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Studies of Ocean Predictability at Decade to Century Time Scales Using a Global Ocean General Circulation Model in a Parallel Computing Environment.

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OBJECTIVES: Determine the structure of oceanic natural variability at time scales of decades to centuries; characterize the physical mechanisms responsible for the variability; determine the relative importance of heat, fresh water, and moment fluxes on the variability; determine the predictability of the variability on these times scales.

ACCOMPLISHMENTS: Documented the sensitivity of the MM mode of thermohaline circulation (THC) to various noise forcings. Explained, for the first time, the physics of the MM mode. Developed a coupled model of the THC and show that prediction of the THC is likely an ill-posed problem. Completed coupling Jim Price's Marginal Sea Model (MSM) to the LSG ocean model' finished an experiment demonstrating utility of the technique, simulating the Mediterranean outflow.

Discovered a new mode of decadal climate variability in the N. Pacific and the physics responsible for it. Identified the large impact of this mode on weather over N. America. Showed the mode is predictable at least three years into the future. Completed 23 years of a "hindcast" run of Los Alamos' POP ocean model on the T3D, covering the years 1965-1987, to evaluate how well POP reproduces observed El Niño variability. A comparable simulation aimed at decadal time scales is in progress. Completed a hybrid coupled model that simulates the newly discovered mode. Currently tuning it to produce operational decadal climate forecasts.

The work has produced 17 papers already published in refereed journals, plus 4 additional papers submitted.

HIGHLIGHTS OF RESEARCH EFFORTS:

S. Tett and T.P. Barnett, 1998: North Pacific decadal variability in an AOGCM. Part I: Description and mechanisms.

Simulated decadal variability in a coupled Ocean-Atmosphere General Circulation Model (OAGCM) is described and compared with observations. The principal mode of variability in the simulated North Pacific shows a significant spectral peak at a period of 10 years. The principal mechanisms for this mode are, over the most of the North Pacific, a response to Ekman pumping by the wind and, in the Kuroshio region, an acceleration of the northward baroclinic flow caused by a delayed response to wind stress forcing. The atmospheric wind stress response to the SST changes is largely stochastic though there is some weak evidence of coupling.

DISCLAIMER

Barnett, T.P., D.W. Pierce, and R. Saravanan, 1998: On the origins of the Pacific decadal oscillation:

The origins of decadal climate variability in the Pacific ocean are examined by comparing the response of an atmospheric general circulation model to two different lower boundary conditions: 1) seasonally-varying, climatological sea surface temperatures; 2) full coupling to an oceanic general circulation model. It is found that there is a spectral peak in the variability of the fully coupled system at interdecadal time scales, with patterns in 500 mb height and sea surface temperature anomaly corresponding to the Pacific Decadal Oscillation. No such peak exists in the climatologically-forced run, which has a white spectrum. Therefore, decadal variability in the north Pacific ocean is not simply a passive result of stochastic atmospheric forcing, but arises from properties of the coupled ocean/atmosphere system that act to amplify variability in the interdecadal time band.

Jones, P.D., K.R. Briffa, T.P. Barnett and S.F. B. Tett, 1998: High-resolution palaeoclimatic records for the last millenium: Interpretation, integration and comparison with A/OGCM control run temperatures. *The Holocene*., 8(4), 467-483.

Palaeoclimatology provides our only means of assessing climatic variations before the beginning of instrumental records. The various proxy variables used, however, have a number of limitations which must be adequately addressed and understood. Besides their obvious spatial and seasonal limitations, different proxies are also potentially limited in their ability to represent climatic variations over a range of different time scales. Simple correlations with instrumental data over the period since 1881 give some guide to which are the better proxies, indicating that coral and ice-core based reconstructions are poorer than tree-ring and historical ones. It must be remembered, however, that the quality of many proxy time series can deteriorate during earlier times. Suggestions are made for assessing proxy quality over longer periods than the last century by intercomparing neighboring proxies and, by comparisons with less-temporally resolved proxies such a borehole temperatures.

Developing earlier work, that was limited to decadal resolution, we have averaged seventeen temperature reconstructions (representing various seasons of the year), all extending back at least to the mid-seventeenth century, to form two annually-resolved hemispheric series (NH10 and SH7). Over the 1901-91 period, NH10 has 36% variance in common with average NH summer (June to August) temperatures and 70% on decadal time scales. SH7 has 16% variance in common with average SH summer (December to February) temperatures and 49% on decadal time scales, markedly poorer than the reconstructed NH series. The coldest year of the millenium over the NH is 1601, the coldest decade 1691-1700 and the 17th is the coldest century.

A Principal Components Analysis (PCA) is performed on yearly values for the 17 reconstructions over the period 1660-1970. The correlation between PC1 and NH10 is 0.92, even though PC1 explains only 13.6% of the total variance of all 17 series. Similar PCA is performed on thousand-year long General Circulation Model (GCM) data from the Geophysical Fluid Dynamics Laboratory (GFDL) and Hadley Centre (HADCM2), sampling these for the same locations and seasons as the proxy data. For GFDL, the correlation between its PC1 and its NH10 is 0.89 while for HADCM2, the PCs group markedly differently. Cross-spectral analyses are performed on the proxy data and the GFDL model data at two different frequency bands (0.02 and 0.03 cycles per year). Both analyses suggest that there is no large-scale coherence in the series on these time scales. This implies that if the proxy data are meaningful, it should be relatively straightforward to detect a coherent near-global anthropogenic signal in surface temperature data.

A. Grötzner, M. Latif, and T.P. Barnett, 1998: A decadal climate cycle in the North Atlantic Ocean as simulated by the ECHO coupled GCM .

In this paper a decadal climate cycle in the North Atlantic that was derived from an extended-range integration with a coupled ocean-atmosphere general circulation model is described. The decadal mode shares many features with the observed decadal variability in the North Atlantic. The period of the simulated oscillation, however, is somewhat longer than that estimated from observations. While the observations indicate a period of about 12 years, the coupled model simulation yields a period of about 17 years. The cyclic nature of the decadal variability implies some inherent predictability at these time scales.

The decadal mode is based on unstable air-sea interactions and must be therefore regarded as an inherently coupled mode. It involves the subtropical gyre and the North Atlantic Oscillation The memory of the coupled system, however, resides in the ocean and is related to the oceanic adjustment to low-frequency wind stress curl variations. In particular, it is found that variations in the intensity of the Gulf stream and its extension are crucial to the oscillation. Although differing in details, the North Atlantic decadal mode and the North Pacific mode described by M. Latif and T. Barnett are based on the same fundamental mechanism: a feedback loop between the wind driven subtropical gyre and the extratropical atmospheric circulation.

M. Christoph, T. Barnett, A. Bacher, and J. Oberhuber: The Antarctic Circumpolar Wave in a Coupled Ocean-Atmosphere GCM

The existence of the so-called Antarctic Circumpolar Wave (ACW) suggested by White and Peterson (1996) from fragmentary observational evidence has been confirmed in an extended integration of a Max Planck Institute coupled general circulation model. The ACW constitutes a coupled mode of the ocean-atmosphere-sea ice system that inhabits the high latitudes of the southern hemisphere. It is characterized by anomalies of such climate variables as sea surface temperature, sea level pressure, meridional wind and sea ice, to name a few. The ACW signal in the ocean propagates eastward over most of the high latitude southern ocean, advected along in the Antarctic Circumpolar Current and/or by a complex air/sea interaction. On average, it completes a circuit entirely around the southern ocean, but is strongly dissipated in the S. Atlantic and in the southern Indian, just marginally maintaining statistical significance in these areas, until it reaches the south Pacific where it is reenergized. In extreme cases, the complete circumpolar propagation is more clear, requiring about 12-16 years to complete the circuit. The oceanic component of the mode is forced by the atmosphere via fluxes of energy and Ekman-induced advection. The impact of the SST anomalies on the overlying atmosphere is to establish patterns of SLP in spatial quadrature with the associated SST patterns. However, the main SLP signal is more of a standing wave pattern, as described below and likely due mainly to other sources.

The atmospheric component of the ACW in the sea level pressure field, a driver of the ACW, is the Pacific South American (PSA) oscillation described originally by Mo and White (1985). This appears to be a preferred, natural standing mode of variability in the SLP field of the southern Hemisphere. The coupled climate model shows the origins of the PSA, and so the ACW, are associated mainly with mid latitude climate interactions. There is some ENSO-related signal in the ACW due to anomalous latent heat release associated with precipitation anomalies in the central and western tropical Pacific. However, this component explains at most 30% of the ACW variance, and generally much less. Thus, the PSA, like its counterpart in the North Pacific, is essentially a natural mode of the high southern latitudes. The time scale of the ACW in the coupled climate model integration, about 4-5 years, could not be related to the time scale of the model ENSO. Rather, it seems the dominate time scale has to do with the fact that the ACW has a wave number three pattern . This, coupled with the 12-16 year transit time around Antarctica, results in the local reappearance of energy peaks about every 4-5 years at which times they can selectively be reinforced by the standing atmospheric pattern.

It is hypothesized that the ACW as an entity represents the net result of a moving coupled climate anomaly interacting with a spatially-fixed forcing pattern in the SLP field (the PSA). As the ACW moves into and out of phase with the resonant backgroun ttern the ACW is selectively amplified or dissipated.

T.P. Barnett. K. Arpe, L. Bengtsson. M. Ji, A. Kumar, 1997: Potential Predictability of Midlatitude Climate Variability in Two General Circulation Models.

Ensembles of extended AMIP runs from the general circulation models (GCMs) of the National Meteorological Center and Max Planck Institute (Hamburg) are used to estimate the potential predictability (PP) of an index of the Pacific-North America (PNA). The PP of this pattern in 'perfect' prediction experiments is 20-25% of the index's variance. The models, particularly that from MPI, capture virtually all of this variance in their hindcasts of the winter PNA for the period 1970-93.

The high levels of internally-generated model noise in the PNA simulations reconfirm the need for an ensemble averaging approach to climate prediction. This means the forecasts ought to be expressed in a probabilistic manner. It is shown that the models' skills are higher by about 50% during strong SST events in the tropical Pacific, so the probabilistic forecasts need to be conditional on the tropical SST.

M. Latif and T.P. Barnett, 1996: Decadal climate variability over the North Pacific and North America: Dynamics and predictability. M. Latif and T.P. Barnett, 1996:

The dynamics and predictability of decadal climate variability over the North Pacific and North America were investigated by analyzing various observational datasets and the output of a state of the art coupled ocean-atmosphere general circulation model which was integrated for 120 years. Both the observations and model results support the picture that the decadal variability in the region of interest is based on a cycle involving unstable ocean-atmosphere interactions over the North Pacific. The period of this cycle is of the order of a few decades.

The cycle involves the two major circulation regimes in the North Pacific climate system, the subtropical ocean gyre and the Aleutian low. When, for instance, the subtropical ocean gyre is anomalously strong, more warm tropical waters are transported poleward by the Kuroshio and its extension, leading to a positive SST anomaly in the North Pacific. The atmospheric response to this SST anomaly involves a weakened Aleutian low and the associated fluxes at the air-sea interface reinforce the initial SST anomaly, so that the ocean and atmosphere act as a positive feedback system. Both the anomalous heat flux and reduced ocean mixing in response to a weakened storm track contribute to this positive feedback.

The atmospheric response, however, consists also of a wind stress curl anomaly which spins down the subtropical ocean gyre, thereby reducing the poleward heat transport and the initial SST anomaly. The ocean adjusts with some time lag to the change in the wind stress curl, and it is this transient ocean response that allows continuous oscillations. The transient response can be expressed in terms of baroclinic planetary waves, and the decadal time scale of the oscillation is therefore determined to first order by wave time scales.

The existence of such a cycle provides the basis of long-range climate forecasting over North America at decadal time scales. At a minimum, knowledge of the present phase of the decadal mode should allow a "nowcast" of expected climate "bias" over North America, which is equivalent to a climate forecast several years ahead. The implications of the Pacific mode for the climate of the Atlantic region were also discussed. It was shown that a large part of the low-frequency SST variability in the subtropical Atlantic can be attributed to remote forcing at the Pacific.

D.W. Pierce, K.Y. Kim, and T.P. Barnett, 1996: Variability of the thermohaline circulation in an ocean general circulation model coupled to an atmospheric energy balance model

The variability of the ocean's thermohaline circulation in an oceanic general circulation model (OGCM) coupled to a two-dimensional atmospheric energy balance model (EBM) is examined. The EBM calculates air temperatures by balancing heat fluxes, including that from the ocean surface; air temperature and ocean circulation evolve together without imposed temperature restrictions except specification of the solar constant. The heat coupling is scale dependent such that small-scale ocean temperature anomalies are damped quickly while large-scale ones lose heat slowly by longwave emission to space. These boundary conditions are more realistic than restoring conditions even when weak coupling is used, since they allow changes in air temperature and wholesale shifts in the planetary heat balance.

It is found that coupling the EBM to the OGCM increases the stability of the ocean's thermohaline circulation. This increased stability arises from the ability of the coupled model to develop a four times greater sea surface temperature response to a given change in thermohaline overturning than when traditional restoring boundary conditions are used. The sense of this increased response works to stabilize the thermohaline overturning. The specific value of the small-scale thermal coupling coefficient also influences the stability even though the large-scale coefficient is always small (2 W m^{-2} C^{-1}); this suggests that small scale processes might determine the large-scale stability.

Latif, M. and T.P. Barnett, 1994: Causes of decadal climate variability over the North Pacific/North American sector. *Science*, 266, 634-637.

The cause of decadal climate variability over the North Pacific Ocean and North America is investigated by the analysis of data from a multidecadal integration with a state-of-the-art coupled ocean-atmosphere model and observations. About one-third of the low-frequency climate variability in the region of interest can be attributed to a cycle involving unstable air-sea interactions between the subtropical gyre circulation in the North Pacific and the Aleutian low-pressure system. The existence of this cycle provides a basis for long-range climate forecasting over the western United States at decadal time scales.

GRANT-RELATED PUBLICATIONS:

1998

Barnett, T.P., D.W. Pierce, and R. Saravanan, 1998: On the origins of the Pacific decadal oscillation. GRL, submitted.

Tett, S. and T.P. Barnett, 1998: . North Pacific Decadal Variability in a coupled AOGCM: Description and Mechanisms. *J. Clim.*, submitted.

Barnett, T.P., D. Pierce, M. Latif, D. Dommenget and R. Saravanan, 1998: Interdecadal interactions between the tropics and midlatitudes in the Pacific Basin, *GRL*, submitted.

Christoph, M., T.P. Barnett, and E. Roeckner 1998: The Antarctic Circumpolar Wave in a Coupled Ocean-Atmosphere GCM. *J. Clim.*, **11(7)**, 1659-1672.

Barnett, T.P., 1998: Comparison of near surface air temperature variability in eleven coupled global climate models, *J. Clim.*, accepted.

Grotzner, A., M. Latif, and T.P. Barnett, 1998: A decadal climate cycle in the North Atlantic Ocean as simulated by the ECHO coupled GCM. *J. Clim.*, **11,** 831-847.

Jones, P.D., K.R. Briffa, T.P. Barnett and S.F. B. Tett, 1998: High-resolution palaeoclimatic records for the last millenium: Interpretation, integration and comparison with General Circulation Model control-run temperatures. *The Holocene.*, **8(4)**, 455-471.

Latif, M., D. Anderson, T. Barnett, M. Cane, R. Kleeman, A. Leetmaa, J. O'Brien, A. Rosati, and E. Schneider, 1998: A review of predictability and prediction of ENSO, *JGR*, **103(C7)**, 14,375-14,393.

Pierce, D. W., Barnett, T. P., and Latif, M., 1998: Connections between the tropics and midlatitudes on Decadal Time Scales. *J. Climate*, submitted.

Xu, W. and T.P. Barnett, 1998: Decadal variability in the North Pacific as simulated by a hybrid coupled model. *J. Clim.*, 11, 297-312.

1997

Barnett, T.P., K. Arpe, L. Bengtsson, M. Ji, and A. Kumar, 1997: Potential predictability of midlatitude climate variability in two general circulation models: AMIP implications. *J. Clim.*, **10**(9), 2321-2329.

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Latif, M. and T.P. Barnett, 1996: Decadal climate variability over the North Pacific and North America: Dynamics and predictability. *J. Clim.*, 9, 2407-2423.

Pierce, D. W., 1996: Reducing phase and amplitude errors in restoring boundary conditions. J. Phys. Oceanogr., vol. 26, p. 1552-1560.

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Pierce, D.W. and B.K. Stephens: Visualizing geophysical data: Teasing Meaning from Models. IEEE Comp. Science and Engineering, Winter, 1995.

Pierce, D.W., T.P. Barnett, and U. Mikolajewicz, 1995: On the competing roles of heat and fresh water flux in forcing thermohaline oscillations. J. Phys. Oceanogr., **25**(9), 2046-2064.

Pierce, D.W., K.Y. Kim, and T. P. Barnett, 1995: Variability of the thermohaline circulation in an ocean general circulation model coupled to an atmospheric energy balance model. J. Phys. Oceanog., 26(5), 725-738.

Barnett, T.P., M. Chu, R. Wilde, and U. Mikolajewicz, 1995: Low frequency ocean variability induced by stochastic forcing of various colors. In Natural Climate Variability on Decade-to-Century Time Scales, D.G. Martinson et al. (Eds), Proceedings of the National Research Council Workshop on Decade-to-Century Time Scales of Climate Variability, September 21-25, 1992, Irvine, CA, pp. 398-407.

1994

Kim, K.-Y., T.P. Barnett, and G.R. North, 1994: Noise response characteristics of a coupled LSG-EBM model, Proceedings of the AMS Fifth Annual Symposium on Global Climate Studies, Nashville, TN, January 23-28, 1994.

Latif, M. and T.P. Barnett, 1994: Causes of decadal climate variability over the North Pacific/North American sector. *Science*, 266, 634-637.

1993

Barnett, T.P., M. Chu, R. Wilde, and U. Mikolajewicz, 1993: Low frequency ocean variability induced by stochastic forcing of various colors. Proceedings of the Fourth Symposium on Global Change Studies, AMS. Anaheim, January 17-22, 1993.

GRADUATE STUDENT THESES AND DISSERTATIONS:

Timothy J. Osborn: Ph.D. Thesis: "Internally-generated variability in some ocean models on decadal to millennial time scales." Climatic Research Unit, School of Environmental Sciences, University of East Anglia, U.K., September, 1995.

COLLABORATIONS:

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