statistical and dynamical prediction systems. It was to give focus to the challenges of Atlantic Sector climate prediction that a workshop was organised at the University of Reading in April of this year. The specific aims of the workshop were:

1. To provide an up to date assessment of the state of knowledge concerning the predictability of climate in the Atlantic Sector, with particular emphasis on the role of the Atlantic Ocean.
2. To improve communication between the operational prediction centres and regional fora and the research community concerning the predictability of Atlantic Sector climate.

3. To identify gaps in knowledge, and in observing systems, required for the further development of systems for forecasting Atlantic Sector climate.
4. To recommend priorities for future research, observational programmes and development of prediction systems.

The workshop brought together scientists from operational forecasting agencies with academics and others involved in more basic research. The first session focused on reports from the operational centres and similar organisations involved in routine climate forecasting. Organisations represented included international bodies, such as the International Research Institute (IRI) and the European Centre for Medium Range Weather Forecasting (ECMWF), National Meteorological Services, and Climate Outlook Fora. These reports provided an excellent survey of the current achievements and challenges in climate prediction around the Atlantic Basin. The developing experience of interaction with user groups was a major theme in many of the presentations.

In the second session a series of 9 "White Papers" was presented. The purpose of these papers was to review the current state of the art and highlight important issues that need to be addressed, and summaries of these papers provide the core of this issue of CLIVAR Exchanges. The papers break into three groups. First are two papers on the physical basis for climate prediction in the Atlantic Sector. Second are two papers on the infrastructure for climate prediction: on the observing system and the climate prediction systems themselves. Third are five papers, each of which focuses on a particular region: West Africa, Southern Africa, North America, South America and Europe. Collectively these papers provide a thorough survey of the state of Atlantic climate prediction at this time.

In addition to the above elements the workshop programme was significantly enhanced by a lively poster session and two guest lectures. Dr Tim Palmer (of ECMWF) discussed "Developments and future prospects in understanding predictability". Dr Neil Ward (of IRI) discussed "Merging forecasts with applications".

Following the formal oral presentations, discussions were held to identify priorities for future progress. A short summary of the recommendations from these discussions is also included in this issue of Exchanges. The full proceedings of the workshop are being published by the International CLIVAR Project Office (CLIVAR Publication Series no. 81 (Unpublished manuscript); WCRP Informal Report No. 11/2004) and will be available soon on request. The organising committee would like to acknowledge generous support for the workshop from the U.S. NOAA, the U.K. Met Office and the U.K. Natural Environment Research Council.

Challenges in the development of prediction systems for Atlantic Sector Climate
A synthesis of discussions held at the CLIVAR Workshop on Atlantic Predictability
19–22 April 2004, University of Reading, UK

Rowan Sutton
Corresponding author: R.Sutton@reading.ac.uk

Climate prediction is a complex task which requires the effective bringing together of many components - fundamental understanding, the observing network, climate models, data assimilation systems, user "interfaces" - if success is to be achieved. It is no surprise, therefore, that discussions held at the workshop, both in break out groups and a plenary session, highlighted a wide range of specific issues that need to be addressed to advance climate prediction for the Atlantic Sector. There is not space here to discuss all these issues in any detail. However, two overarching challenges were recognised, and these provide a useful synthesis of the discussions:

1. To realise fully the potential of seasonal predictions for the tropical Atlantic region

The potential skill and value of seasonal forecasts is highest in the tropical Atlantic. The challenge is to build a seasonal climate prediction system for the tropical Atlantic region that is comparable (in terms of data coverage, model fidelity, and – subject to physical limits – forecast skill) to that in the tropical Pacific. This will entail:

- Significant enhancement of sustained observations in the tropical Atlantic region, in the ocean, at the land surface, and in the free troposphere.
- Major effort to reduce the systematic errors in simulation of tropical Atlantic climate in models used for seasonal prediction.
- Research to better understand the fundamental ocean-atmosphere-land processes that control the climate of the tropical Atlantic region, its variability and predictability, including the statistics of sub-seasonal variability.
- Improvement of data assimilation systems for the Atlantic Ocean (especially the treatment of salinity).
- Development of reliable methodologies for making seasonal forecasts relevant and useful to decision makers.

2. To take the lead in the development of systems for decadal climate prediction

The development of useful decadal climate predictions, incorporating both initial condition constraints and transient boundary forcings, is a "grand challenge" whose importance is increasingly recognised. Because of the key role played by the Atlantic Ocean in the global overturning circulation, the Atlantic climate community is naturally placed to take a lead in this area. A number of specific challenges may be identified, for example:

- Development of an observational system for monitoring the meridional overturning circulation (MOC) (already in progress).
- Understanding the limits of predictability in the MOC and the mechanisms that determine predictability.
- Identifying which aspects of the oceanic initial conditions most constrain the future behaviour of the MOC.
- Development of data assimilation methods for initialisation of decadal MOC forecasts
- Understanding how initial conditions and changing external forcings combine to determine climate evolution on decadal timescales, and (relatedly) development of suitable ensemble techniques for sampling forecast uncertainty.
- Understanding and quantifying the regional climate impacts of MOC change and the predictability of these impacts

The above challenges offer an agenda for Atlantic climate prediction over the next 5-10 years.

The Physical Basis For Predicting Atlantic Sector Seasonal-to-Interannual Climate Variability

Yochanan Kushnir[1], Walter A. Robinson[2], Ping Chang[3], Andrew W. Robertson[4],
[1]Lamont-Doherty Earth Observatory, Palisades, NY, USA
[2]University of Illinois at Urbana-Champaign, IL, USA
[3]Texas A&M University, College Station, TX, USA
[4]International Research Institute for Climate Prediction, Palisade, NY
Corresponding author: kushnir@ldeo.columbia.edu

Introduction

Attempts to describe and predict seasonal to interannual (S/I) climate anomalies tend to make use of the existence of coherent, large-scale atmospheric anomaly patterns and their link to anomalies at the land or sea surface. In the Atlantic Basin there are three such major patterns (Marshall et al. 2001): (i) The North Atlantic Oscillation (NAO), which describes the variability of the Northern Hemisphere circulation from the subtropics to the polar latitudes; (ii) El Niño, which influences the climate anomalies, primarily of rainfall in the tropics and North America, and (iii) tropical Atlantic variability (TAV), which involves the relationship between regional SST variability and, in particular the seasonal migration of the Atlantic ITCZ and its associated rainfall over South America and West Africa. Here we summarize what recent studies reveal about the dynamical aspects of the NAO and TAV relevant to their role in S/I prediction. A full version of this paper will appear in the Proceedings of the CLIVAR Workshop on Atlantic Predictability, held during April 2004 at the University of Reading, UK (International CLIVAR Project Office (2004))

Predictability of the NAO

The NAO (Hurrell et al. 2002) is an intrinsic atmospheric structure, which dominates the regional geopotential height variance. It is excited by the chaotic dynamics of the atmosphere and its spatial scale is determined by its quasi-stationary nature. The NAO is also seen as a self-maintaining meridional shift in the location of the eddy-driven extratropical jet and its associated stormtrack across the North Atlantic. Time series calculated by projecting daily data on the NAO pattern are nearly indistinguishable from red noise with a decorrelation time during winter, the season of its greatest persistence, of less than 10 days. There is plentiful evidence that this persistence is provided by reinforcing interactions with transient baroclinic eddies in the Atlantic storm track. The fall and winter decorrelation curves display a curious “shoulder” at lags between 15 to 30 days. Wintertime monthly means of the NAO index (December to January and January to February) correlate at a level of about 0.3, a value larger than expected based on time averages of a red-noise model with a decorrelation time based on daily data (about 0.2).

One of the candidates for the increased wintertime persistence is the upper ocean with its long thermal memory. Barsugli and Battisti (1998)(hereafter B&B) provide a simple linear framework useful for quantifying the role of the upper ocean in enhancing atmospheric persistence stemming from a responsive ocean mixed layer. The B&B model can be tuned to produce the observed daily and monthly persistence of the winter NAO but with parameter values different from the ones chosen based on coupled and SST-forced GCM integrations. These bring the model close to its stability threshold and thus may be unrealistic. Recent GCMs that realistically reproduces the observed structure and variability of the NAO do not show any increased persistence in the NAO when coupled to an ocean mixed layer. Thus this issue is not resolved.

When it comes to persistence between seasons there is evidence that the early winter NAO pattern is preceded in summer and fall by a distinct SST pattern referred to as the “North Atlantic Horseshoe” pattern. It apparently evolves from the “tripole” pattern, which is forced by the NAO in winter. This phenomenon is currently exploited in an experimental prediction procedure used by the Hadley Centre. However, the horseshoe was found ineffective in forcing the NAO in a recent GCM study (Peng et al. 2004). That experiment and observational evidence suggest that the cause for the summer-to-winter SST influence is in the tropical Atlantic part of the SST tripole pattern. This tropical portion may also be responsible to the horseshoe pattern. Quantitatively, the typical GCM response to the tripole is 20 m in 500 hPa geopotential height per degree. Since the tripole is typically about 0.5°C, this suggests that at most 10 m out of 80 m of the typical, NAO-related wintertime 500 hPa height anomaly may be predicted from SST.

A discussion of NAO predictability is incomplete without addressing the role of the stratosphere. Evidence is accumulating that the strength of the boreal stratospheric polar vortex influences the tropospheric circulation on intraseasonal timescales, especially the Northern Annular Mode (NAM), which is well correlated with the NAO. Because the polar vortex exhibits dynamical memory over tens of days, such stratospheric influences can extend the persistence of the NAM or NAO when there is strong dynamical coupling between the troposphere and stratosphere (i.e., winter). The dynamical mechanisms for this downward influence are not entirely understood, but presumably involve the secondary circulations induced by anomalous stratospheric wave driving, altered planetary wave propagation, tropospheric transient eddy feedbacks, and possibly planetary-scale baroclinic waves. The stratospheric influences may also provide some interseasonal or interannual predictability via the quasi-biennial oscillation (QBO) of the equatorial stratosphere. The last influences the polar vortex and affects the NAO through that link. The stratosphere plays a predictable role in climate forcing after volcanic eruptions and may be important in explaining an observed relationship between fall snow cover over Eurasia and the NAO, in the following winter.

Climate predictability in the tropical and South Atlantic

Two, well known types of atmosphere-ocean interaction govern tropical Atlantic (TA) variability: in boreal spring, changes in the meridional SST gradient and related convection and surface wind response in the western TA, and in summer equatorial SST variability with changes in the eastern TA atmosphere (Marshall et al. 2001).

TA boreal spring variability is closely tied to two sources of forcing, El Niño and the anomalous distribution of SST within the TA. An example of how these two agents act to force one aspect of TAV is given by a comparison between observed and simulated indices of Nordeste (in northeast Brazil) rainfall during March to May. Three atmospheric GCMs forced with observed, time-varying global SSTs from 1950 to 1994, tropical Pacific SST only (with climatology values elsewhere) and tropical Atlantic SST only, produce Nordeste rainfall, which correlates with observations at 0.76, 0.4, and 0.65, respectively. This suggests that information on SST anomalies in the TA Ocean is crucial for seasonal climate forecasting in the region. While El Niño can affect TAV directly through an atmospheric bridge, the TA ocean-atmosphere responds through local feedbacks to create influential internal SST variability. In a similar way, climate variability in the extratropics, primarily NAO-related tradewind variability also brings into play TA SST anomalies. In general, both ENSO and NAO-related tradewind variability forces SST changes in the subtropics with direct influence on the ITCZ. Local ocean thermal advection acts as a damping mechanism, so the ocean is rather passive. Close to the equator however, an important wind-evaporation-SST (or thermodynamic) feedback kicks in to enhance the SST pattern. Lately, attention has also been called to the importance to the tropics of climate variability originating from the Southern Hemisphere that acts similarly to the way the NAO does from the north (i.e., through affecting the trades). The problem of the summer, eastern TA variability is referred to as the Atlantic Niño because it seems to involve a similar coupled, dynamical interaction. This process however, is much more elusive when prediction is considered (Zebiak. 1993).

To summarize, addressing the predictability of climate variability in the tropical Atlantic requires, in the first place, addressing the predictability of the state of El Niño, the NAO, and the Southern Hemisphere anticyclone, but also handling the local SST interactions well (Goddard and Mason 2002). Most present generation coupled global models do not simulate the climatological state in the equatorial Atlantic correctly (Davey et al. 2002) and this appears to be important in coupled model initialization and prediction.

Variability over the tropical Atlantic has strong ties to the South Atlantic (SA). The meteorological equator over the Atlantic, as given by the latitude of the ITCZ, is mostly north of 0°N, so that a large segment of the equatorial mode of TAV resides in the SA, bounded to the north by West Africa; a landmass with no counterpart in the eastern Pacific. The SST pattern extends southward along the Lower Guinea Coast where it represents fluctuations in the strength of the seasonal cold tongue (Bengula Niños). Tropical SE Atlantic SSTs affect rainfall over Angola and Namibia and possibly over larger regions of South Africa. The southern pole of the gradient mode of TAV, located over the SA, appears to play an important preconditioning role on the impact of ENSO on NE Brazil rainfall during the February–May rainy season.

Conclusions

A broad-brush view of large-scale, S/I climate anomalies in the Atlantic suggests that they can be divided into three types: internal to the basin are extratropical fluctuations driven firstly by atmospheric chaotic dynamics (in the North and South Atlantic) that is to first order insensitive to surface anomalies, and secondly by tropical variability for which the atmosphere is sensitive, even coupled, to surface conditions, particularly SST variability, and is thus potentially predictable. The third kind, are anomalies forced from outside the Basin, particularly from the Pacific (El Niño). In seeking to advance Atlantic climate prediction in the extratropics, future research should focus on better quantifying and understanding the apparent marginal persistence of monthly and seasonal anomalies. While small, this marginal predictability can be useful to certain users. The challenge in making forecasts of such variability is to prove that they are reliable. In the tropics the potentially predictable signal is large compared to the chaotic variability. Thus breakthroughs in tropical Atlantic climate prediction will be of high value to a broad range of social activities. Future research should focus on developing better coupled models or new coupling strategies that can overcome the limitations of the present models in tracking the combined evolution of the atmosphere and the ocean.

Continued improvement of ENSO prediction methodology is clearly important to the cause of advancing Atlantic Sector prediction. Not enough is known on the interplay between local conditions and the remote forcing and its dependence on the intensity of the remote forcing and the season. In the particular case of the tropical Atlantic, the influence from the relatively unpredictable extratropical dynamics can be thought of as an external source of variability, interfering with the more predictable ENSO influence. Better understanding of this interference is warranted.

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The Physical Basis for Prediction of Atlantic Sector Climate on Decadal Timescales

M. Latif [1], M. Collins [2], R.J. Stouffer [3], H. Pohlmann [4], and N. Keenlyside [1]
[1]Leibniz-Institut für Meereswissenschaften, Kiel, Germany
[2]Hadley Centre for Climate Prediction and Research, Met Office, Exeter, UK
[3]GFDL, Princeton, New Jersey, U.S.A.
[4]Max-Planck-Institut für Meteorologie, Hamburg, Germany
Corresponding author: mlatif@ifm-geomar.de

Abstract

This white paper discusses the physical basis and the potential for decadal climate predictability over the Atlantic and its adjacent land areas. Many observational and modelling studies describe pronounced decadal and multidecadal variability in the Atlantic Ocean. However, it needs still to be quantified to which extent the variations in the ocean drive variations in the atmosphere and over land. In particular, although a clear impact of the tropics on the midlatitudes has been demonstrated, it is unclear if and how the extra-tropical atmosphere responds to midlatitudinal sea surface temperature (SST) anomalies. Recent studies, however, indicate that there is indeed a discernable impact of the midlatitudinal ocean on the atmosphere at decadal timescales.

Although the mechanisms behind the decadal to multidecadal variability in the Atlantic Sector are still controversial, there is some consensus that the longer-term multidecadal variability is driven by variations in the thermohaline circulation (THC). The variations in the thermohaline circulation appear to be predictable one to two decades ahead, as shown by a number of perfect model predictability experiments. The next few decades will be dominated by these multidecadal variations, although the effects of anthropogenic climate change are likely to introduce trends. A clear impact of the variations of the thermohaline circulation on the atmosphere can be demonstrated, so that useful decadal predictions with economic benefit are in reach.

1. Introduction

Over the last twenty years we have seen major developments in seasonal forecasting, and now many centers around the world routinely make seasonal forecasts. The success of these efforts is largely based on the predictability of the El Niño Southern Oscillation (ENSO) phenomenon, and in our ability to capture it in our models and statistical schemes. Process studies, observations and simple models have played a central role in the development of seasonal forecasting and have lead to the design and implementation of the TOGA/TAO observational array (McPhaden et al. 1998) which is integral in monitoring and prediction.

In contrast to seasonal forecasting, decadal to multidecadal climate predictions are at an infant stage[1]. Nonetheless, there are many things that can be learned from seasonal forecasting experience. Paramount among these is the recognition that better understanding of the physical mechanisms involved and better monitoring systems are needed for advances to be made. In terms of understanding decadal variability, we are handicapped much more significantly by a lack of adequate data, and we shall have to wait much longer to get it. Thus, in decadal variability studies there has been a heavy reliance on models. But models do not always agree with each other or with observations, and thus while models have been helpful in identifying possible mechanisms, the true mechanisms for decadal variability are still not known. However in this respect, observations can play a crucial role: They can be used to reduce model uncertainties, through improvements in model physics, especially those aspects believed important to decadal and multidecadal timescales, and on which models disagree.

As with seasonal forecasting, decadal to multidecadal climate predictions are of economic, political and public interest. Their value lies in planning the future in all fields that depend on climate to some degree. This includes for example the choice of agricultural species, insurance fees, plans of infrastructure, the energy sector, or simply the diameter of gutters. Unlike seasonal forecasting, the relevant periods are longer than a single political reign, and anthropogenic forcing of climate becomes an issue.

2. Global pattern of decadal to multidecadal predictability

In this section we examine the global pattern of decadal predictability as found in potential (diagnostic) and classical (prognostic) predictability studies, which are two common methods for estimating decadal predictability. Decadal potential predictability is defined as the ratio of the variance on the decadal timescales to the total variance (Boer 2000). A value approaching one indicates an enhancement of variability on decadal timescales, and would argue for the presence of an oscillatory mode of variability and against the null hypothesis of the stochastic climate model (Hasselmann 1976). Classical predictability studies consist of performing ensemble experiments with a single coupled model perturbing only the initial conditions (e.g. Griffies and Bryan 1997). In these studies, the predictability of a variable is given by the ratio of the ensemble variance to the actual signal variance. These experiments provide an upper limit of predictability, since they assume a perfect model and near perfect initial conditions. Although potential predictability can be estimated from observations, in practice data records are rather short and tend to be less reliable for earlier periods, and hence, it is often estimated from model simulations. Thus, both these predictability estimates rely heavily on models. A third method exists that is also model-based. This method compares the variability simulated with and without the inclusion of active ocean dynamics and identifies those regions in which ocean dynamics are important in generating the variability. It is likely that these regions are also the regions of high predictability potential (Park and Latif 2004).

All three methods, the potential predictability approach (Boer 2001), the classical predictability studies (e.g,. Pohlmann and Keenlyside 2004), and the ocean dynamics approach indicate four regions where predictability may exist at decadal timescales: The North Atlantic, the Southern Ocean, the North Pacific, and the Tropical Pacific. The identification of regions is shown to be largely model independent by Boer (2001), where the potential predictability of decadal means of surface air temperature (SAT) from an ensemble of eleven climate models was calculated (Fig. 1 page 15). The most prominent regions are the North Atlantic and the Southern Ocean, where more than 50% of the variance exists in the decadal band.

3. Decadal climate predictability in the North Atlantic-European region

There have been several classical decadal predictability studies of North Atlantic variability. As discussed below, they all seem to indicate that North Atlantic THC variations are predictable out to a decade or more However, there are major disagreements on the level and extent of predictability of SST and atmospheric quantities, such as SAT and sea level pressure (SLP). But there are some positive indications of decadal predictability of SAT and SLP over Europe.

In the PREDICATE project (Sutton et al. 2003) a systematic comparison of the predictability of five state-of-the-art European CGCMs (HadCM3, ECHAM5/MPI-OM, ARPEGE3/ORCA, BCM, ECHAM4/ORCA) was made. The results indicate that in general the strength of

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[1] The term "decadal to multidecadal" is a rather loose definition of time scales usually covering anything from a few years to a few centuries. While this is somewhat inadequate, it pervades the literature and is used liberally in meetings and at conferences. Hence we accept its use in this paper and, when specific studies are quoted, every effort is made to be specific about the time scales and averaging periods used.

the Atlantic THC is potentially predictable at least a decade in advance and, in some situations, multidecadal predictions of the THC may be possible (Fig. 2 page 15, left panel). In addition, THC-related variations in SST and SAT are potentially predictable one or two decades in advance (Fig. 2 page 15, right panel). The exact level of predictability is dependent on the oceanic initial conditions and on the coupled model used.

4. Anthropogenic climate change

Climate models predict that anthropogenic climate change will become more and more important. How precisely global and regional climate will evolve, however, is highly uncertain. The strong internal decadal to multidecadal variability is likely to mask the anthropogenic climate signal during the next few decades. Likewise the regional climate of the Atlantic sector during the twentieth century was, in contrast to global climate, dominated by the internal variability. Global warming will, however, introduce a warm bias on the multidecadal timescale. The predicted strength of this warming depends on the selected scenario and the selected climate model. The warming may well override the amplitude of the internal decadal to multidecadal variability on the global scale. Regionally, however, changes in the ocean circulation may provide important feedbacks. For the Atlantic sector, the fate of the thermohaline circulation will be important in shaping regional climate change.

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Climate Observing System for the Atlantic Sector

Antonio J. Busalacchi[1], Roberta Boscolo[2], Bob Dickson[3], Alberto Piola[4], Jacques Servain[5] and Ning Zeng[6]
[1] ESSIC, University of Maryland, [2]ICPO, [3]CEFAS, UK, [4]Servicio de Hidrografia Naval, Argentina, [5]IRD, France, [6]Meteorology/ESSIC, University of Maryland
Corresponding author: tonyb@essic.umd.edu

Ocean Based Observations.

The current existing components of the international effort in the Atlantic comprise in situ 1) Fixed Point Time Series 2) Global Surface Drifting Buoy Array; 3) Argo Profiling Float Array 4) Global Tide Gauge Network; 5) Global Ships of Opportunity Network; 6) Ocean Carbon Monitoring Network; 7) VOS Surface Marine Network: 8) Moored Buoy Networks. Several elements are part of the Sustained Ocean Observing System for Climate while the rest are short-term measurements as part of specific process studies. More information can be found at: http://www.clivar.org/organization/atlantic/IMPL/index.htm http://www.clivar.org/organization/atlantic/IMPL/proc-stud.html

Fixed Point Time Series.

Fixed-point time series are an essential element of the global ocean observing system. These Eulerian Observatories are uniquely suited for fully sampling 2 of the 4 dimensions (depth and time), thus complementing other components of the observing system (satellites, floats, ships). They resolve a wide range of temporal variability and sample the water column from the surface to the bottom. Fixed-point stations will resolve multi-disciplinary variability and processes like fluxes of heat, freshwater momentum and other properties between the ocean and atmosphere.

Global Surface Drifting Buoy Array.

The primary goal of this project is to assemble and provide uniform quality control of sea surface temperature (SST) and surface velocity measurements. These measurements are obtained as part of an international program designed to make these data available in an effort to improve climate prediction. Climate prediction models require accurate estimates of SST to initialize their ocean component. Drifting buoys provide essential ground truth SST data.

Subsurface Floats and Argo Project.

Argo is a new method of collecting information from the upper ocean using a fleet of robotic floats. Argo data complement other in-situ observations (many restricted to shipping routes) and data from earth-observing satellites. Argo floats drift at depths between 1 and 2 km. Every 10 days each float surfaces and measures a profile of temperature and salinity.

Global Tide Gauge Network.

The tide gauge data from the international program Global Sea Level Observing System (GLOSS) aims at the establishment of high quality global and regional sea level networks, including the South and tropical Atlantic Ocean, in an evenly distributed spatial sampling. The NODC and the University of Hawaii provide access to the sea level data through the Joint Archive for Sea Level (JASL). These data, primarily since 1980, are hourly, daily and monthly from stations in tropical and subtropical areas of all ocean basins, including the South and tropical Atlantic. However present data are measured with different standards and have a Northern Hemisphere bias.

Global Ships of Opportunity Network.

The Ship-of-Opportunity Program (SOOP) is an international effort directed primarily towards the continued operational maintenance and co-ordination of the XBT ship of opportunity network but other types of measurements are being made (e.g. TSG, XCTD, CTD, ADCP, pCO2, phytoplankton concentration).

Ocean Carbon Monitoring Network.

Between 1990 and 1998 the WOCE Hydrographic Programme (WHP) occupied a grid of 20000 full depth hydrographic stations (the WHP One Time Survey). Together with other occupations of some of these sections (repeat hydrography), these sections document changes in oceanic properties and circulation on decadal timescales based on physical, chemical and transient tracer measurements. They also form the basis for determining oceanic heat and freshwater transports. During the WHP, collaboration between WOCE and JGOFS led to the complementary measurement of parameters to enable ocean carbon storage and transports to be determined. CLIVAR is concerned with further refining the WOCE determinations of oceanic heat and freshwater transports and with documenting decadal and shorter period ocean changes based in large part on the reoccupation of a subset of the hydrographic sections that formed the WHP.

VOS Surface Marine Network.

The international scheme by which ships plying the various oceans and seas of the world are recruited by National Meteorological Services (NMSs) for taking and transmitting meteorological observations is called the World Meteorological Organization (WMO) Voluntary Observing Ships (VOS) scheme. During the past few decades, the increasing recognition of the role of the oceans in the global climate system has placed even greater emphasis on the importance of marine meteorological and oceanographical observing systems. As might be expected, real-time reports from the VOS are heavily concentrated along the major shipping routes, primarily in the North Atlantic and North Pacific Oceans. Of course, as VOS reports are part of a global data capture program, their reports are of value from all the oceans and seas of the world, and even the well frequented North Atlantic and North Pacific Oceans require more observational data.

Moored Buoy Networks.

Moored buoys are deployed in the coastal and offshore waters to measure and transmit barometric pressure; wind direction, speed, and gust; air and sea temperature; and wave energy spectra from which significant wave height, dominant wave period, and average wave period are derived. Even the direction of wave propagation is measured on many moored buoys. In addition to their use in operational forecasting, warnings, and atmospheric models, moored buoy data are used for scientific and research programs. The PIRATA (Pilot Research Moored Array in the Tropical Atlantic, http://www.pmel.noaa.gov/pirata/) is a project designed by a group of scientists involved in CLIVAR, and is implemented by the group through multi-national cooperation. The purpose of PIRATA is to study ocean-atmosphere interactions in the tropical Atlantic that are relevant to regional climate variability on seasonal, interannual and longer time scales. The scientific goals of the PIRATA array are: to provide a description of the seasonal-to-interannual variability in the upper ocean and at the air-sea interface in the Tropical Atlantic; to improve our understanding of the relative contributions of the different components of the surface heat flux and ocean dynamics to the seasonal to interannual variability of SST within the tropical Atlantic basin; and to provide a data set that can be used to develop and improve predictive models of the coupled Atlantic climate system. To achieve these objectives PIRATA designed, deployed and maintain a pilot array of ATLAS moored oceanic buoys that measure a set of oceanic and atmospheric parameters. Data are collected and transmitted in real time via satellite and posted in a web page.

North Atlantic MOC Observations and Link to Arctic.

It has long been recognized that the Atlantic meridional overturning circulation (MOC) is potentially sensitive to greenhouse gas and other climatic forcing, and that changes in the MOC have the potential to cause abrupt and perhaps global climate change. Though the mechanisms remain poorly understood, the exchanges of heat, mass and salt between the North Atlantic, the Arctic Ocean, and lower latitudes are known to be implicated, and their interplay and variability are becoming known from two main data sets: - first, from standard hydrographic sections worked across the main gateways of exchange for periods of over a century; second, from direct flux measurements conducted across each of the main choke-points. From this long-sustained effort, we would now recognise that the entire ocean-atmosphere system of the North Atlantic, the Arctic and subarctic seas is involved in driving the multi decadal changes we observe, and as our understanding has grown, we have begun to appreciate both the complexity and the systematic nature of these changes.

A substantial portfolio of process studies and observations targeting the Atlantic MOC in the Northern Hemisphere is now taking shape (http://www.clivar.org/organization/atlantic/IMPL/procstud.html#moc). This includes ongoing national CLIVAR programs in Canada, Norway, France, Germany, and USA as well as two international thematic programs:

- The activities under and associated with the Arctic - Subarctic Ocean Fluxes study (ASOF; http://asof.npolar.no/). The ASOF program is structured around 7 main tasks: warm water inflow to Nordic Seas, exchanges with Arctic Ocean, ice and freshwater outflow, Greenland-Scotland Ridge exchanges, overflows and storage basins to Deep Western Boundary Current (DWBC), Canadian Arctic Archipelago (CAA) throughflow and modeling processes and predictions. ASOF is an international programme funded mainly by NSF, NOAA, ONR and EC Framework Programme V. ASOF has received the status of a CLIVAR endorsed project by the CLIVAR SSG.
- The activities under and associated to the UK RAPID Climate Change programme (http://www.nerc.ac.uk/funding/thematics/rcc/). In particular a moored array at 26.5°N to measure directly the meridional mass flux, time series of transient tracers in North Atlantic deep waters, an array along the western margin of the Atlantic to look at boundary wave signals, and an array between New England and Bermuda which has been jointly funded by the UK and USA.

The South Atlantic Climate Observing System.

The South Atlantic (SA) is a relatively poorly sampled ocean. Long-term observations are needed to better quantify the role of the SA on climate, one example of which would be the role of the SA on the shallow tropical cells in the upwelling areas in the eastern basin and their influence on the SST gradients at low latitude. It is expected that the Argo float program and the repeat XBT lines will contribute to fill in the data gap, but it will take several years to obtain the observational base required to improve our understanding of the SA subsurface tropical – subtropical interactions and its long-term variability. Extension of the existing PIRATA array both to the SW and SE should allow the monitoring and prediction of the Benguela Niño. A monitoring program for the SA should involve measurements of the varying ocean meridional fluxes and the air-sea fluxes and estimates of the modifications in the two major blending regions in the southwest and southeast Atlantic. To monitor the net effect of the varying interocean exchanges and subsequent mixing and water mass modifications on the buoyancy characteristics of the SA and the basin-scale overturning fluxes, a zonal section is proposed across the SA at about 25-30S. In addition, direct, long-term current and temperature measurements are needed in the eastern and western boundaries. Maintaining these observations is essential for the detection and understanding of large-scale climate fluctuations in the South Atlantic. The observations include expendable bathythermograph sections and Argo profiling floats, designed to monitor the heat content of the upper ocean and its space – time variability. Two additional lines were initiated this austral summer between southern Brazil and Argentina and the Antarctic Peninsula. Multidisciplinary, long-term time series stations are planned in the central subtropical South Atlantic and in the Cape Basin. In addition two time series stations will be deployed in the western South Atlantic. Surface drifters provide information on the circulation in the Ekman layer and also sea-level pressure data in remote areas, where observations are dramatically sparse. Summer repeat surface CO_2 lines have been in place in the western South Atlantic since 2000. These measurements are to continue until 2010. Additional CTD and XBT sections will be occupied across Drake Passage in South of Africa.

Atlantic Region Land Observations.

It is generally agreed that seasonal to interannual variability is mostly influenced by ocean-atmosphere interaction, with land processes playing a secondary role. However, as our ultimate goal is to predict climate over continental regions where people live, the importance of land-surface processes is much elevated. Land processes become particularly important in semiarid regions located at the edge of the seasonal migration of convective centers where a slight weakening or shift of monsoon rainfall can make large differences to the climate and ecosystem. The circum-Atlantic region includes some of the world’s most climatically sensitive zones such as the West Africa Sahel and northeastern Brazil (Nordeste), where the impact of climate variability is far reaching and the sensitivity to land processes is highest. The American monsoon system has only recently been widely accepted as a coherent continental scale climate system that straddles the Pacific and the Atlantic Ocean basins. For example, the shear size of tropical South America, namely the Amazon basin, may enable it to play an important role in Atlantic climate variability.

There is no single program aimed at circum-Atlantic land observations. The Global Climate Observing System (GCOS) established in 1992, identified the needs to facilitate the establishment or enhancement of networks to obtain observations in the areas of meteorology and atmospheric chemistry. Toward this end, it has defined two networks as sub-systems of the WWW Global Observing System. The GCOS Upper-Air Network (GUAN) has been established to ensure that appropriate upper-atmospheric observations for climate purposes will be available. One hundred and fifty stations were selected from the roughly 1000 World Weather Watch

(WWW) upper-air stations on the basis of their location, quality and record length. Similarly, for surface observations, GCOS worked with climate change detection experts to define a global network of high-quality stations for monitoring global temperatures. The GCOS Surface Network (GSN) consists of 989 stations. The Coordinated Enhanced Observing Period (CEOP) initiated by GEWEX, with its emphasis on global reference sites and satellite observation, collects consistently formatted land and atmosphere data from around the world for the period 2001-2004. Most of the reference sites coincide with sites used by CLIVAR programs such as VAMOS and AMMA. Thus there is an opportunity for the CLIVAR-Atlantic program to provide the impetus and coordination for linking the land observations on both sides of the Atlantic. Compared to ocean observations, a great challenge with land observation systems is how to extrapolate point observations to larger scales. Remote sensing provides one of the most useful scaling tools. For this reason, projects such as CEOP coordinate closely with the Committee on Earth Observation Satellites (CEOS). Success in TRMM, TERRA, AQUA, ESA ENVISAT missions have provided or will provide key information in integrating ground based land observations. For instance, the MODIS sensor on board TERRA, with its balanced resolution and coverage has already provided a suite of information from vegetation characteristics to land cover change of unprecedented quality since 1999.

Remotely-Sensed Observations.

The present suite of remotely sensed observations that provide coverage of the Atlantic Ocean and adjacent continents is expected to continue into the foreseeable future. NASA, NOAA, ESA, CNES, and JAXA are all striving to ensure data continuity from the research and operational satellites that provide SST, scatterometry, altimetry, and chlorophyll concentration for the ocean, temperature profiles, humidity profiles, radiation, cloud properties, aerosols, and precipitation for the atmosphere, and surface temperature and vegetation cover for the land surface. This suite of Earth observations will continue via a series of discipline specific Earth Probe and Earth Explorer research missions and multi-discipline/operational platforms such as ENVISAT, NPOESS, GOES, and EUMETSAT platforms. New sensors expected over the next decade will focus on the hydrological cycle. ESA's SMOS mission will provide information on Soil Moisture and Ocean Salinity (SMOS), NASA's Aquarius and HYDROS satellites will provide complementary information on salinity and soil moisture, respectively. NASA's Global Precipitation Mission will serve to extend in both space and time rainfall rate estimates that began with the Tropical Rainfall Measurement Mission (TRMM).

A particular difficulty to be confronted in the years to come is that most of the measurements mentioned above are either from research satellites or from operational platforms that serve the needs of Numerical Weather Prediction (NWP). The fundamental requirements (e.g., accuracy, calibration, continuity, reprocessing, data stewardship) for remotely-sensed observations in support of climate monitoring and prediction are not equivalent to those for NWP. Although many of the satellite agencies have taken on or support the mandate to understand climate variability and change, most have not yet marshaled the resources necessary to produce and maintain climate quality data records from remotely-sensed platforms. Moreover, the synthesis and integration of remotely-sensed observations together with in situ observations is only now beginning for the climate problem.

Challenges for the Future.

For the most part, the vast majority of climate observations in the Atlantic sector are for general climate monitoring or are deployed to support specific process studies. In this regard there is no Climate Observing System for the Atlantic Sector per se. Rather the "observing system" we have is really an amalgam of various, yet complementary, observational platforms serving a variety of needs and purposes. Nonetheless, climate observations in the Atlantic sector are among the most extensive across the world's oceans. The absence of any routine or operational climate prediction for the Atlantic sector has also meant that climate prediction has not been a major driver to the design and deployment of climate observations in the region. Except for a few examples, observing system simulation experiments for the Atlantic have been minimal at best. This stands in stark contrast to the Pacific where sustained climate observations have been predicated on the needs of seasonal to interannual climate forecasts based on ENSO. As part of GODAE, ocean data assimilation efforts have begun in the Atlantic basin, but the emphasis here is on ocean state estimation and nowcasting, not climate prediction. CLIVAR is just beginning its ocean climate synthesis and integration via the newly formed Global Synthesis and Observations Panel. A major challenge for the future is the prospect for prediction in the Atlantic sector. As CLIVAR efforts within the Atlantic Panel, VAMOS, and VACS establish the level of prediction skill within the region, it is reasonable to expect this will lead to specific observational requirements. Some of the observational requirements are likely to be met by the existing suite of observations, others may be satisfied in the near term by process oriented or field experiments, and others may call for totally new observations required in direct support of advancing forecast skill. At the present time this interplay between the observation and prediction communities is in its formative stages for the Atlantic.

Coupled prediction systems for Atlantic Sector climate

T. Stockdale and M. Balmaseda, ECMWF, Shinfield Park, Reading, UK
Corresponding email: T.Stockdale@ecmwf.int

Introduction

On a global scale, it is the ENSO related SST variability in the Pacific which is the biggest single driver of seasonally averaged climate anomalies. In comparison to ENSO, Atlantic Sea Surface Temperature (SST) variability is typically weaker, and is often given little attention in 'global' seasonal forecast systems. Yet Atlantic SST variability is by no means negligible, and can have a substantial impact on the atmosphere and on seasonal weather patterns. In this summary (as in the full paper) we focus on our present capabilities to predict tropical Atlantic SST anomalies on seasonal timescales, and the implications this has for seasonal prediction of climate anomalies in the Atlantic sector.

There are relatively few coupled models that have been used to investigate seasonal prediction skill in the Atlantic sector, and many operational seasonal forecast systems still use empirical methods to specify Atlantic SST. As will be clear by the end of this paper, such a strategy is not unreasonable at the present time, given the challenges involved in trying to get coupled model forecasting systems to work. Some global coupled model forecasting systems do exist, for example those at ECMWF and the UK Met Office and the NASA Seasonal to Interannual Prediction Project (NSIPP). An especially useful set of integrations for looking at Atlantic prediction skill are those from the EU-funded DEMETER project, which has run seasonal forecasts with a set of 7 different global coupled models, for a period covering more than 40 years in some cases (Palmer et al, 2004). This gives a fairly rich dataset for investigating Atlantic predictability, and particularly in understanding the model dependence of the results.

The ability of coupled GCMs to simulate the mean climate of the Atlantic sector

The first challenge for a coupled General Circulation Model (GCM) prediction system is to produce a reasonable simulation of the mean state of the Atlantic sector. Past experience has shown that simulating the mean state in the tropical Atlantic is not easy. For example, the STOIC project (Davey et al, 2002) showed that the SST gradient along the equator had the wrong sign in all but one of a set of non-flux corrected coupled GCMs. In forecasting systems that run for only 6 months, the errors typically are not that large, but the DEMETER runs show that today's models still have difficulty in reproducing the seasonal cooling in the eastern equatorial Atlantic in July, and that at this time of year the zonal SST gradients are poorly represented.

Many errors in coupled GCMs can be traced to problems with the atmospheric model. Common problems include wrongly distributed precipitation, inaccurate surface winds in the equatorial oceans, and a lack of low-level stratus over the eastern sub-tropical oceans. Progress is being made on the stratus problem, but the location and magnitude of convection with respect to land seems still to be a challenging problem. The limited size of the Atlantic basin (compared to the Pacific, for example) makes this a particularly vital issue for the Atlantic sector.

The quality of ocean analyses in the Atlantic

The ocean provides the most important part of the initial conditions for making a seasonal forecast. In the Pacific, the observing system for the equatorial ocean is good, and comparing analyses against independent data (eg altimetry in the case of the ECMWF system, which does not use altimeter data in the ocean analysis) shows the ocean analyses to be good. The quality of analyses in the Atlantic is much more problematic. Firstly, if no in-situ ocean data are used and an ocean model is driven with different estimates of the wind field, the resulting estimates of the ocean state can be very different. Secondly, assimilating in-situ data actually *reduces* the agreement between the ocean analyses and (independent) altimetry. Two difficult aspects of the tropical Atlantic are (i) the extreme paucity of the in-situ observing system and (ii) the bigger role of salinity in setting density gradients. We might hope that analyses will be improved in the future, both by the further improvement of assimilation techniques and ocean models, and by enhancement of the observing system. At present, however, the level of uncertainty in the ocean initial conditions is comparable to the size of the interannual signal.

The skill of coupled GCM forecasts for the tropical Atlantic sector

Analysis of the DEMETER runs teaches us many things about SST predictability and prediction in the Atlantic. The impact of sub-surface perturbations on the ensemble spread of SST forecasts shows that the sub-surface (*i.e.* the ocean state below the mixed layer) has only a weak impact on SST forecasts in the Atlantic - very unlike the situation in the Pacific. SST predictability (in an anomaly correlation sense) is also much lower than in the Pacific. However, the impact of the ocean sub-surface on equatorial SST is largest at the height of the upwelling season (JJA), the time at which forecast errors are also largest. Since we believe that the coupled models systematically underestimate the climatological upwelling at this time of year, it is likely that the ocean sub-surface is more important in reality than our model results indicate. How much more important is difficult to say.

We can also compare predictability estimates with the actual forecast skill. In the northern part of the Tropical Atlantic the forecasts compare relatively well with the estimated predictability limit, and in particular seem to do a reasonable job in picking up 'remotely driven' SST variability. In the equatorial and southern Tropical Atlantic, performance is not so good, and errors are substantially worse than the predictability limit. Plots of actual forecasts show that although some anomalous episodes are predicted (notably in 1997/98), others are missed, and variability is underestimated.

The behaviour of multi-model ensembles in the equatorial and southern Tropical Atlantic shows that, unlike the Pacific, the forecast errors from the different models are quite correlated. Unless our estimates of predictability are badly wrong, this cannot be explained by lack of predictability in the observations, but must be due either to common errors in the initial conditions, and/or common errors in the forecast models. Since we have good reasons for not trusting either the analyses or the coupled models in this part of the ocean, and since we also know rather little about the ultimate causes of SST variability in this region, it is difficult at present to know where our biggest problems lie, and what predictive skill might ultimately be obtained with a good observing system and good models.

Conclusions

Our abilities to predict the future evolution of tropical SST anomalies in the Atlantic Ocean seem to be still rather limited. In the northern Tropical Atlantic, the main issue seems to be the fundamental predictability limit: our model forecasts are not too bad when measured against this. For the equatorial and southern Tropical Atlantic, there seem to be other problems as well. There are a number of reasons behind our overall performance:

1. The potentially predictable signal is relatively small. Stochastically forced damped persistence, with a bit of remote forcing from the Pacific, is not a bad approximation to what happens in much of the Atlantic, at least on seasonal timescales. There are other signals present, but they are modest.

2. Partly because the signals are not large, past observing systems give a rather inadequate basis for initialising and sometimes even verifying model forecasts.

3. The latest wind-forced ocean model runs capture a moderate amount of the altimeter-estimated sea-level variability over the last decade, but assimilation of data to produce consistent ocean analyses remains difficult. Treatment of salinity and appropriate multivariate constraints remain important issues.

4. Coupled models have significant errors. In the Pacific, model error can be shown to be the dominant cause of forecast error. In the Atlantic this is harder to be sure of, because the initial conditions are also relatively poor, but results suggest that model error is playing an important role in degrading the forecasts.

5. When it comes to predicting atmospheric response, whether forced from within the Atlantic sector or remotely, the limitations of the models are important.

So how can we take things forward? Several points seem worth making on this topic:

1. The observing system has recently improved, both in terms of in-situ data and data available to create forcing fields. Testing of our models and their forecast abilities might benefit from detailed work in this (very short) recent period. Note that the adequacy of today's observing system has not yet been established.

2. Serious work is needed on assimilation schemes to reconstruct the tropical Atlantic ocean state from limited data, in order to have reasonable estimates for some historical period.

3. Improved models are needed to improve both our forecasts and our understanding of the predictability of the system.

4. Over the last few years, many global coupled GCM forecasting experiments have been run, but little attention has been given to the tropical Atlantic. More analysis is needed. Note that a lot of model output is available to outside researchers, for example data from the European DEMETER project can be freely downloaded from http://www.ecmwf.int/research/demeter/data/index.html.

5. The possible role of soil moisture, vegetation and aerosol sources in both seasonal and longer timescale variability in the Atlantic sector should be investigated.

6. Although the tropical Atlantic is not a globally dominant source of seasonal predictability, it is important to acknowledge that the Atlantic does have an impact and is inadequately treated at present. Until the Atlantic is better handled, our forecasting capabilities are incomplete, and thus we need to commit the resources and the effort to improve the situation.

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Seasonal-to-Decadal Predictability and Prediction of West African Climate

M. Neil Ward[1], Kerry Cook[2], Arona Diedhiou[3], Bernard Fontaine[4], Alessandra Giannini[1], Andre Kamga[5], Peter J. Lamb[6], A. Ben Mohamed[7], Abdallah Nassor[5], Chris Thorncroft[8]
[1]International Research Institute for Climate Prediction, Columbia University, Palisades, USA, [2]Cornell University, Ithaca, USA, [3]Laboratoire d'Étude des Transferts en Hydrologie et Environnement, IRD, Grenoble, France, [4]Centre de Recherches de Climatologie, Dijon, France, [5]African Centre of Meteorological Applications for Development, Niamey, Niger, [6]Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, USA, [7]Université de Niamey, Niger, [8]University at Albany, SUNY, Albany, USA

Introduction

Some of the first studies of tropical Atlantic variability were driven by an interest in climate variations over West Africa. This review article focuses on the teleconnections between ocean-atmosphere features and the West African monsoon. These teleconnections are particularly relevant because they have been shown to lead to a degree of predictability on seasonal timescales. Other factors also will contribute to the way in which the monsoon varies from one year to the next and over decades, including continental land surface characteristics and internal atmospheric processes, so the prediction skill from ocean-atmosphere coupling alone will never be perfect. Some, and conceivably most, of these other aspects of variability may be fundamentally unpredictable. Research into other potential sources of predictability, such as initial land surface conditions, is still emerging and discussion of some of the issues will be included in the concluding section. That final section also touches on predictability at smaller spatial scales and of weather statistics through the season, features which often strongly project on environmental aspects that most matter for society.

The Sahel region, lying along the southern fringe of the Sahara desert, receives almost all its 100-400mm of annual precipitation during April-October, with the peak of the rainy season during June-September. Moving south from the Sahel, annual rainfall totals increase (Fig. 1), but in West Africa, during the Sahel rainy season, conditions to the south are relatively drier toward the Gulf of Guinea coast. Indeed, these regions have a bimodal annual cycle of rainfall, with August usually marking a reduction of rainfall in the annual cycle, defining a "Little Dry Season" at the time when the heaviest rains associated with the Inter-Tropical Front (ITF) are usually at their most northerly location. The July-September rainfall in this southern region (here referred to as the Guinea Coast Region) is climatically interesting because, in some years, the ITF remains active further south than normal and rainfall is substantial in this region too, often at the expense of rainfall in the Sahel. The transition seasons of March-June and October-December are of interest in both the Sahel and the regions to the south. In the Sahel, they include the characteristics of the onset and recession of the rainy season. To the south across the Guinea Coast region and Central Africa, they form the two main rainy seasons. The Sahel dry season is also included in this review as there is increasing interest in interannual and decadal climate variability at this time of year as well as, in particular, the variations in atmospheric dust.

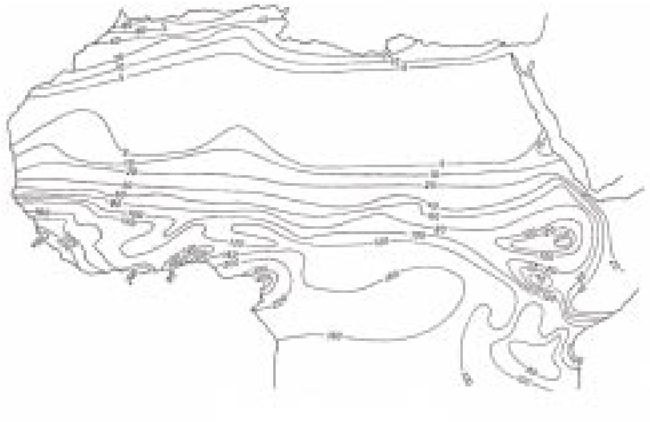


Fig 1.Climatology of Africa (North of the Equator). Mean annual rainfall (cm). (From Nicholson, Mon. Wea. Rev., 1980, Vol. 108, 473-487)

This review builds upon an earlier one with an ocean-atmosphere focus (Lamb and Peppler 1991) and complements a more recent one with a more land-atmosphere perspective (Nicholson 2000). Due to space limitations, readers are referred to the full article (International CLIVAR Project Office, 2004) for other references and to the West African monsoon experiment known as the African Monsoon Multidisciplinary Analysis (AMMA) at http://medias.obs-mip.fr/amma/english/doc/livre_blanc.html

Ocean-Atmosphere Variations and West African climate

A series of papers during the 1970s and 1980s used the newly available historical datasets of near-surface oceanic and atmospheric climate variables in combination with continental rainfall records. They identified relationships between West Sahel rainfall, tropical Atlantic sea-surface temperatures (SSTs), and tropical Atlantic near-surface atmospheric circulation. Wetter years appeared to be associated with a warmer tropical North Atlantic, cooler tropical South Atlantic and an associated northward displacement of the Inter-tropical Convergence Zone (ITCZ) over the tropical Atlantic. Drought years essentially exhibited opposite characteristics. Further research established that wetter years in the Sahel were associated with warmer SSTs throughout much of the

continued on page19

From Latif et al (page 6) The Physical Basis for Prediction of Atlantic Sector Climate on Decadal Timescales

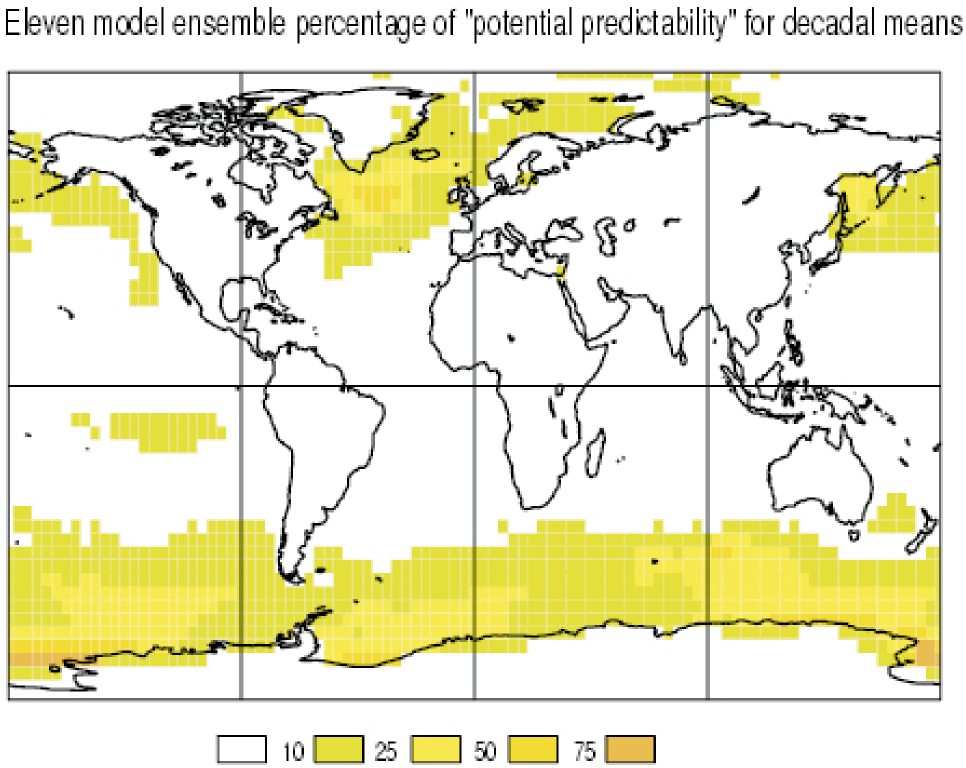


Figure 1: Map of potential decadal predictability as derived from extended-range control integrations with coupled ocean-atmosphere general circulation models. From Boer, 2001

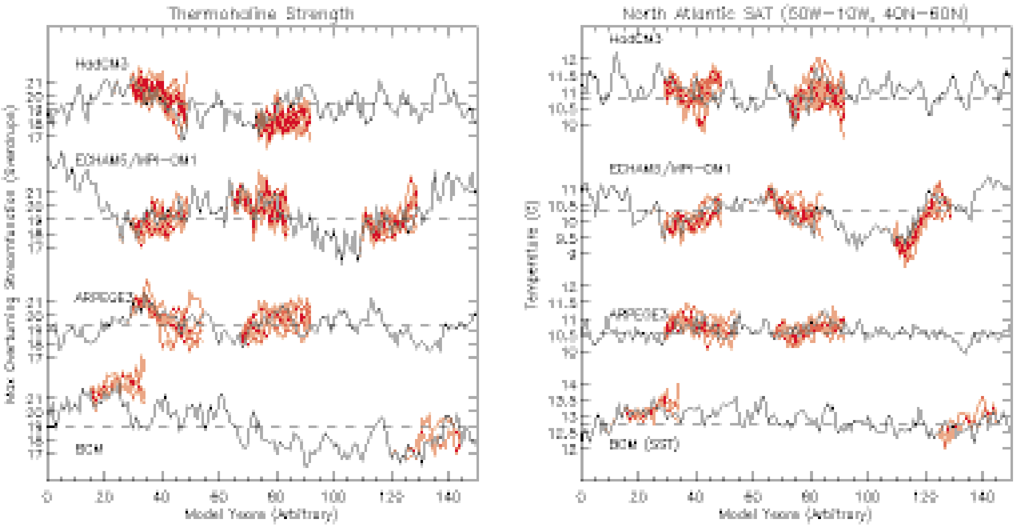
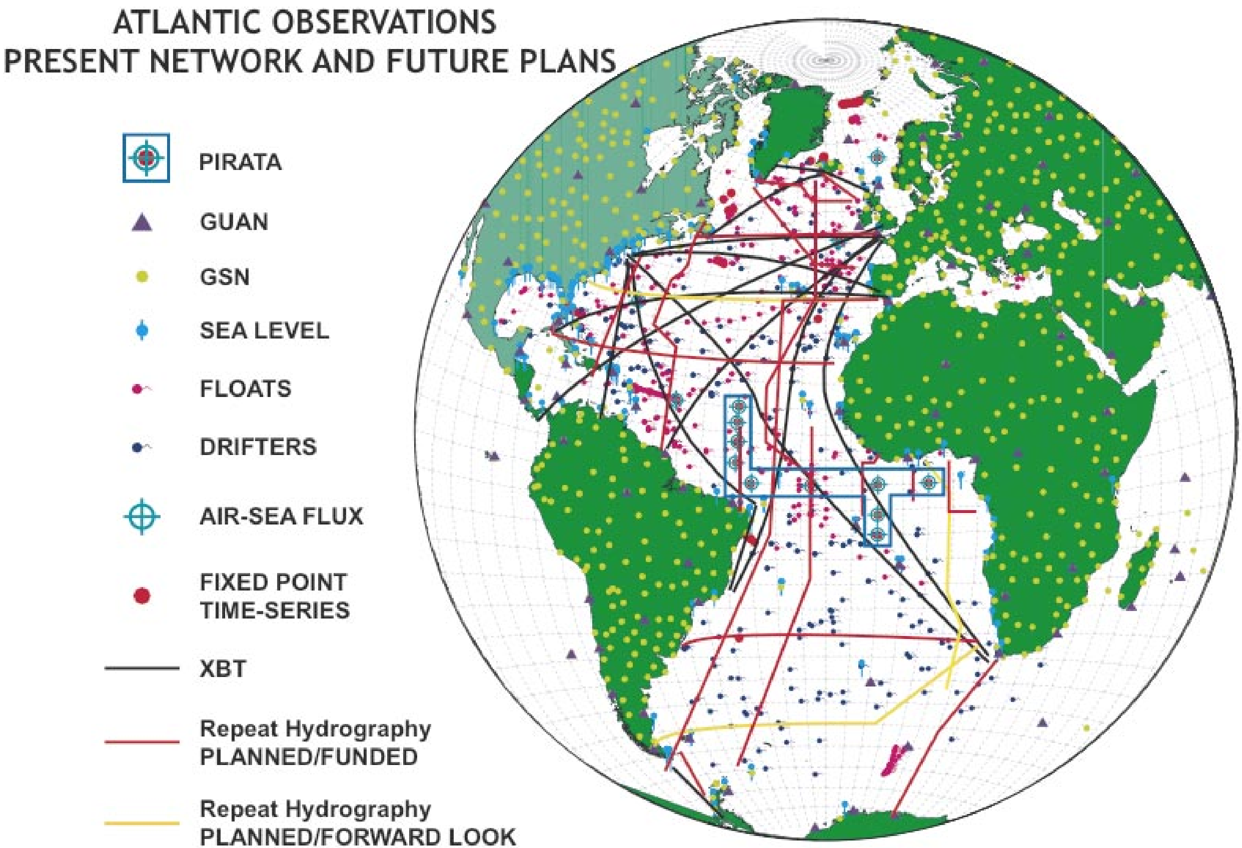


Figure 2: Classical predictability experiments with different European coupled ocean-atmosphere GCMs. Left: Prediction of thermohaline strength. Right: Prediction of North Atlantic SST. Only the atmospheric initial conditions were perturbed in these experiments. From Sutton et al. 2003

From Busalachi et al (page 8) Climate Observing System for the Altantic Sector



Courtesy of R. Boscolo, ICPO

From Rodwell et al (page 28) Predictability and prediction of European climate

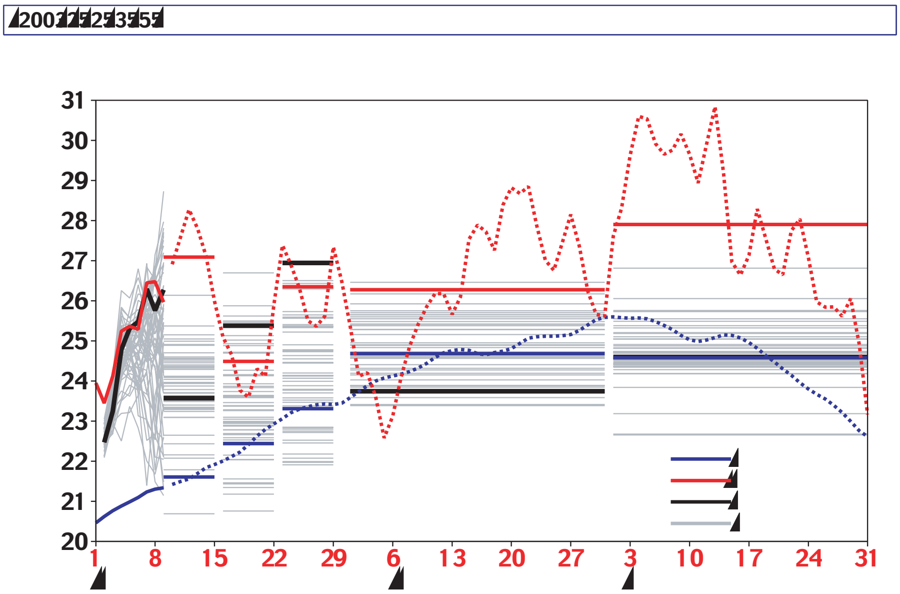
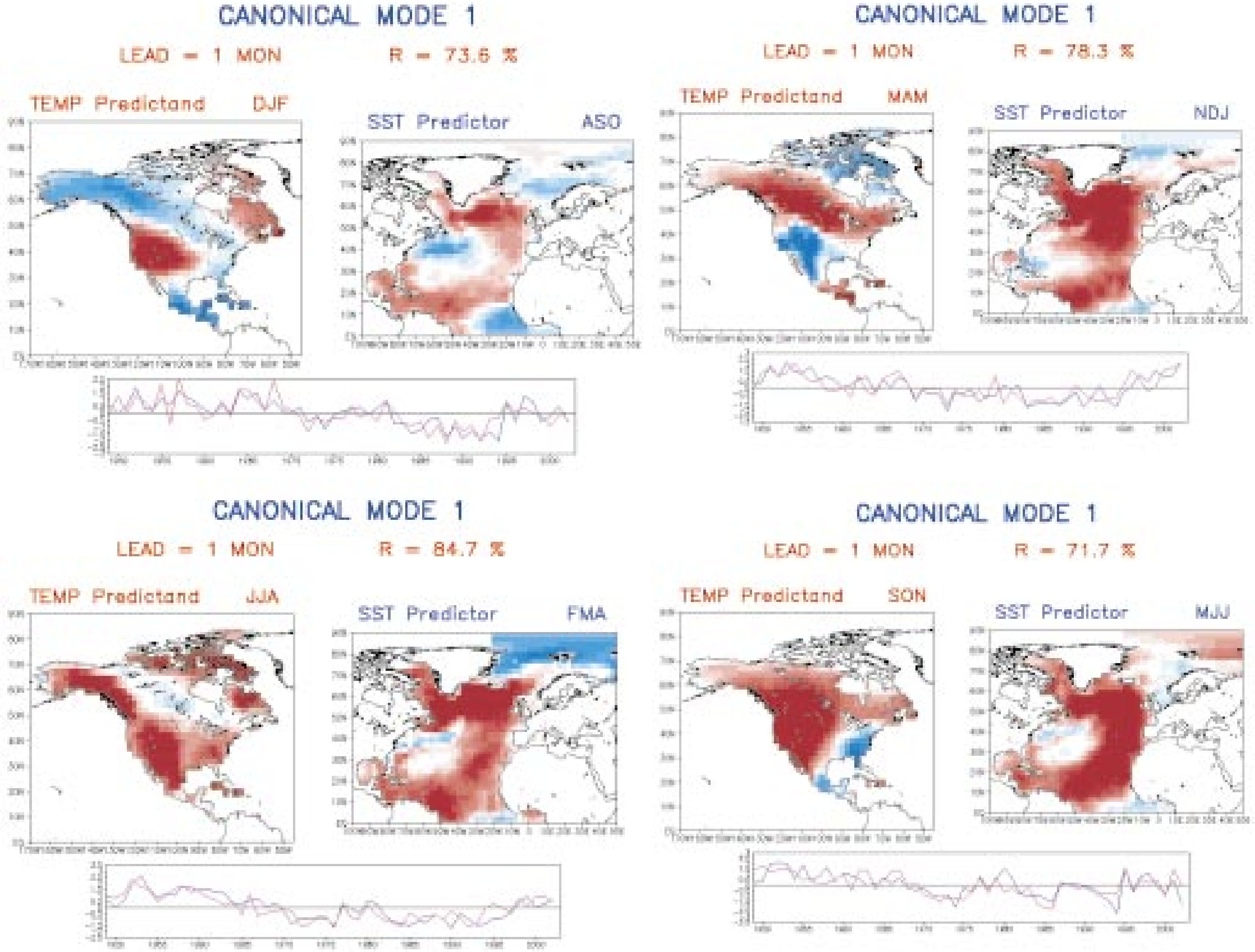


Fig. 1: Observations (red) and forecasts (black and grey) made by ECMWF at the beginning of June of European 2m land temperatures in the box[5oW-25oE, 35-55oN] (oC). Also shown (blue) are the climatological mean values based on ERA40 (1962-2001). Horizontal lines show weekly and monthly-mean values. For the period 2-9 June the control forecast (black) is made at a resolution of T511 and the ensemble forecasts (grey) are made at a resolution of T255. The weekly-mean forecasts 9-15 June, 16-22 June and 23-29 June are based on T159 forecasts started on 4 June (black signifies the first member of the ensemble). The monthly-mean forecasts for July and August are based on T95 forecasts initiated on 1 June.

From van den Dool et al (page 23) Seasonal-to-Decadal Predictability and Prediction of North American Climate - The Atlantic Influence



From Nobre et al (page 25) Season-to-decadal predictability and prediction of South American Climate

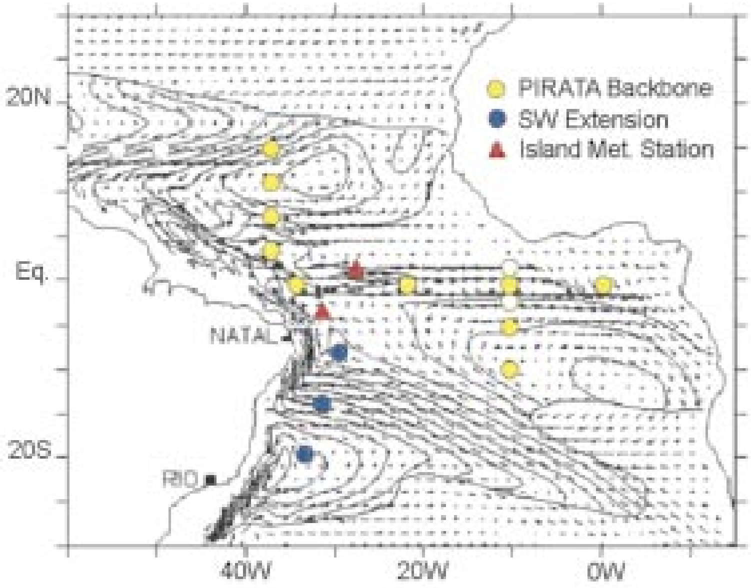
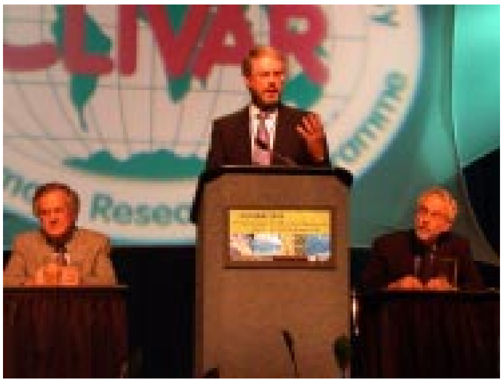


Figure 2 – PIRATA array of moored buoys over the tropical Atlantic (circles: yellow – active; white – inactive; blue – proposed SW Extension) and island meteorological stations (red triangles). Background map showing simulated currents by Lazar et al (2002).

First International CLIVAR Science Conference, June 21st - 25th 2004, Baltimore, U.S.A.

Baltimore's inner harbour was the excellent setting for the 640 delegates

Poster sessions provided time to peruse the 650+ poster and catch up with old friends



Keynote speakers set the framework for formal and informal discussions

The packed auditorium was the setting for the formal sessions

But the event was not all work and no play!

Ideas and plans were discussed in all settings

continued from page 14

Northern Hemisphere and cooler SSTs throughout much of the Southern Hemisphere, including the whole Indian Ocean. The potential influence of these large-scale SST anomalies on West African rainfall was confirmed in General Circulation Model (GCM) experiments forced with prescribed SST anomalies throughout the globe and/or in individual ocean basins. It has nonetheless emerged that while some GCMs capture the variability of the West African monsoon very well and are excellent tools for its study and potential prediction, many other GCMs have a very poor representation of this aspect of the climate system.

One problem posed to the diagnostic analyses is the strong multi-decadal variability that exists in time series of the West African monsoon (Fig. 2). Thus, it has proved useful to study the decadal and interannual variability separately. At the sub-decadal timescale for the West African monsoon, two key controls on July-September rainfall that have emerged are ENSO (in which covarying Indian Ocean SSTs likely play an active forcing role) and the Equatorial Atlantic SST mode, supplemented with additional components of tropical Atlantic variation, including the tropical North Atlantic. The warm phase of the Equatorial/tropical South Atlantic SST is associated with reduced rainfall in the Sahel and enhanced rainfall over a region south of about 10°N. The warm phase of ENSO is associated with reduced precipitation in the Sahel, with no clear tendency of rainfall anomalies south of about 10°N, at least for the July-September season that is under consideration here. Statistically, the influence of ENSO has been stronger during the drought epoch, whereas the tropical Atlantic influence has been stronger during the wetter Sahel epoch. While mechanisms to explain this have been proposed, due caution is needed as such variability can also be attributed to sampling variations given the magnitude of the correlations and small sample size. At zero lag, the ENSO and Equatorial Atlantic mode appear to have little linear correlation in boreal summer, though possible interactions with lags between the two ocean basins may play a role in determining the West African monsoon variability. Also critical is how forcing from the tropical Pacific and tropical Atlantic interact over West Africa.

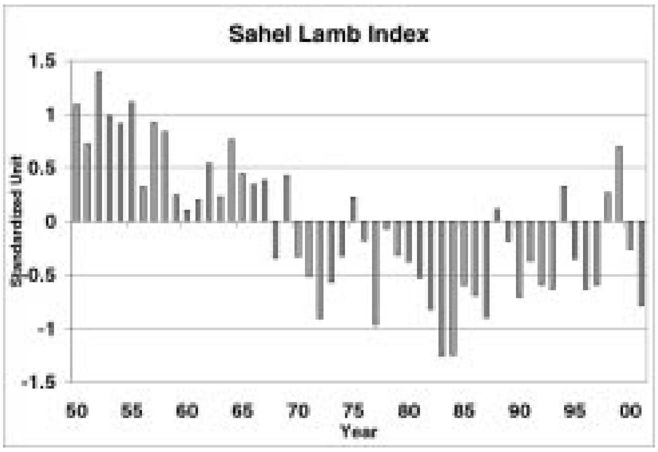


Fig. 2. Index of April-October Sahel rainfall, 1950-2002. Rainfall indices are found to be consistent and reliable records of climate variations in the region, provided sound analysis procedures are applied to the rainfall stations. (Lamb, personal communication)

At multi-decadal timescales, teleconnections are found between Sahel drought epochs and anomalies in the interhemispheric SST gradient, both within the Atlantic and more globally, especially involving the Indian Ocean. The atmospheric circulation anomalies are large scale, connecting the South Atlantic and West Africa with other regional circulation systems in the Indian and Pacific Oceans. Some of these large-scale decadal atmospheric features resemble those associated at the interannual timescale with ENSO. In contrast, the circulation anomalies associated with the Equatorial/tropical South Atlantic SST anomalies (see above) appear more local from the Atlantic into West Africa, driving the dipole of rainfall anomalies across the Sahel and Guinea Coast regions.

In addition to the West Africa monsoon, more work is also now emerging for the other seasons in West and Central Africa. Predictability has been demonstrated for the October-December season, especially in western parts of Central Africa. For the variability of dry season dustiness in West Africa, demonstrations have been made that it too is part of large-scale teleconnection modes reaching into tropical ocean-atmosphere variability as well as into mid-latitude variability related to the North Atlantic Oscillation. Deducing causality is complex, as the needed research is led into the fully coupled nature of ocean-atmosphere-land system.

Seasonal Prediction

The early work on Atlantic and global SST relationships with West African rainfall was translated into experimental seasonal forecast methods for the July-September season using both statistical and dynamical approaches. Early work with a UK Met Office GCM suggested substantial sensitivity to persisting SSTs even a couple of months ahead. This sensitivity is emerging in studies with other GCMs as well. Linear statistical methods with observed SST predictors are less sensitive to SST changes, and provide moderate skill from April and May SSTs, though SST prediction is still a key issue to enhance skill and lead-time. National Meteorological and Hydrological Services (NMHSs) have been using such statistical models, included as part of the West Africa Climate Outlook Forum (PRESAO), which, through a consortium of partners bringing statistical and dynamical forecast methods, has produced seasonal rainfall outlooks for the region for the July-September season each year since 1998. An addition that requires consideration is stimulated by the proposed importance of meridional moist static energy gradients for the West

African monsoon. In addition to SST, this gradient is modified by land surface conditions in West Africa. The potential of initial land surface conditions to add to predictability is considered again in the concluding section, and evidence is likely to be clearer through the enhanced observations planned (especially 2005-2007) for the aforementioned AMMA experiment and associated research. Since 2002, a similar approach to PRESAO has been initiated to anticipate the October-December rainfall for the Guinea Coast region and Central Africa (PRESAC), based on tropical Atlantic and other SST indices.

Conclusions and Future Directions

When evaluating the boreal summer West African teleconnections for the period of historical observations, it is important to appreciate that the links with SST anomalies appear to account for up to about 50% of the total large-scale seasonal rainfall anomaly variance, and less than that once the decadal rainfall variance is removed. Thus, there is a large fraction of the rainfall variability that so far is unaccounted for by large-scale linkages with the ocean-atmosphere system. In addition, there is a need to assess teleconnections with finer spatial resolution in the rainfall fields and how the large-scale predictability is expressed in terms of changes in extreme weather events, rainfall disturbances and dry spells within the season. For this, better understanding of the interannual variability of synoptic disturbances in the region will be needed, including through the application of high resolution regional modeling. The predictability of some features important to society, such as crop production and water resource availability, also will benefit from intensification of work on the relation of high resolution spatial variations and weather statistics to the now well-established large-scale predictability. Advancing lead-time for seasonal predictions through better representation and anticipation of ocean-atmosphere coupled evolution through boreal Spring is also a key area for active research, and great improvement is still needed in fully coupled ocean-atmosphere models. Finally, improving understanding of the transition from the dry season to rainfall onset in the Sahel, which has started to be addressed by a number of recent studies, brings the potential for information that could greatly assist in crop planting, though relating likely rainfall onset dates to SST forcing has so far proved difficult.

There are also a number of themes for ongoing research into land surface interaction (Nicholson 2000). For predictability, a key question concerns the extent to which initial land surface conditions have a role. Studies are hampered by uncertainties in long historical records of land surface properties. However, land surface conditions especially to the south of the Sahel may conceivably have a role. For understanding decadal scale variability, the land surface has long been posed as a possible initiator of variability, as well as a possible contributor through feedback. Recent modeling studies have supported the role of the land surface as an amplifier of variability in the region. The land-surface also can potentially play a role in amplifying the chaotic (unpredictable) component of seasonal variability. Strong evidence already has been presented that land-atmosphere feedbacks can act to amplify local rainfall anomalies through a season. Wherever the land surface is seen to have a role in contributing to the large-scale circulation variability, then that land surface influence can be expected to extend beyond the West African continent itself, and affect ocean-atmosphere interactions in the surrounding oceans. Such influence may be through the long-proposed land-atmosphere interaction mechanisms modifying circulation, or through the increasing awareness of the magnitude of dust that enters the Sahelian atmosphere and can influence atmospheric characteristics both over the continent and, through export of the dust, into the surrounding tropical Atlantic region and beyond. Many of the issues for further investigation mentioned in this section will benefit from the intensification of observations and research expected through the AMMA. The intensification of observations of the land-ocean-atmosphere system and associated research can also be expected to provide opportunity to better understand the reasons for the inability of many GCMs to capture the variability of the West African monsoon, and to advance prediction efforts on the seasonal to decadal timescales. These insights, combined with the application of high resolution GCMs and/or regional climate models, offer the prospect for some enhancement of skill levels and lead-time for seasonal predictions in the region. While the scientific basis for the enhancements will be rooted in physical process, empirical diagnostic, and modeling studies, advances may well be incorporated in statistical forecast methods as well, so that the resulting forecast systems continue to be a mix of numerical models and statistical methods rooted in the understanding of the climate system.

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Seasonal to decadal predictability and prediction of southern African climate

C.J.C. Reason[1], W. Landman[3], M. Tadross[2], W. Tennant[3], M–J. Kgatuke[3]
[1]Oceanography Dept. University of Cape Town
[2]EGS Department, University of Cape Town
[3]South African Weather Service, Pretoria, South Africa
Corresponding author: cjr@egs.uct.ac.za

1. Introduction

Southern Africa is prone to pronounced flood and drought events and significant climate variability on a range of time scales. Some of this variability is thought to be forced remotely via ENSO (e.g., Nicholson and Entekhabi, 1986; Lindesay *et al.*, 1988; Reason *et al.*, 2000) while some is related to variability in the neighbouring Indian and Atlantic Oceans (e.g., Hirst and Hastenrath, 1983; Mason, 1995; Reason and Mulenga, 1999; Behera and Yamagata, 2001; Rouault *et al.*, 2003) or to local land surface processes. It should be stated at the outset that climate variability over southern Africa is complex with a multitude of forcing factors that interact with each other and wax and wane in their importance through the record (Richard *et al.*, 2000; Allan *et al.*, 2003).

The potential influence of the Atlantic on southern African climate is mainly related to the variability in the Inter-tropical Convergence Zone (ITCZ) over the region, the South Atlantic anticyclone and, to lesser extent, the midlatitude westerlies. Compared to the eastern side of Africa and the neighbouring Indian Ocean, the annual cycle in ITCZ location over the Atlantic and neighbouring western Africa is far less pronounced. The southwestern Cape (SWC) region of South Africa is a mainly austral winter rainfall region, the south coast an all season rain region, whereas rainfall over most of the rest of subtropical southern Africa occurs mainly in the summer and is generated largely from convective thunderstorms, driven for the most part by tropical-extratropical interaction and associated cloudbands. Over tropical southern Africa, the main rainy seasons shift towards bimodal in the east and late summer/autumn in the west. The Atlantic seaboard of southern Africa and the neighbouring hinterland contains the Namib, western Karoo and Kalahari deserts.

2. Interannual variability

ENSO is the dominant mode of interannual variability over the tropical Southern Hemisphere whereas the Antarctic Oscillation or Southern Annular Mode (SAM) is the leading mode in the mid- to high latitude atmospheric circulation. Trends towards high-index polarity in the SAM have been noted (Thompson et al., 2000), but the effects of such trends on southern African climate are unclear. ENSO is known to project strongly over southern Africa and the South Atlantic (e.g., Lindesay *et al.*, 1988; Reason *et al.*, 2000) and has significant rainfall impacts, particularly during the mature phase. Anomalously wet winters in the SWC region of South Africa have been linked to the SAM (Reason *et al.*, 2002). In addition, the tropical Atlantic develops both its own zonal SST variability on interannual timescales, the so-called Atlantic ENSO (Houghton, 1991; Zebiak, 1993). The relationship between this mode and the so-called Benguela Niños (Shannon *et al.*, 1986), which are known to impact on Namibian / Angolan rainfall (Rouault *et al.*, 2003), remains to be properly investigated. In general, SST variability in the South Indian Ocean is generally believed to exert more influence over southern Africa than that over the South Atlantic (e.g., Nicholson and Entekhabi, 1986; Mason and Jury, 1997). However, it is also true to say that the climate impacts of the Atlantic on southern Africa are less well understood and that Southern African climate variability is sensitive to a range of factors, posing great challenges for predictability.

3: Regional forecasting efforts using GCMs and statistical methods

Most centres in the region use statistical relationships between SST and rainfall to produce seasonal forecasts. The South African Weather Service (SAWS) uses output from various GCMs (three of which are run at local institutions) and from IRI to produce a consensus seasonal forecast every month. Because of the tight forcing gradients in the region and local complexities, it has been found necessary to downscale or recalibrate GCM output to the regional level, either using a regional climate model (RegCM3 or MM5) or statistical techniques (empirical remapping of GCM fields to regional rainfall has been shown successfully over southern Africa (Landman and Goddard (2002)).

An empirical downscaling method that is currently being used operationally by the South African Weather Service uses a combination of model output statistics (MOS) and perfect prognosis (Wilks 1995). MOS equations are developed using 24-member ensemble ECHAM4.5 GCM simulation rainfall data and then 24-member ensemble rainfall real-time forecasts fields at different lead-times from the same GCM are subsequently used in these MOS equations to predict rainfall for 1028 stations. It is therefore assumed that the skill with which the GCM can produce forecast at lead-times is as good as skill obtained from simulation data, reminiscent of the assumption of a perfect prognosis approach where "perfect" forecasts are assumed.

Seasonal forecast maps produced by SAWS are widely disseminated in the media and used by farmers, water resource managers and other users. Given the arid to semi-arid climate, better forecasting of streamflow and dam levels is a high priority. Research at the SAWS indicates that it is possible to obtain some skill in forecasting streamflow at the inlets of major dams (Fig. 1) by statistically downscaling GCM-simulated fields (ECHAM3.6). The correlation values between the ensemble mean MOS from this GCM and the observed streamflows vary between 0.54 and 0.65. A high association is found between the observed streamflow and the observed rainfall of the region that contains the catchments of the dams. The high association is a manifestation of the effect rainfall has on the streamflow at the inlets of these dams, and indicates that the MOS for the rainfall prediction skill is a reasonable choice as predictor for streamflow also. Streamflow forecast skill should improve further if other non-atmospheric variables were allowed to participate in the recalibration process. SAWS plan to start operational streamflow forecasts in time for the 2004/5 summer rainfall season.

4. Summary

Significant progress has been made in the region towards seasonal forecasting based on dynamical methods. Dynamical models have also been used to better understand the processes underpinning southern African variability. Of major concern within the region is the severe decline in atmospheric observations, both of surface parameters such as rainfall, and soundings – this decline impacts on testing the ability of models to represent the regional climate and its variability as well as on developing new prediction techniques. Future efforts at realising the potential of forecasting in the region ultimately rely on improvement in the current observing system over both Africa itself and the neighbouring oceans where large gaps exist in current monitoring efforts (surface drifters, Argo floats and the PIRATA moored array in the equatorial region). The recent South Atlantic Climate Observing System (SACOS) workshop concluded that better monitoring of air/sea fluxes, SST and upper ocean variability in the subtropics and midlatitudes are needed in order to progress towards better understanding of South Atlantic modes and assessment of their predictability.

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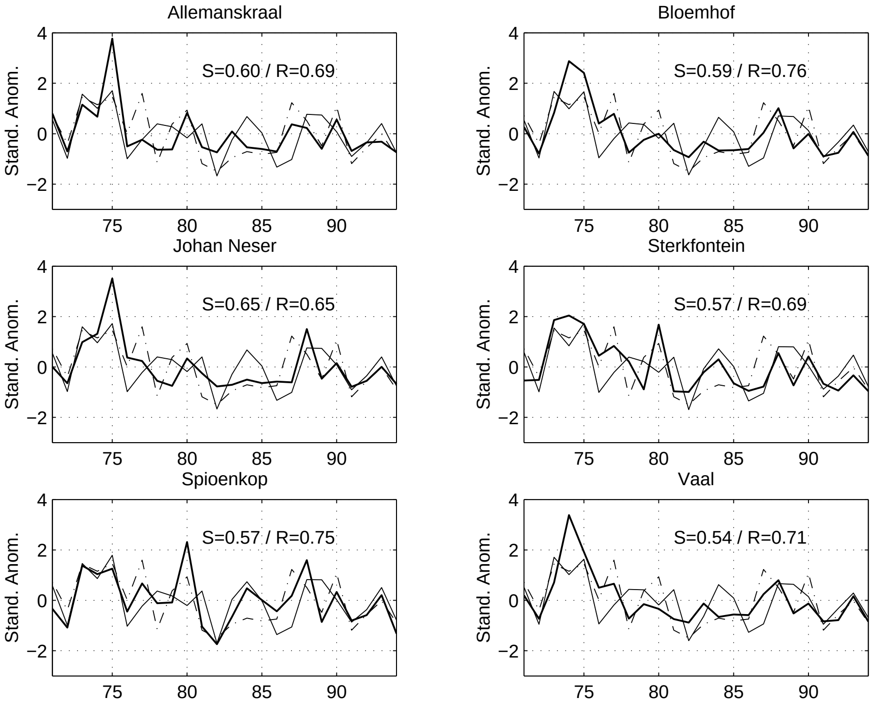

Figure 1. Cross-validated MOS normalized DJF streamflow anomalies (thin line) versus the observed DJF normalized streamflow anomalies (thick line) for each of six dams of the Vaal and upper Tugela river catchments of South Africa. Normalized DJF rainfall anomalies (dashed-dotted line) of the northeastern interior are also shown. The correlations between the predicted and observed streamflow anomalies (S) and the observed streamflow and rainfall anomalies (R) are shown in the top right of each dam.

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Seasonal–to–Decadal Predictability and Prediction of North American Climate – The Atlantic Influence

Huug van den Dool[1], Peitao Peng[1], Åke Johansson[2], Muthuvel Chelliah[1] and Amir Shabbar[3], and Suranjana Saha[4] .
[1]Climate Prediction Center, Washington DC, USA
[2]Swedish Meteorological and Hydrological Institute, Norrköping, Sweden
[3]Meteorological Service of Canada, Downsview, Ont. Canada,
[4]Environmental Modeling Center, Washinton DC, USA
Corresponding author: huug.vandendool@noaa.gov

Introduction and summary

The central theme throughout this white paper is that of the Atlantic as a possible source of predictability or even actual seasonal prediction skill for North America (NA). We take this rather restricted point of view and stay away for the most part from other predictor areas, such as Pacific ENSO (El Niño-Southern Oscillation), even though ENSO could influence the Atlantic and may have delayed indirect effects on NA if the Atlantic, in turn, influences NA. In a non-linear environment it may be a challenge to isolate the influence of a single factor like the Atlantic (or any other ocean, or other predictors), without considering all at once. But such is our task. Basic material was collected from the literature (Van den Dool et al, 2004) and a review of seasonal forecast procedures in Canada and the US is given in Van den Dool 2004. Some fresh calculations, reproduced here, were made using the NCEP/NCAR Reanalysis data.

The general impression is one of low predictability (due to the Atlantic) for seasonal mean surface temperature and precipitation over NA. Predictability may be slightly better in the Carribean and 'intra-America', even for precipitation (Enfield and Alfaro 1999). The NAO is widely seen as an agent making the Atlantic influence felt in NA. While the NAO is well established in most months, and has a large simultaneous impact over NA (Higgins et al 2000; Shabbar and Bonsal 2004) its prediction skill is not much better than that of 'weather' (Rodwell 2003). We also found year-round evidence for an equatorially displaced version of the NAO (named ED_NAO) carrying a good fraction of the variance.

In general the predictability from the Pacific is thought to dominate over that from the Atlantic sector, which explains the minimal number of reported AMIP runs that explore Atlantic-only impacts. Caveats are noted as to the question of the influence of a single predictor in a non-linear environment with many predictors. Skill of a new 1-tier Coupled Model System at NCEP has been reviewed (Saha et al 2003); we find limited skill in mid-latitudes and modest predictability to look forward to.

There are several signs of enthusiasm about using 'trends' (low frequency variations): a) Seasonal forecast tools for NA include persistence of the last ten years' averaged anomaly (relative to the official 30-yr climatology), the so-called OCN (Huang et al 1996), b) Hurricane forecasts (high skill!) are based largely on recognizing a global multi-decadal mode (Bell and Chelliah 2004; Chellaih and Bell 2004) which is similar to an Atlantic trend mode in SST (Kushnir 1994 and Enfield et al 2001) and c) two recent papers, one empirical (McGabe et al 2004) and one modeling (Schubert et al 2004), giving equal roles to (North) Pacific and Atlantic in 'explaining' variations in drought frequency over NA on a 20 year + time scale.

We refer to the full white paper (Van den Dool et al, 2004) for most topics we considered. Here we only present a few new calculations in detail.

New calculations

We present some new calculations regarding the influence of the Atlantic on NA. (This was done because while the existing literature is vast, it does not sufficiently focus on the question of the impact of the Atlantic on upstream NA.) The areal extent of the domains are as follows: a) Atlantic SST: all ocean points north of the equator, between longitudes 100W and 60E, with the exclusion of Pacific points between 100W - 75W, and Eq to 20N, b) Atlantic + NA Atmosphere: all gridpoints north of equator between longitudes 130W and 60E and c) NA surface: all land points north of 10N between 170W and 45W, with the exclusion of Hawaii and Greenland. We keep the Atlantic atmosphere large enough so it could contain the NAO. The data used is the NCEP/NCAR Reanalysis 1948-2003 (Kistler et al 2001). An EOF type analysis does not address cause and effect, only simultaneous relationships. We here move to time lagged relations, which are, at the very least, suggestive of cause and effect. To this end we employ the CCA software used at CPC (Barnston 1994) operationally and elsewhere (Shabbar and Barnston 1996; Johansson et al 1998) for both research and for producing operational forecasts. This particular version of CCA is very close to maximizing the covariance between two data sets via singular vector decomposition (SVD; Bretherton et al 1992; Lau and Nath 1994). The number of predictor/predictand maps is huge (too large for presentation). This is in part because it takes order 5 canonical modes to capture most of the covariance between the predictor and predictand data sets, and because there are 4 predictors seasons in Barnston(1994). Moreover there are several predictors. Hence, in order to simplify matters in this presentation we collapse the four predictor seasons into one and consider only the one month lead time (an example of a 1 month lead forecast: predict DJF T2m over NA from August - September (ASO) SST in the Atlantic). For added realism and honesty, when quoting skill levels of the CCA, a full package of cross-validation was used.

Fig. 1 (page 17), upper left shows the first CCA mode between ASO SST and DJF T2m over NA. Zonal bands of warm Atlantic near 20N and 55N, with cold near 40N in the west Atlantic in ASO appear associated with warmth in the Southwest US and NE Canada, as well as cold in central America and Alaska in the following DJF. The time series (blue for SST; red for T2m) expresses both interannual and interdecadal variations but the latter dominates. The R value in the graph refers to the correlation between the red and blue time series. The SST pattern of mode#1 is not(!) the pattern one gets when the ocean is forced by an atmosphere in pure NAO state, but rather looks like the 'horseshoe' pattern discussed by Czaja and Frankignoul (2002). (Our CCA does produce the standard tri-pole SST and NAO for simultaneous SST and height fields, in agreement with Czaja and Frankignoul(2002)). We will see the horseshoe pattern repeatedly below. Fig.1 shows all 4 seasons, i.e. the first mode for the predictand T2m in target season DJF, MAM, JJA and SON when coupled to the predictor SST in antecedent ASO, NDJ, FMA, MJJ. All seasons show a large amount of trend in the time series, and an association between a warm Atlantic and a warm SW US and NE Canada in all seasons except spring. To first order the SST pattern is independent of season, and so are the time series, with a maximum in the 1950's and a minimum around 1990.

We constructed a figure just like Fig. 1 but now NA seasonal precipitation as the predictand. We are somewhat amazed to find that the 1st mode for predictands T2m (Fig. 1) and precipitation (not shown, but see Van den Dool et al, 2004 their Fig.7) are essentially the same in all 4 seasons. The time series and SST patterns are very similar among T2m and precipitation as predictand. It took some coordination of choices of polarity to bring this out.

The quantitative bottom line is one of modest predictive ability due to Atlantic SST, the anomaly correlation (AC in %) for NA T2m being 15.7, 9.0, 20.4, and 20.6 respectively for DJF, MAM, JJA and SON. Although modest, CCA beats persistence in all seasons except spring (AC values are 8.2, 12.0, 7.9 and 13.1 for persistence).

The number of modes retained is 5 (except for DJF when it is 4). This truncation is based on cross validated skill upon the admission of a new mode. Of the (squared) covariance retained by 4-5 modes it takes 2 modes to explain 80%, but as seen from the AC values this may be no more than 5% of the predictand's variance.

In real time practice the Pacific Ocean is included and skill, not shown, would be much higher in winter and early spring. But even with the Atlantic alone we have some skill (the authors were not disappointed!), especially in summer and fall for T2m.

We redid all calculations with a 10 year time filter applied to create high and low frequency data, i.e. we prepared one version of CCA that used high frequency data (which accounts for 78-87% of the variance in seasonal mean data) and another that used low frequency data (which accounts for the remaining 13-22% of the variance). In both cases however, we verified the cross-validated forecasts against unfiltered data. The high-frequency CCA has certified zero skill!! Rather stunningly we thus did not find any prediction skill due to interannual variations in Atlantic SST. All skill we reported before is due to trends or interdecadal variation. To some degree this is already clear from Fig. 1.

One may wonder whether this skill has anything to do with the Atlantic specifically. It is very possible that 'something' orchestrates low frequency changes in both global SST and climate over land. It is possible that SST is not really the predictor, even though CCA was set up that way. The same applies to McGabe et al(2004) and Schubert et al(2004).

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Seasonal-to-decadal predictability and prediction of South American climate

P. Nobre[1], J. Marengo[1], I. A. F. Cavalcanti[1], G. Obregon[1], V. Barros[2], I. Camilloni[2], N. Campos[3] and A. G. Ferreira[3]
[1]CPTEC/INPE, Brazil, [2]UBA, Argentina, [3]FUNCEME, Brazil,
Corresponding author: pnobre@cptec.inpe.br

Abstract

The basis for seasonal-to-decadal climate predictions and predictability over South America is reviewed. It is shown that global tropical Sea Surface Temperature (SST) affects both predictability and predictions over South America; the lack of SST predictability over the South Atlantic, in particular, represents a stringent limitation to seasonal climate predictions over portions of the continent. Also, it is suggested that current two-tier approaches might represent a major limitation to forecast or even simulate coupled ocean-atmosphere phenomena like the South Atlantic convergence zone. The possible effects of global climate change on regional predictability of seasonal climate are also discussed.

Introduction

South America represents an interesting case concerning seasonal climate variability. The largest fraction of the continent lies within the tropics, where seasonal climate predictability is higher compared to mid latitudes. Of particular interest is the contrast between the highly predictable seasonal rainfall interannual variability over northern Nordeste and the practically nil predictability of seasonal rainfall variations just south of the Nordeste, as realized by atmospheric general circulation models (AGCMs) (Marengo et al., 2003). Such contrast can be explained by the roles of surface conditions on the principal atmospheric phenomena modulating rainfall interannual variability over those regions: the

Intertropical Convergence Zone (ITCZ) and the South Atlantic Convergence Zone (SACZ), respectively.

Discussion:

The ITCZ is modulated in part by surface features, like the interhemispheric gradient of SSTA over the equatorial Atlantic, and it modulates interannual variability of seasonal rainfall over eastern Amazonia and northern Nordeste. The SACZ, on the other hand, is influenced by Sea Surface Temperature Anomalies (SSTA) over the southwestern tropical Atlantic, has a strong impact on the rainfall regime over southern Nordeste, Southeast and Southern Brazil, and contributes to modulate underlying SSTs over the SW tropical Atlantic (Chaves and Nobre, 2004). Differently from the ITCZ, however, the SACZ is observed predominantly over negative SSTA (Robertson and Mechoso, 2000), suggesting that atmospheric-forcing is operative at zero lag.

Chaves and Nobre (2004) used an atmospheric and an oceanic GCM to study the feedback processes linking SST and SACZ variability. Their results suggest that the frequently observed negative SSTA under the SACZ is predominantly an ocean response to the reduction of downward solar radiation due to increased cloudiness during the formation of the SACZ. Their results thussupport the speculation that the poor performance of AGCM simulations and predictions over the SACZ region is the consequence of the lack of coupled interactions between SST and the model atmosphere. Koster et al (2000) focus their analyses on precipitation variance, and they analyze the contributions of ocean, atmosphere, and land processes using a simple linear model. The resulting clean separation of the contributions leads to the conclusion that land and ocean processes have essentially different domains of influence, that is, the amplification of precipitation variance by land–atmosphere feedback is most important for regions such as southeast Brazil and the South American monsoon, while for the tropics (Amazonia and Nordeste) rainfall variance is more affected by ocean surface temperatures. Yet, SSTA predictions over the southern tropical Atlantic one season in advance can barely beat the skill of persistence. Fig. 1 shows the anomaly correlation maps of SSTA forecasts for March-May (MAM) using the persistence of SSTA from December, January, and February and as the result of a Canonical Correlation Analysis (CCA) prediction scheme developed by Repelli and Nobre (2004). The authors show that the higher skill of the CCA predictions over the northern tropical Atlantic is due in part to teleconnections from the equatorial Pacific ENSO.

The southern portion of the continent, encompassing southern Brazil, Uruguay, Paraguay, and northern Argentina also presents some degree of predictability, which nevertheless is hardly realized during the actual exercise of seasonal climate predictions (Berri et al., 2003). The results of observational as well numerical studies indicate, however, that a large fraction of seasonal climate predictability over southern South America is originated from links to the equatorial Pacific ENSO phenomenon. ENSO is also a major player to modulate seasonal rainfall interannual variability over northern South America and the Caribbean.

One limitation of using AGCMs for regional climate predictions is the inability of present day models to resolve sub-grid atmospheric processes of fundamental importance (e.g. clouds and regional scale inhomogeneities of surface fluxes), which are likely to play a role on climate statistics. The use of regional atmospheric models nested in AGCM outputs have suggested that it might be possible to predict higher statistics of the regional climate, like the probability density function (pdf) distribution of daily rainfall over a region. Nobre et al (2001) obtained encouraging results using a regional model nested into an AGCM to predict the daily rainfall pdf and the spatial distribution of consecutive number of days with no rainfall over the Nordeste during the period of February to May 1999. Sun et al (2004) used essentially the same dynamical downscaling technique but over a period of 30 years and demonstrated that the regional model can simulate the interannual variability of daily rainfall pdf over the Nordeste better than the AGCM in which it was nested. These results represent an encouraging indication that the limit of seasonal climate predictability can go beyond seasonal averages, at least in regions with high predictability like the Nordeste.

On larger time scales, from decades to centennial, South America also plays an important role in the climate system. Primarily, due to the supposed hole of the Amazon forest as a carbon dioxide source/sink in today's CO_2-rich atmosphere. Yet, recent global climate change research indicates that the capacity of tropical and temperate forests to grow – and therefore extract carbon dioxide from the atmosphere through photosynthesis – is limited to a certain amount of temperature increase, beyond which the biological systems reach breakdown and start liberating large amounts of CO_2 to the atmosphere (Cox et al., 2001). It is not yet known to what extent seasonal climate predictability will change on regional scales in a scenario of global climate change; whether it will increase (in the case of increased dryness over semi arid regions) or will diminish (e.g., in the case of increased frequency of extreme events on a warmer and more humid atmosphere). In any case, the prospects of regional climate change are robust enough to justify a vigorous scientific undertaking to improve the models and monitor the environment to help society to learn to adapt to a changing climate.

Observations

The Tropical and South Atlantic constitute one notable data-void area of the world oceans. The need to better understand the coupled modes of variability of the tropical Atlantic Ocean led Brazil, France, and the United States to create and maintain an array of moored ATLAS buoys over the tropical Atlantic (Fig. 2 page 17) as part of the PIRATA project (Servain et al., 1998). The array relays measurements of surface meteorological variables and upper ocean temperature and salinity in near real-

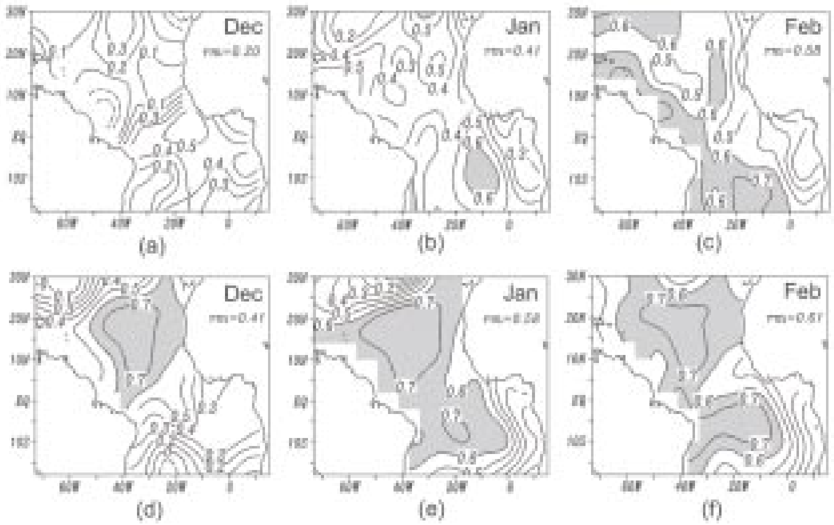

Figure 1 – Anomaly correlation maps between march - May predicted and observed SSTA over the tropical Atlantic for (a through c) persistence of SSTA from the month of initial condition; and (d through f) for the CCA scheme developed by Repelli and Nobre (2004). Month of initial condition and area mean correlations are stated on the right up corner of each panel. Adapted from Repelli and Nobre (2004).

time via Service Argos. Presently, Brazil is proposing a southwestern extension of the original PIRATA backbone (indicated by the blue circles in Fig. 2) to study three major phenomena over the South Atlantic and their impact on regional climate variability and predictability: a) the southern branch of the ITCZ; b) advection of buoyancy anomalies by the South Equatorial Current (SEC), and c) surface and upper ocean heat fluxes related to the SACZ variability.

Summary

Seasonal climate predictions over South America can benefit from "ocean-driving" conditions of atmospheric circulation and precipitation patterns. Therefore, slowly varying ocean temperature fields as those associated to the ENSO over the equatorial Pacific and the meridional gradient of SST anomalies over the tropical Atlantic imprint seasonal predictability to the regional climate. However, model improvements and research quality data are in need to both increase predictions skill and lead time. Furthermore, the evidences pointing to the dynamical limitations of using AGCM forced by prescribed boundary conditions to predict SACZ variability represents a major stumbling block to improvement of seasonal prediction skill over southeastern South America.

In short, seasonal climate prediction over South America presents two major challenges: first, for the regions in which the mean state of the atmosphere is modulated by external forcing, like SST, effective forecasting tools are needed to predict SSTA, particularly over the South Atlantic; second, for phenomena that cannot be reproduced by the "ocean forcing" paradigm of climate variability, it is necessary to develop coupled models which include not only the ocean and the atmosphere, but also interactions with the biosphere, the cryosphere, and the stratosphere.

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Predictability and prediction of European climate

Mark J. Rodwell[1], Francisco Doblas-Reyes[1], Christophe Cassou[2] and Laurent Terray[2]
[1]European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, UK
[2]Climate Modelling and Global Change Team, CERFACS, 42 Ave. G. Coriolis, 31500 Toulouse, France
Corresponding author: mark.rodwell@ecmwf.int

Introduction

As a means of motivating this topic, we first consider the European June - August (JJA) heatwave of 2003 (Schär et al, 2004). JJA temperature anomalies peaked at over 4K (and 5 standard deviations) above the 30-year mean over France and Switzerland and European rainfall was also reduced, particularly over southern France. The heatwave was responsible for (or at least accelerated) the deaths of nearly 15,000 people in France alone, caused billions of Euros in damage to crops and had detrimental impacts on metropolitan pollution levels and alpine glaciers. Figure 1 (page 16) shows (blue curve) the daily climatological average 2m temperatures (T_{2m}) based on the full ERA40 record (1962-2001). The much higher daily observed values are shown by the red curve. Horizontal blue and red lines show weekly and monthly-mean values. Important questions are how well was this event "predicted" and what impact did the predictions have on decision making?

The black curve shows a single control forecast, traditionally known as the "deterministic forecast". It follows quite closely the observed rise in European temperatures during the first 10 days of June. Although the control forecast was quite accurate over the medium-range, it is only the ensemble forecast that can provide a measure of the likelihood that temperatures will rise. Since all ensemble members (grey curves) showed a temperature on 8 June (T_{8June}) greater than the climatology (T_{clim}) a prediction could be made that there is almost 100% probability that $T_{8June}>T_{clim}$. We say "almost" because there is an assumption that the model represents faithfully the dynamics and physics of the real system and that the ensemble (with 51 members) captures the full range of chaotic uncertainty. If we are happy to sacrifice 100% determinism, we could also have forecast the event $T_{8June}>T_{clim}+$ 3°C with a probability of 75%: $P(T_{8June}>T_{clim}+3)=0.75$. This event did verify in the observations (for a "reliable" forecast system, an event with 75% probability of occurring would verify 75% of the time). For this particular event, Fig. 1 suggests that forecast skill extends over the entire first month of the forecast. For example $P(T_{9\text{-}15June}>T_{clim})=0.98$, $P(T_{9\text{-}15June}>T_{clim}+1)=0.90$, $P(T_{16\text{-}22June}>T_{clim})=0.80$ and $P(T_{16\text{-}22June}>T_{clim})=0.75$ with all of these events verifying in the observations. (In a more general analysis, not just for this extreme event, we find skillful prediction of European 850 hPa temperatures throughout the first month). Forecast skill is less clear for the second and third months although the extreme nature of the heatwave means that it is not necessarily an indication of a general lack of skill. At these and longer forecast ranges, predictability of the mean weather, if it exists, comes increasingly from 'boundary forcing'. For monthly and seasonal forecasts sea-surface temperature (SST) and soil moisture, for example, may provide a boundary forcing that allows some atmospheric predictability.

Observed European predictability

Persistence of anomalies is perhaps the simplest form of prediction and does lead to some skill for European-average T2m. One-month lead MAM persistence skill appears to arise from the albedo and latent heat effects of snow and the influence of North Sea and Baltic SST in coastal regions. For JJA, persistence skill appears to arise from changes in the Bowen ratio associated with soil moisture anomalies in the more arid southern regions of Europe. There appear to be reasonable levels of persistence skill for much of western Europe in SON with grid-point anomaly correlation coefficients (ACCs) of ~0.3. For DJF, atmospheric internal variability is strong and this may explain the reduced skill of the persistence forecast. Using a lagged maximal covariance analysis (MCA) technique, Czaja and Frankignoul (2002) found a significant influence of Atlantic SST on the North Atlantic Oscillation (NAO) in early winter (NDJ). (Warm subtropical SSTs and cool SSTs off the east coast of the USA coincide with a negative NAO anomaly). Rodwell and Folland (2002) suggested that SSTs in the preceding May provided the best predictor of the subsequent DJF NAO, yielding a statistically significant correlation skill of 0.45. Seasonal and longer timescale predictability may also come from interdecadal timescale changes in SST associated with the Thermohaline and Gulf-stream circulations (Kushnir 1994) and the influence of SSTs from other regions such as the Indian Ocean, the South Atlantic and those of the El Niño - Southern Oscillation (ENSO). As appears to be the case for the US, it is possible that some predictability for European climate may also be obtained from using observed trends associated with anthropogenic forcing. The shortness of the observational record and the inability to perform sensitivity studies means that model-based studies are also required to investigate the mechanisms through which the predictability arises.

Boundary-forced potential predictability

In the real world, there is two-way ocean-atmosphere coupling at the intraseasonal timescale (Barsugli and Battisti 1998) and so SSTs cannot strictly be considered to be boundary conditions for the atmosphere. Nevertheless, for atmospheric model intercomparison and for making a first estimate of "potential predictability" (the upper-bound of true predictability), it has proved useful to treat the observed SSTs as boundary conditions to atmospheric model simulations. Potential predictability can be estimated by applying the analysis of variance (ANOVA) technique (e.g., Rowell 1998) to ensembles of atmospheric model simulations. Results from many models suggest that there is relatively high potential predictability of seasonal-mean anomalies in the tropics and subtropics but that this drops-off rapidly as we move to mid-latitudes. Results from atmospheric models within the EC-funded PREDICATE project suggest that less than 20% of the decadal variance of mean sea-level pressure, T_{2m} or precipitation at each European grid-point can be explained by SST forcing. Note, however, that there are still large differences between potential predictability estimates from different models, even in the tropics, and these need to be understood.

Other boundary conditions may also be able to force an atmospheric response and thus augment long-range predictability. For example, model sensitivity studies suggest that Arctic sea-ice anomalies can affect the NAO (Deser et al. 2004). Land properties such as soil moisture and snow depth also show significant persistence at the monthly to seasonal timescale and may be considered as partial boundary conditions for monthly and seasonal forecasts. A reduction in initial soil moisture conditions prior to the heatwave of JJA 2003 has been shown to lead to warmer (+2-3^{o}C), more realistic, T_{2m} throughout the season (personal communication, Laura Ferranti).

Coupled GCM predictability

The EC-funded DEMETER project (Palmer et al., 2004) was aimed at investigating "end-to-end" seasonal predictability in coupled models and constructing a multi-model operational seasonal forecasting system. Figure 2a (page 30) shows ACCs for European winter T_{2m} from the seven individual DEMETER models and the simple multi-model. There is some modest predictability with the multi-model mean (filled bars) showing the most skill. Forecasts of European precipitation (Fig. 2b) are less skillful than for T_{2m}. The general improvement in skill obtained by using the multi-model is more obvious in a probabilistic setting. It has been shown that, for the Brier skill score (BSS) for the event "European winter T_{2m} > normal", the multi-model out-performs each individual model and the persistence forecast. Palmer et al (2004) found that the increased skill over the single models can be attributed partly to the larger ensemble size and partly to improved reliability (associated with an increase in ensemble spread) and "resolution" (associated with the increase in reliability and the cancellation of model errors).

Potential predictability can be estimated for each individual coupled model by taking each ensemble member in turn, assuming it represents the truth and comparing the other ensemble members with it. We find that these estimates are highly variable between the individual DEMETER models and the differences appear to be mainly related to the choice of atmospheric model component. This suggests that we do not at present have a reliable estimate of the true potential skill of seasonal forecasts. Less models have been used to estimate potential predictability on longer timescales and so conceivably there could be even larger uncertainties associated with these estimates. Nevertheless Collins (2002), using the single coupled model HadCM3, did find a statistically significant anomaly correlation of 0.82 for 5-year-averaged North Atlantic SST (and 0.22 for European surface air temperature).

Mechanisms and model validation

Although the North Atlantic atmosphere does appear to respond to SST, the ANOVA technique does not indicate which ocean basin is most important for the forcing. Different authors have pointed to the roles played by different ocean basins. Sutton and Hodson (2003) used an optimal detection method that can identify which SSTs are most important for forcing an atmospheric model. They found a (primarily North Atlantic) SST pattern and NAO-like response which have strong similarities with those of the observational lagged MCA results. When low frequencies were analyzed separately, the optimal SST pattern was more uniform over the whole North Atlantic. Should this pattern be associated with the Thermohaline Circulation (THC), then any decadal predictability of the THC may imply predictability of the North Atlantic / European climate. A high frequency analysis emphasized a dual influence of ENSO and tropical Atlantic SST.

To investigate the apparent high sensitivity of potential predictability estimates to the choice of atmospheric model Rodwell et al (2004) conducted some controlled experiments with the PREDICATE atmospheric models to determine more clearly the model differences and the mechanisms of the atmospheric response to imposed North Atlantic SST anomalies. They found that the magnitude of the multi-model mean response was stronger than the inter-model spread although significant model differences, even in the tropics, were apparent. Much of the large-scale response appeared to be forced by the tropical part of the SST anomalies but extratropical SSTs appeared to be also important. Although Europe does not stand out in ANOVA results as a region that is generally affected by SST variability, this experiment showed that there could be “windows of opportunity” when a strong (possibly predictable) European SON and DJF T_{2m} signal could arise for particular north Atlantic SST anomaly patterns.

There is also a need to understand and validate surface heat flux feedbacks in coupled models. Frankignoul and Kestenare (2002) found a strong negative feedback in the observations; particularly in the mid-latitude winter when strong mean windspeeds enhance the influence of anomalous SST on surface turbulent heat flux and lead to values in excess of -40 $Wm^{-2}K^{-1}$. These negative midlatitude feedbacks are substantially underestimated in several coupled models (Frankignoul et al. 2004). These and other results suggest that there is still substantial scope for improvement of models and, possibly, of predictability estimates themselves.

Mitigating actions

Arguably a forecast, however accurate, is only useful if it can have a positive impact on decision-making. It is clear that medium-range weather forecasts and anthropogenic climate change forecasts do have such an impact. However, the levels of skill associated with monthly, seasonal and decadal forecasts for Europe may be such that to demonstrate usefulness, the whole “end-to-end” forecast-to-user-decision process needs to be optimized in a single integrated step for each individual user.

One aspect of this process is the nature of the action a user can make based on forecast information. Fig. 3 shows that an optimized decision making process of the form discussed by Palmer et al. (2000) can benefit a user if the cost of taking mitigating action is independent of the probability that the event will occur: compare the curves for “never take action” (solid), “always take action” (dotted) and “take action if the event is sufficiently likely” (dashed). The recent DEMETER coupled model seasonal hindcasts indicate that these predictions may be of interest to a utility company which has the appropriate cost:loss ratio and which is exposed to, and can take mitigating action against, European-wide climate anomalies. On the other hand, Fig. 3 demonstrates that forecast information actually reduces the effectiveness of an insurance-based mitigation strategy in reducing a user’s cash volatility: compare the curves “never take action” (solid), “insure with no forecast information” (dotted) and “insure with a knowledge of the probabilistic forecast” (dot-dashed)“. The reduction in effectiveness of insurance is because it is reasonable to assume that the insurance broker also has access to the forecast and so the insurance premium will reflect the probability of the event occurring. One could argue that predictability does not favor the insurance industry as a whole either. Although the models used in Fig. 3 are simple and ignore many issues such as the access to information and bankruptcy, it is clear that the forecast community should consider carefully which user communities to target when developing long-term plans for integrated forecasting systems.

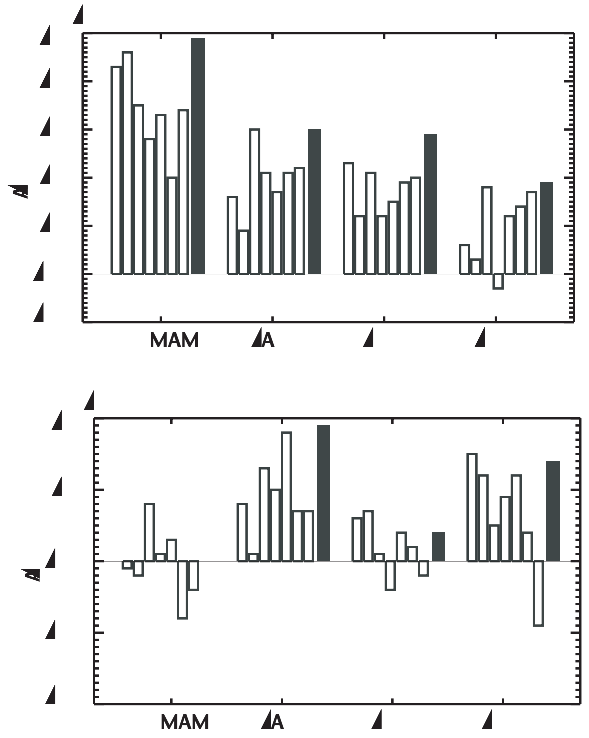

Fig. 2: Seasonal evolution of the ensemble-mean anomaly correlation coefficient (ACC) for (a) 2-meter temperature and (b) precipitation from each of the seven individual DEMETER models (open bars) and the multi-model-mean (solid bars) over Europe [12.5ºW-42.5ºE, 35-75ºN]. The results for DJF come from hindcasts initiated on 1 November for the years 1980-2001. The same lead-time is used for the other forecasts. Note that the ACC for the multi-model MAM precipitation is zero

Conclusions and key issues

Medium-range forecast skill has increased substantially over the last few decades. For example, a 7-day ECMWF forecast of European 500 hPa geopotential height is as good today as a 5-day forecast was in 1980. Indeed, present ECMWF forecasts show probabilistic skill for European 850hPa temperatures throughout the first month. We have shown here modest levels of European predictability at seasonal timescales that may be of real value to specialized customers. It is possible that there may be “windows of opportunity” where European predictability is enhanced by the existence of particular patterns of SST, soil moisture or snow-cover. We have also discussed the scope for model improvement (e.g. soil moisture, heat flux feedbacks etc) that could lead to better seasonal forecasts in the future. Other improvements may come from improved ocean data assimilation, improved land surface initialization, improved techniques for the generation of coupled-model ensemble perturbations and improved numerical or statistical downscaling to user-specific areas. One thing that is certain, however, is that the ultimate levels of seasonal to decadal predictability will be rather low for Europe and the utility or otherwise of seasonal to decadal forecasts may rely on careful optimization of the whole "end-to-end" forecast-to-user decision-making process. The identification of users and mitigation strategies, working with the variables and thresholds that they are sensitive to, and education about probabilistic techniques will be essential if the long-range forecasting industry is to develop. It is possible that over the next decade, the largest "value" to users will be found within the monthly forecast range. Please see International CLIVAR Project Office (2004) for a fuller version of this paper including a more extensive reference list.

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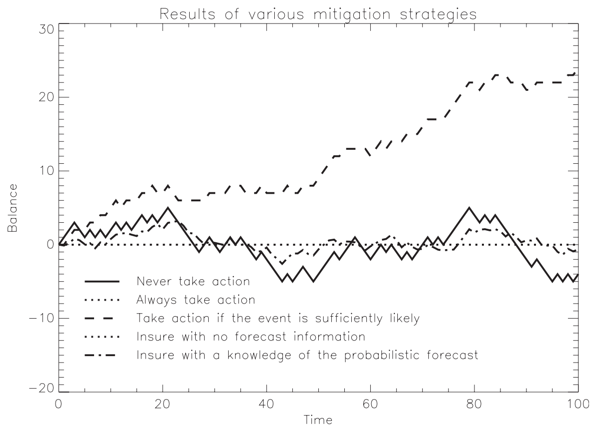

Fig. 3: The effect over 100 time intervals on a user's cash balance of different mitigation strategies against a particular climate "event". On average, the event is assumed to occur in 50% of the time intervals (p_{clim}=0.5). For time interval, t, the forecast probability of the event occurring is p(t). In the discretised situation, the event actually occurs a fraction p(t) times (so the forecast is assumed to be completely "reliable"). (a) No action is ever taken (solid line) and the change in balance over time interval t is $\Delta B(t)$ = profit - event(t)×loss where event(t)=0 or 1 depending on whether the event occurs, loss=2 units and "profit" (=1) is chosen to make the long-term average $\Delta B = 0$. (b) Action is always taken (horizontal dotted line) so that ΔB = profit - cost = constant. The fixed "cost" (=1) of taking action is chosen for simplicity to make $\Delta B \equiv 0$. (c) Action is taken (action=1) if the forecast probability exceeds the critical threshold, p_{crit}(=0.5, which optimizes the benefit for a cost:loss ratio of 1:2) (dashed line). ΔB = profit - action(t)×cost - (1-action(t))×event(t)×loss. (d) Insurance is taken with only a knowledge of p_{clim} (also horizontal dotted line). The insurance premium is p_{clim}×loss and so ΔB = profit - p_{clim}×loss ≡ 0. (e) Insurance is taken out with a knowledge of p(t) (dot-dashed line). The insurance premium is p(t)×loss as it reflects the forecast probability. Hence ΔB(t) = profit - p(t)×loss and so volatility is no longer completely removed.

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