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Scientific assessment of the prospects for seasonal forecasting: a European perspective

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Summary

Prediction beyond the average limit of deterministic predictability of synoptic-scale weather is possible because:

- the time-averaged atmospheric circulation is somewhat more predictable than its instantaneous state
- some circulation types are more predictable than average
- slow and predictable variations in lower boundary forcing (especially sea surface temperature) influence the statistics of the atmospheric circulation.

The northern winter circulation tends to reside in quasi-stationary states, or weather regimes, on timescales of a few weeks. Transitions between regimes tend to occur on more rapid synoptic timescales. Predictions for the medium range up to a month are largely concerned with forecasting the persistence of, or transition between, specific regimes.

Evidence suggests that predictability of the time averaged flow arising from memory of the atmospheric initial conditions only might extend to 15 or possibly 20 days, depending on the atmospheric circulation. Beyond this range, it appears that specific transitions in weather regimes become extremely difficult to predict.

On timescales approaching a season, however, there is evidence that anomalous SST has an impact on weather regime statistics of the atmosphere. Thus whilst specific regime transitions will not be predictable during the season, the probability of the atmosphere residing in a given regime can be significantly influenced by SST anomalies. Thus, for example, SST anomalies can increase or decrease the probability that the atmosphere will be blocked or zonal. Such an impact of SSTs has been unambiguously demonstrated for atmospheric flow over the Pacific and North America. More research is needed to clarify the role of SST on regime statistics over Europe, though there is evidence of an impact over Europe during El Niño episodes, particularly in spring.

As far as can be assessed at present coupled interactions between ocean and atmosphere are not such a major influence on atmospheric predictability on the monthly time-scale. Therefore the monthly prediction problem may be treated as a straightforward extension of the medium-range forecast problem, though arguably it is possible that coupling to a 1-D mixed layer ocean in the extratropics may be beneficial.

Studies in support of the WCRP TOGA (Tropical Ocean Global Atmosphere) programme have demonstrated seasonal predictability of tropical SST and the overlying large-scale tropical circulation, using both empirical and dynamical coupled ocean-atmosphere models. There is also evidence that interannual fluctuations in regional rainfall associated, for example, with the monsoons, are also predictable.

Considerably more experimentation is required to establish the potential for seasonal forecasting in the extra-tropics, including an assessment of the predictability of lower boundary forcing outside the tropics. It is essential that such experimentation be carried out using ensembles of integrations, in order to be able to assess reliably the impact on atmospheric regime statistics. Considerable development of the ensemble technique has recently taken place for the medium range, some aspects of this work may be relevant for the seasonal timescale. Medium-range probabilistic product development can be extended for longer timescales.

For predictions on the seasonal timescale, uncertainties in physical parametrizations may have as large an impact as uncertainties in initial conditions. Analysis of ensemble forecast integrations from different modelling centres will be useful in quantifying the relative importance of uncertainties in model formulation. This highlights the importance of a joint European collaborative programme on seasonal prediction.

Research on seasonal prediction is likely to benefit the refinement of physical parametrizations for the medium-range problem. The main requirement is for improved experimental and physical description of the phenomena and processes at work at work in the atmosphere. However, the diagnostic information provided by extended runs is a valuable supplement to this effort. Indeed, development of a revision to the ECMWF surface heat flux parametrization in low wind speed conditions arose through analysis of seasonal integrations.

Seasonal integrations provide a straightforward way of determining the ability of the model to simulate accurately weather regime statistics. It is difficult to generate useful statistics on weather regimes using just 10-day forecasts.

Since the 'memory' requisite for seasonal forecast skill resides in the ocean, it is essential to have accurate upper-ocean initial conditions which are in balance with the atmospheric model. Development of an ocean data assimilation system for seasonal prediction will allow consistent global analyses of ocean and atmosphere data both from in situ and remote sources. The availability of such consistent analyses will be of considerable interest to the climate community.

CONTENTS

CONTENTS (cont)

1. INTRODUCTION

This document discusses the physical basis for atmospheric predictability on seasonal timescales, and the current status of modelling tools required to realise the potential for seasonal predictions. The evidence for seasonal predictability is outlined in section 2, including the theoretical basis, sensitivity experiments with uncoupled atmospheric and oceanic general circulation models, and forecast experiments with coupled ocean-atmosphere models. There is an implicit assumption in this document that physically-based models of the ocean and atmosphere will eventually be the best tool for seasonal prediction. However, forecasts can also be made using empirical models based on observed correlations and some discussion of this is given in section 2.2. In section 3 there is a discussion of monthly predictability.

Section 4 discusses the modelling needs for seasonal predictions, including data assimilation requirements. Emphasis is placed on the need for a probabilistic approach to such predictions. The benefits of developing a seasonal-timescale forecast capability are discussed in section 5, while in section 6 the opportunity for a European scientific collaboration is considered. Data requirements for seasonal prediction are not discussed explicitly in this document, though they are the focus of a number of international programmes outlined in section 7.

Throughout this document, a distinction is made between predictions for the tropics, and predictions for extratropical regions such as Europe. For the former, the expectation of significant skill is high, whilst for the latter the potential for useful seasonal predictions is limited by internal variability associated with the nonlinear chaotic dynamics of the atmosphere. Concluding remarks are made in section 8.

2. THE EVIDENCE FOR SEASONAL PREDICTABILITY

2.1 The basic premise

Extended-range prediction beyond the average limit of predictability of individual synoptic weather systems rests on two basic premises: that there are large-scale components of the atmospheric general circulation with an intrinsically longer predictability time than that of individual synoptic weather patterns (and there may be periods when this is more the case than others) and that lower boundary forcing which evolves on a much slower timescale than that of weather, can impart significant predictability on atmospheric development. On seasonal timescales, the prospect for atmospheric prediction is based primarily on the second premise. The boundary conditions involved include sea surface temperature (SST), sea-ice cover and temperature, land surface temperature and albedo, soil moisture and snow cover (*Shukla*, 1984). Variations in lower boundary conditions result from the coupling of the dynamics of the atmosphere to the dynamics of the oceans and to the hydrology of the land masses.

2.1.1 *The tropics*

There is considerable evidence that the internal chaotic variability of the large-scale tropical atmosphere is relatively weak. For example, following *Matsuno* (1966) and *Gill* (1980), much of the observed large-scale flow in the tropical atmosphere can be understood in terms of equatorially-trapped linear modes. Nonlinear self-interaction between the linear modes of the tropics appears to be relatively small. This suggests that surface boundary conditions may lead to considerable seasonal predictability in the large-scale tropical atmosphere (*Charney and Shukla*, 1981). Indeed (sec 2.5), the dominant mode of interannual variability of the tropical ocean-atmosphere system associated with the El Niño/Southern Oscillation phenomenon (ENSO) appears to be predictable with a lead time of several seasons.

In general, the theoretical basis for seasonal predictability of large-scale circulation in the tropics is well founded. On the other hand, on scales ~ 1000 km the predictability of crucial meteorological variables such as rainfall is less well known, and quantifying predictability on regional scales must rely on observational and numerical modelling studies.

2.1.2 *The extratropics*

A theoretical assessment of the potential for seasonal predictability in the extratropics is not as straightforward as that for the large-scale flow in the tropics, essentially because much of the variability in the extratropical atmosphere and oceans is directly associated with internal instability and nonlinearity.

Considerations similar to those put forward for the tropics suggest, on the one hand, that the extratropical atmosphere may be most predictable in summer, when internal variability is weakest. On the other hand, predictable planetary-scale circulation patterns in the tropics will influence extratropical circulations through teleconnections induced by Rossby-wave dynamics which are generally largest in the winter season when meridional potential vorticity gradients are strongest. Also, from hindcast studies, it appears that the extratropical ocean SST is more reproducible in winter when the mixed layer is deep than in summer when it is shallow.

A quantitative assessment of seasonal predictability in the extratropics in general, and in regions such as Europe in particular, must rely on results from observational studies, and comprehensive numerical modelling experimentation.

2.1.3 *Weather regimes and their relation to monthly and seasonal forecasting*

The role of boundary forcing and the distinction between prediction on the month and seasonal timescale, can be understood in terms of the weather regime structure of the extratropical flow (*Reinhold*, 1987; *Palmer*, 1993).

A number of independent analyses indicate that the northern winter circulation tends to reside in quasi-stationary states (called weather regimes) typically on timescales of a few weeks, with relatively fast transition times between regimes on the timescale of a few days. Zonal and blocked states could be thought of as typifying such regimes, though in practice objective cluster analysis techniques reveal more complex regime patterns (e.g. *Mo and Ghil*, 1988).

Transitions between regimes do not require external forcing, and are associated with the nonlinearity of atmospheric dynamics. In general, transitions between regimes have small atmospheric predictability, so that beyond the medium-range forecast period, a given transition will often not be predictable. On timescales beyond the medium range, but shorter than one month, it is unlikely that there will be more than one or two regime transitions. Useful predictions on this timescale rely on forecasting such transitions, and are therfore inherently difficult.

On the seasonal timescale, there could well be many regime transitions. However, the goal of the seasonal forecast is to not to predict the timing of such transitions, but rather to estimate the regimes which are likely to be most prevalent over the coming season. The effect of sea surface temperature anomalies is to bias the population statistics of the observed weather regimes (e.g. to make zonal regimes more populated, blocked regimes less populated), by making some regime transitions more likely, others less likely. For some regions, such as Europe, the overall bias associated with the SST anomalies may not be large, and their effect on regime statistics will require ensemble integrations (see section 4.4 below). A seasonal forecast from such an ensemble would give a probabilistic estimate of the likely occurence of specific Grosswetterlagen over the whole season, for example.

2.2 Empirical studies of seasonal predictability

2.2.1 *The tropics*

A particularly convincing piece of evidence for seasonal predictability is the fact that skilful seasonal timescale predictions are currently made on a real-time basis for a number of regions around the world. The models used for such predictions are based on empirical associations between elements of the general circulation of atmosphere and ocean derived from historical data. Such associations are used to define predictors of regional circulation or rainfall. A comprehensive review of seasonal prediction in the tropics using empirical models has been given by *Hastenrath* (1991).

The best known example of the use of empirical prediction modelling for operational seasonal prediction is for the Indian summer monsoon. Sir Gilbert Walker established the validity of many of the predictors for the monsoon used in contemporary empirical models, the Southern Oscillation in particular. Predictors in current models are based on upper-air flow over India, heat-low development over southern Asia, and ENSO (*Hastenrath*, 1991). The use of the latter two classes of predictors confirm the premise outlined above that lower boundary conditions (both sea-surface temperature and land-surface anomalies) contribute substantially to the seasonal predictability of the atmosphere.

An index of ENSO is a very important input to seasonal prediction models for many tropical areas. Fig. 1 (from *Halpert and Ropelewski*, 1992) shows a schematic of statistically significant teleconnections, in terms of surface temperature, during low (Fig. 1a) and high (Fig. 1b) phases of the Southern Oscillation. Examples of statistical predictions of ENSO are given regularly in the Climate Diagnostic Bulletin (Climate Analysis Center, NOAA) for lead times of several months. Extended predictions for several years have also been made by *Keppenne and Ghil* (1992) for the southern oscillation index, using a singular spectral analysis.

However, ENSO is not the only skilful predictor. For the African Sahel empirical studies (*Folland et al.*, 1991) indicate that the Indian and Atlantic oceans are also important. This conclusion, tentatively suggested by *Palmer* (1986) is well supported by an extensive set of modelling experiments (Folland personal communication) where SST is allowed to vary in one ocean at a time, or in combinations, with climatology being used elsewhere. In North East Brazil the Atlantic provides the most important predictors (*Ward and Folland*, 1991). Indian Ocean and Tropical West Pacific anomalies appear to be useful in predicting Australian winter rainfall.

Empirical models for prediction of the intensity of storm activity in the tropics over a season have also been tested with some success. *Gray* (1984, 1990) predicts the strength of hurricane activity in the Caribbean using ENSO, the QBO and Sahel rainfall estimates as predictors. The extent to which the QBO effects the tropical troposphere has yet to be understood theoretically. (This is partly because the QBO is difficult to model and, in fact, there are no published results from a comprehensive numerical model showing an unambiguous simulation of the QBO.)

2.2.2 *North America*

The observational basis for seasonal predictability over North America, and particularly for the United States, is considerable and leaves little doubt that such forecasts can often be made with sufficient skill to have economic value. The operational experience of the US National Weather Service and the results of a relatively large number of quantitative empirical studies are summarised by *Wagner* (1989) and *Livezey* (1990). In the latter, a strong case is made that the concentration of higher skill in certain seasons/regions is non-random and can thereby be more confidently exploited by certain users. In virtually all published results the highest skill is for prediction of temperature in late winter/early spring and the lowest for autumn forecasts, but useable skill exists for temperature/precipitation forecasts for several seasons in particular localities.

These forecasts, which consist of both subjective operational and objective laboratory predictions, have most heavily exploited a combination of known lagged correlations between antecedent SST and upper-air circulation anomalies and target season circulation (with specified surface implications). Recently (cf. especially the canonical correlation analyses of *Barnett and Preisendorfer*, 1987 and *Barnston*, 1993) it has become increasingly evident that the extratropical SST to upper-air height and height-to-height correlations are mostly proxy representations of the effects of interdecadal or tropical (especially ENSO) variability. Indeed, corollary work by *Livezey and Mo* (1987), *Barnston, Livezey and Halpert* (1991), and recent unpublished corroboration of aspects of their results (*Livezey*, personal communication) suggest the possibility of more specificity in ENSO-related winter temperature predictions over N America than the general single pattern results of *Horel and Wallace* (1981) and the highly filtered results of *Halpert and Ropelewski* (1992) have indicated. These possible gains in predictability appear to have their origins in variations in strength, timing and type of ENSO events or in the phase of the stratospheric QBO.

Of additional interest is the very recent linkage of the tropical Atlantic to the wintertime climate of eastern N America by *Wolter* (1989) and *Buchmann et al.* (1990). It is also linked (along with the tropical Pacific and Indian Ocean) to the northern summer's subtropical zonal circulation and US mean temperature by *Barnston* (1993). The latter expands and clarifies the observations made by *Erickson* (1983).

These developments, in concert with recent success in simulation/prediction of the tropical SST variability, imply the possibility of more decisive seasonal "forecasts of opportunity" in the near future for the United States and Canada.

2.2.3 *Europe*

The European region is remote from the tropical Pacific where El Niño originates. Nevertheless, as shown in Fig. 1, there is evidence of the influence of El Niño over Europe. Fraedrich and coworkers have studied this teleconnection more extensively and found a significant response. For example Fig. 2 (from *Fraedrich and Muller*, 1992) shows the regional response in Europe in terms of surface pressure, temperature and precipitation, of about 20 warm and cold strong El Niño events (since 1880). The response at stations with solid circles is deemed to be statistically significant at the 95% level though is generally rather weak. A study of European Grosswetterlagen during ENSO events is discussed in *Fraedrich* (1990) with similar conclusions. The more comprehensive study of *Halpert and Ropelewski* (1992) highlights a strong late winter/early spring ENSO cold event signal over southwestern Europe.

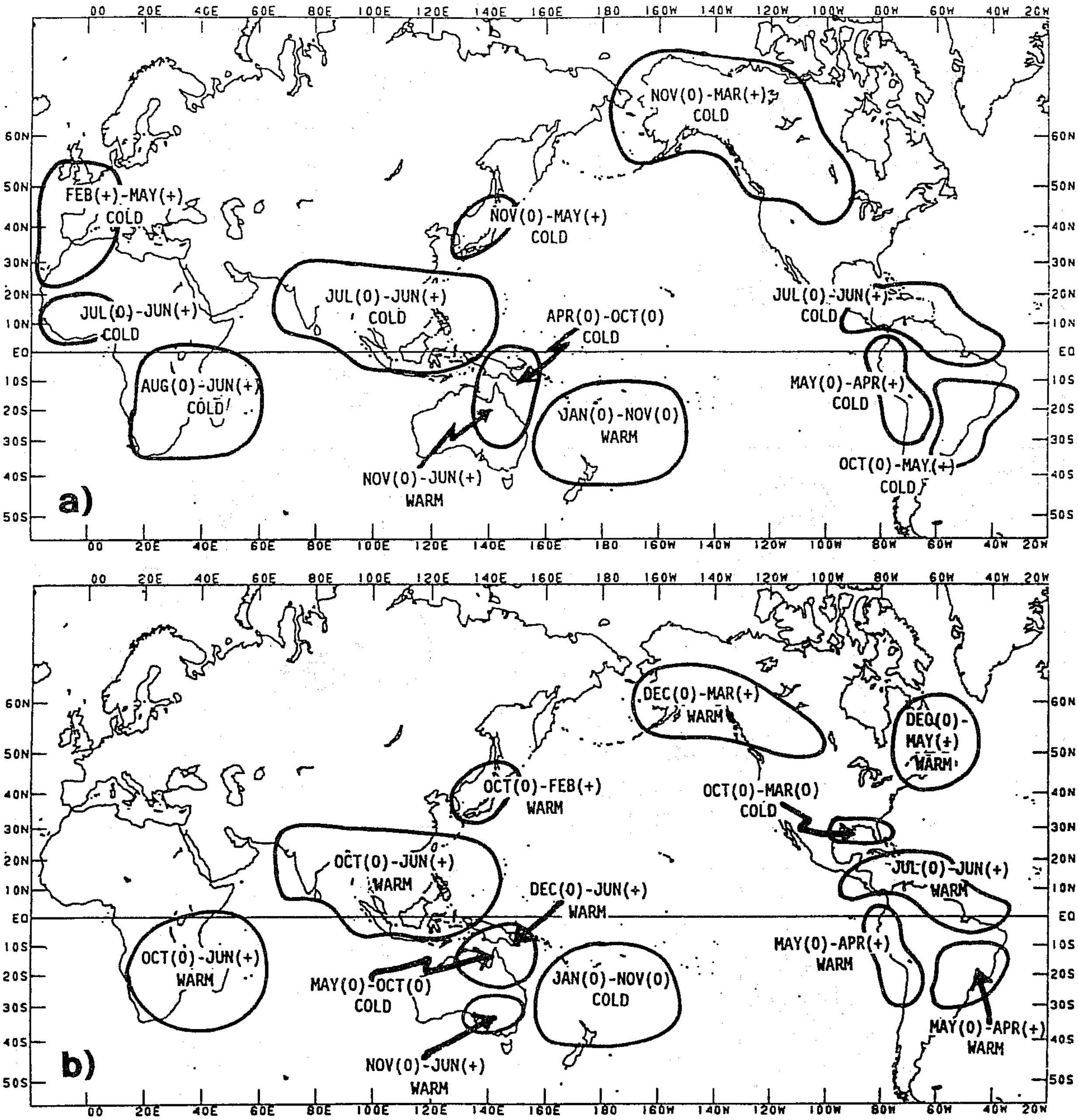


Fig.1 Schematic representation of the principal (a) high and (b) low SO-related temperature (from *Halpert and Ropelewski*, 1992).

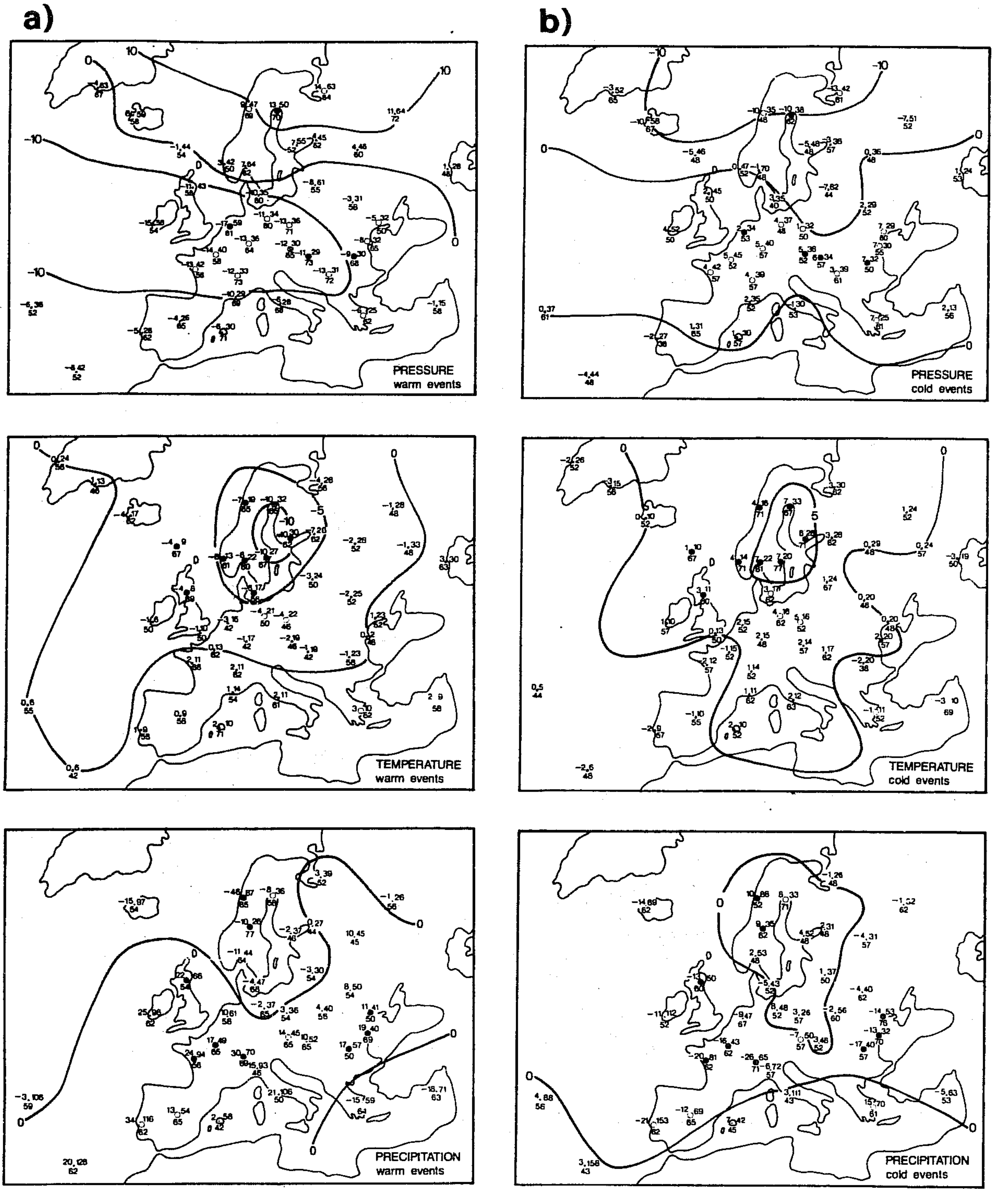


Fig.2 Regional response in Europe on ENSO warm (a) and cold (b) extremes in winter. From top to bottom: surface pressure, surface temperature and precipitation anomalies. The number written at the stations are in tenths of millibars tenths of degrees and millimetres respectively. Numbers represent the deviation from the long-term station mean (left) and the respective standard deviation (right) of the warm (cold) event ensembles. Below, the relative frequency (in per cent) indicates the percentage number of cold or warm-event winters that realise the same positive or negative sign as given by the mean anomaly (From *Fraedrich and Muller*, 1992).

In addition to the above-mentioned signals, *Barnston* (1993) also isolated a statistical connection between southwestern Europe in autumn and the global tropical/subtropical signal mentioned in the last section. Moreover, the studies by *Wolter* (1989) and *Buchmann et al.* (1990) involve teleconnections between the tropical Atlantic and the North Atlantic Oscillation; so these may add to the predictability of European winter.

The observational evidence that lower boundary forcing not associated with ENSO has a significant influence on the predictability of the atmospheric circulation over Europe is at present less clear. There is evidence that mid-latitude SST in the western north Atlantic may influence European weather over timescales of months (*Ratcliffe and Murray*, 1970; *Palmer and Sun*, 1985), though the predictability of the midlatitude SST anomalies themselves has not been established.

2.3 Sensitivity studies with atmospheric GCMS

2.3.1 *The tropics*

The impact of El Niño SST anomalies in atmospheric GCMs has been the focus of much study in the last decade or so. In the early phase of this work, many of the integrations were done in perpetual January mode (e.g. see the model intercomparison study *WCRP*, 1988). Whilst this created potential systematic biases in simulating the winter climate, the statistical significance of the impact of an imposed SST anomaly was easy to assess.

In the tropics, results were unambiguous. In terms of circulation variables such as 200 mb wind, the impact of a composite El Niño SST anomaly was statistically significant around the entire tropical belt. The skill in simulating the tropical large-scale flow with observed SSTs was uniformly superior to simulations with climatological SSTs.

More recently, GCM intercomparison exercises have been made assessing how well current models can simulate observed interannual variations in the summer monsoon circulations and rainfall when forced with observed SST (*WCRP*, 1992). Two specific periods were chosen for study: the El Niño summer 1987, and the La Niña summer year 1988. For both India and the sub-Saharan countries of Africa, 1987 was a severe drought year. In 1988, Sahel rainfall returned briefly to its long-term average, whilst Indian monsoon rainfall was well above average.

An example of three simulations of the difference of JJA rainfall between these two years is shown in Fig. 3a-c using T63 120-day integrations of the ECMWF model with observed SSTs. The only difference between the figures is that the starting dates of the integrations are separated by one day. Over the tropical Pacific and Atlantic regions, simulations of rainfall difference are very similar. Similarly, over much of the Sahel, simulated rainfall differences are relatively independent of starting condition. However, for India and much of SE Asia, the intrinsic predictability of rainfall on a regional scale, is much weaker. Further experimentation is needed to assess reliably the predictability of rainfall in this and other areas.

Skill in modelling interannual (and interdecadal) fluctuations in tropical North African rainfall, given observed SSTs, has been demonstrated in a set of integrations of the UKMO GCM. Fig 4 (from *Rowell et al.*, 1992) and *Folland* (personal communication) shows histograms of observed and simulated July-September rainfall for 10 past years for the Sahel and the Guinea coast. The ability of the model to simulate the relatively wet conditions that prevailed in the 1950s, and drought years in the 1980s is

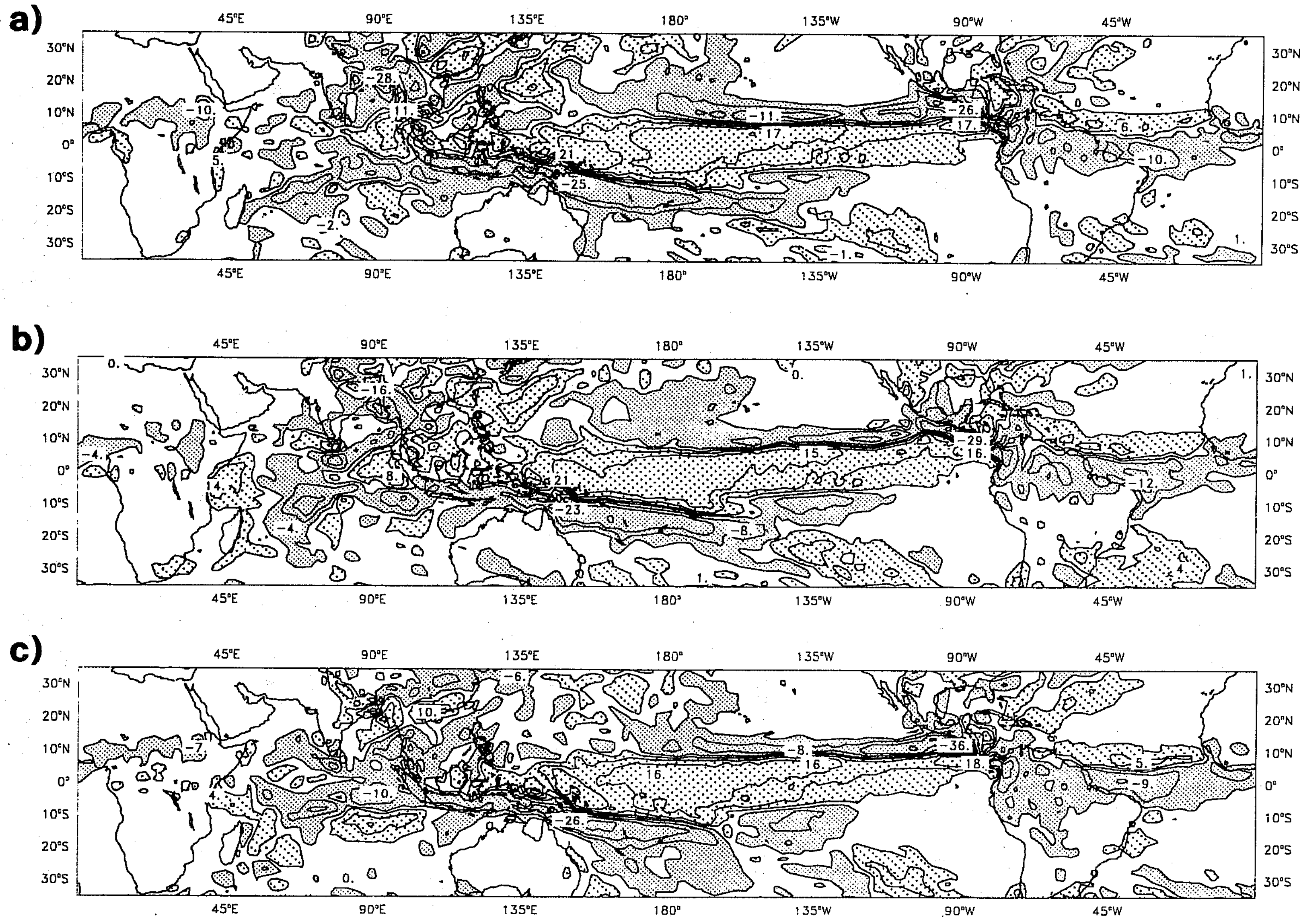


Fig.3 Simulated seasonal-mean rainfall difference between JJA 1987 and JJA 1988 in integrations made using observed SSTs. Differences from integrations initiated on a) 1 May b) 2 May c) 3 May.

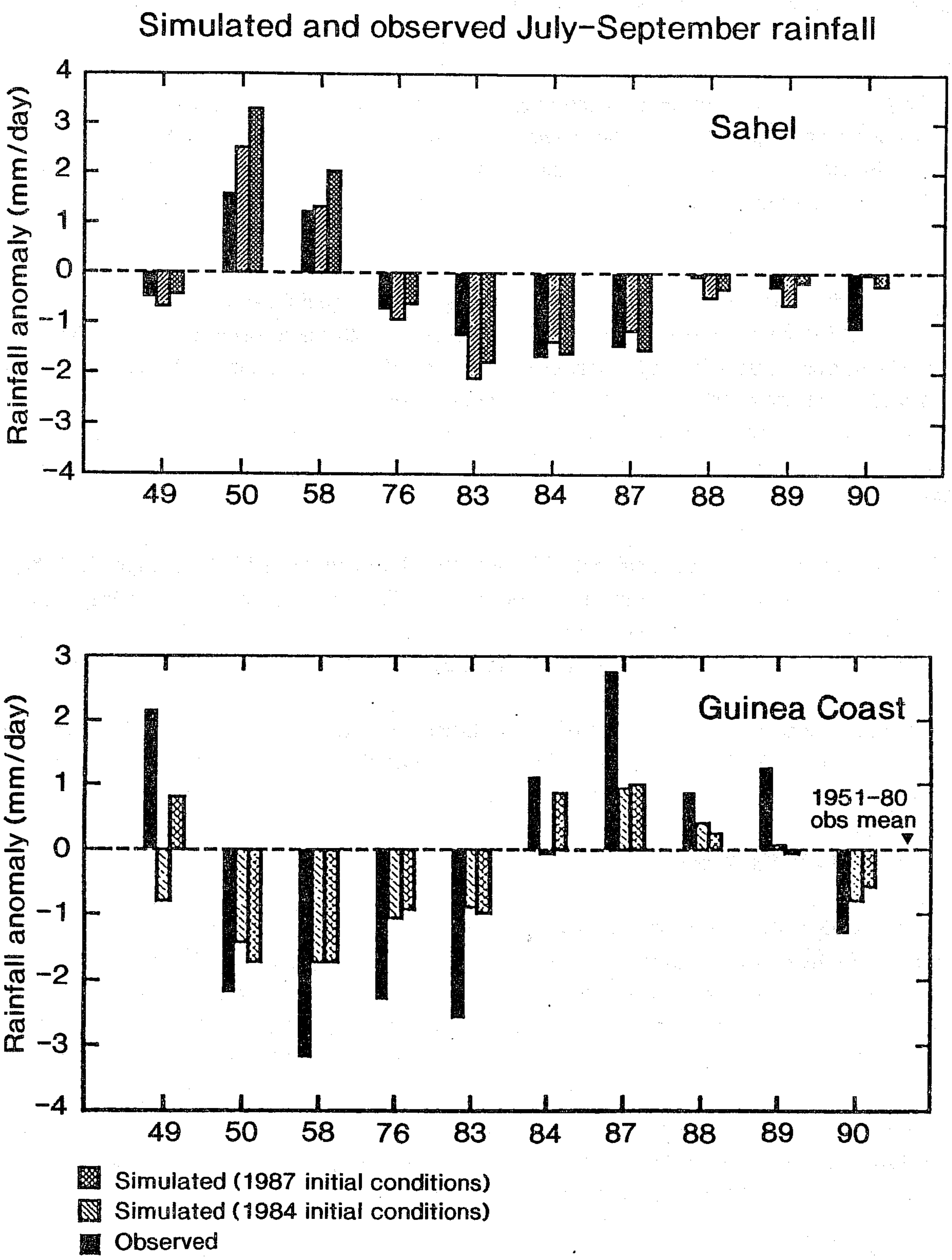


Fig.4 Histograms comparing observed (solid) and simulated July to September Sahel and Guinea Coast rainfall anomalies for ten past years using the UKMO climate model (integrations made with specified observed SST). The two simulations are run from different initial conditions. From *Rowell et al.*, 1992, and *Maskell and Rowell* personal communication.

remarkable. Consistent with the results above, there does not appear to be major sensitivity to initial conditions for this area. Studies to assess the sensitivity to analysis errors in SST are needed.

2.3.2 *Europe*

From the perpetual January experimentation referred to above, there was clear evidence of a statistically significant impact of tropical SSTs on the extratropical circulation over the north Pacific and much of north America. Further downstream, e.g. over Europe, results were mixed, although in the case with SST anomalies from the strong 1982/83 event, significant circulation anomalies over parts of Europe were found in the NCAR and UKMO models.

As an example from the current generation of models, Fig. 5 shows the difference between the mean of two ensembles of 120-day integrations of the T63 ECMWF model. Both ensembles comprised 9 elements, and were initialised from consecutive daily analyses from calendar dates 1-9 November. The first ensemble was initialised using data from 1986, and integrated with global observed SSTs from the El Niño winter 1986/87. The second ensemble was initialised using data from 1988, and integrated with observed SSTs from the La Niña winter 1988/89. Fig. 5a shows ensemble-mean 1000 mb height differences for DJF 1986/7 - 1988/9.

The simulated differences can be compared with the analyzed differences in 1000 mb height for 1986/87 - 1988/89 (Fig. 5b). In general the agreement is quite good. For example, the decrease in height over the tropical eastern Pacific and increase over Indonesia, consistent with a decrease in Southern Oscillation index, is well simulated. The decrease in height over the extratropical north-east Pacific, is also well reproduced.

Over the Atlantic and Europe, the pattern of height difference is well simulated though the magnitude of the difference field is clearly too weak, associated with considerable variability within the ensemble. This is consistent with the observational studies outlined above, that there is an impact of El Niño over Europe, though it is not large compared with the magnitude of internal variability. Indeed, the observed ENSO composites shown in Fig. 2, compare well with the difference field in Fig. 5b.

We note in passing that seasonal ensemble integrations made during the other seasons suggest that maximum predictability in the northern extratropical atmosphere may occur in spring (*Brankovic et al.*, 1993). For example, Figs. 6a, b show the European 850 mb temperature difference between MAM 1987 and MAM 1989 (El Niño and La Niña years respectively). Unlike the wintertime difference fields, the strength of the ensemble-mean differences over Europe is comparable with the analysis differences. Enhanced springtime predictability may arise because internal variability is weaker than in winter, whilst potential vorticity gradients, necessary for Rossby waves to communicate predictable signals from tropics to extratropics, are stronger than in summer. This result may be consistent with the analysis of *Halpert and Ropelewski* (1992) shown in Fig. 1, in which the most significant results over Europe appeared in spring.

As discussed above, there is also evidence that circulation anomalies over Europe on the seasonal timescale are correlated with SST anomalies not directly associated with El Niño. For example, model sensitivity studies have confirmed the observational correlations that midlatitude SST anomalies near Newfoundland can have an influence on downstream atmospheric development (*Palmer and Sun*, 1985). Qualitatively skilful simulations of the very blocked winter of 1962-63 were produced by *Rowntree* (1976) who related

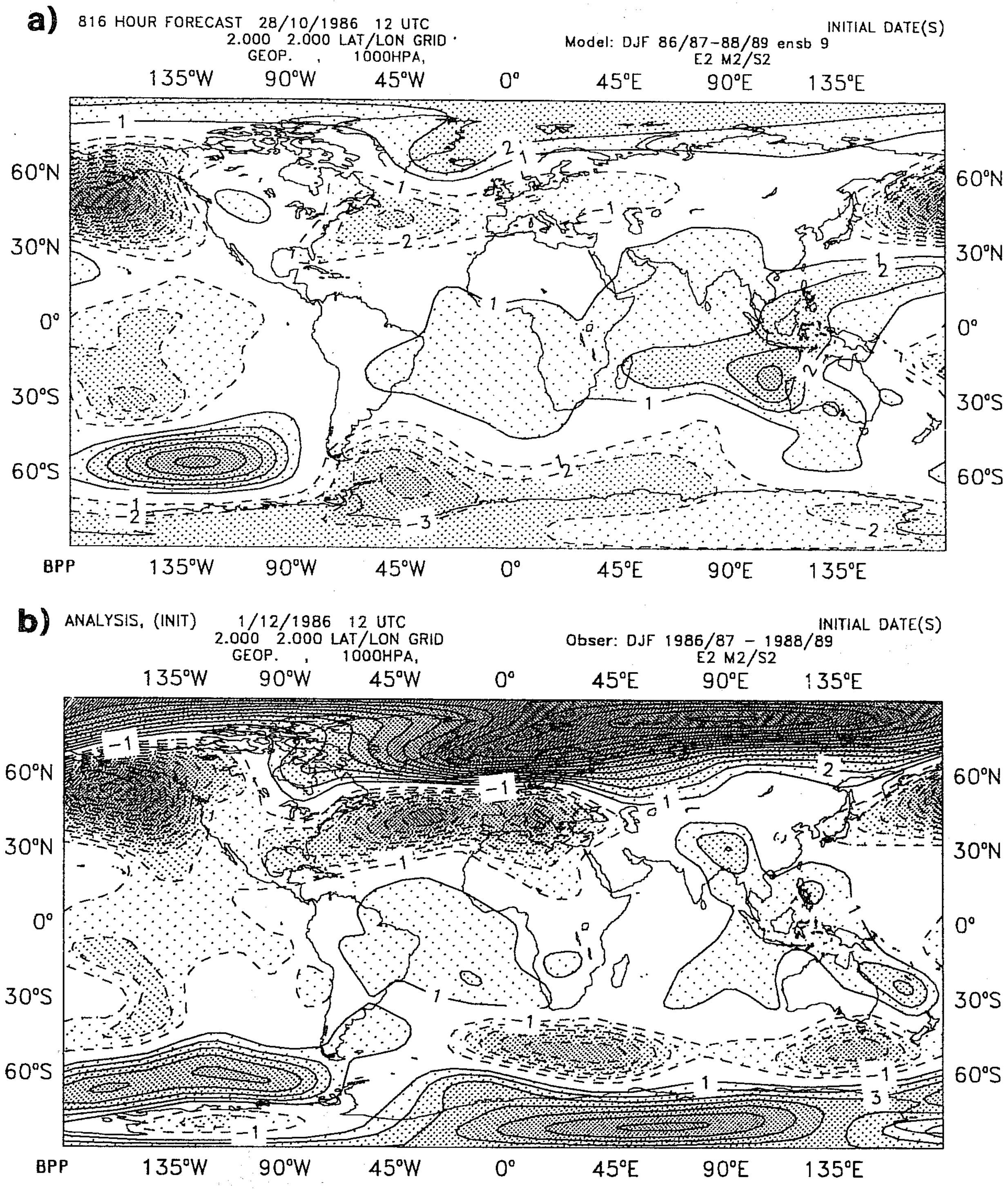


Fig.5 Seasonal-mean 1000 mb height difference estimates for DJF 1986/7-DJF 1988/9. a) from 9-member ensemble-mean integrations initiated on 1, 2..9 November and run with observed SSTs, b) from operational analyses. Contour interval 1 dam.

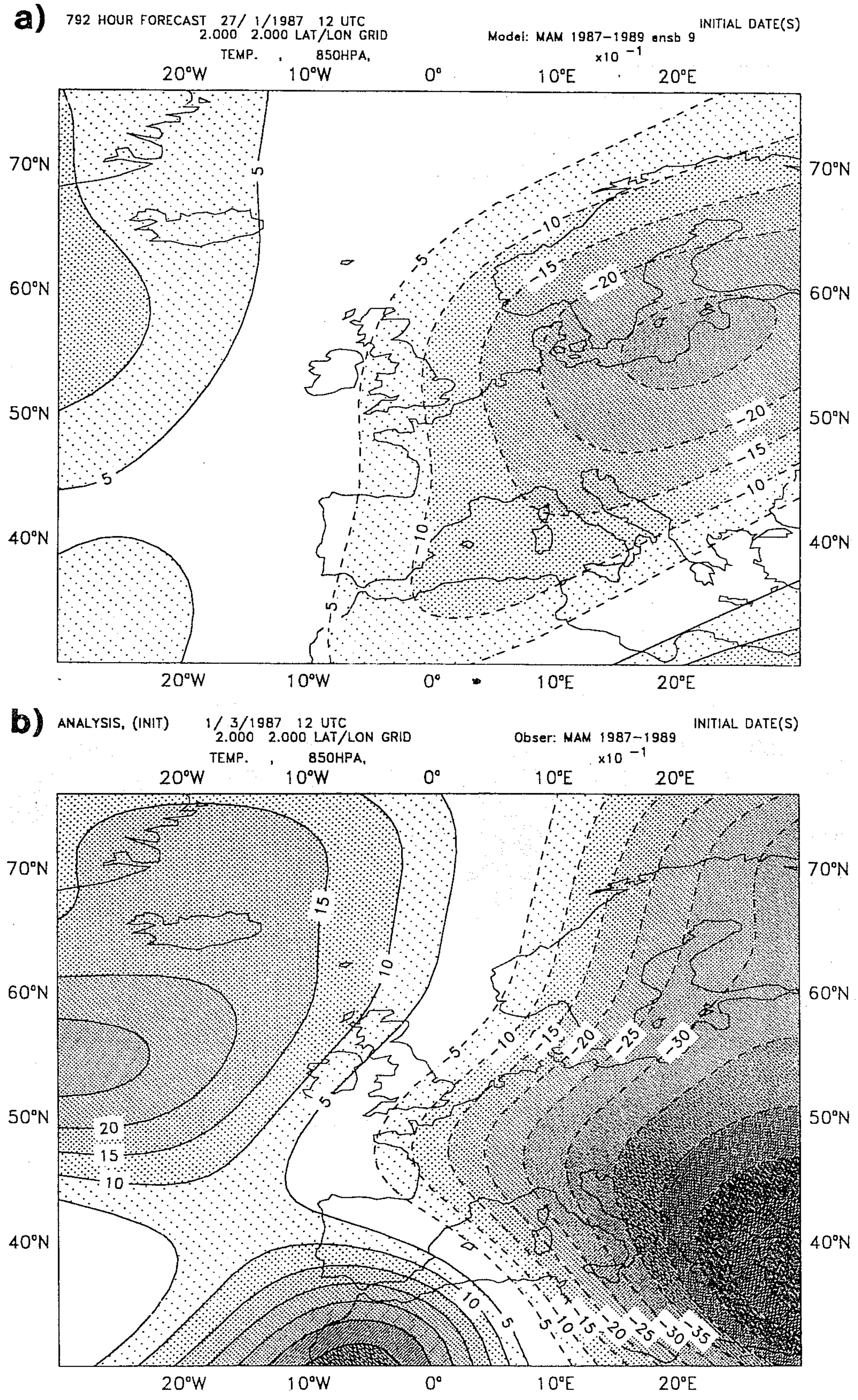


Fig.6 As Fig. 5 but for 850 mb temperature over Europe for MAM 1987-MAM 1989. Units are tenths of a degree K. Contour interval is therefore 0.5 K. Integrations started 1, 2...9 February.

the enhanced blocking to warm SST anomalies in the tropical North Atlantic, though this experiment should now be repeated with ensemble simulations to assess statistical significance.

2.4 Sensitivity studies with ocean models

Simulation of interannual variability, particularly El Niño events in the Pacific Ocean has been the focus of many modelling studies in the last decade. The fluxes of momentum, heat, and in some calculations fresh water, are needed in order to force ocean models. If these were known sufficiently accurately on the timescales appropriate for ocean modelling, then the accuracy of the modelling results could be more precisely assessed by comparing model output with ocean observations. Even so it might still be necessary (as at present) to provide appropriate feedbacks to the observed sea surface temperature and salinity fields to ensure that systematic errors in the forcing fluxes for heat and fresh water do not cause the model simulations to drift unrealistically. As it is, the errors in all forcing fields are sufficiently large as to create a serious hindrance in model verification. None the less, despite these uncertainties, it has been possible to validate ocean models to some useful degree and to show that they are capable of simulating important features of tropical Pacific interannual variability. Less is known about their ability to simulate interannual variability at mid-latitudes.

2.4.1 *Interannual variability of tropical SSTs*

The ocean has internal instabilities (eddies) just as the atmosphere, but their scale is small O(100 km) and in the tropics, at least, their role on the large-scale flow is thought to be weak. This means that the ocean is rather predictable in the sense that the large-scale ocean state is mainly determined by the external forcing from the atmosphere. Ideally, one would like to validate the ability of ocean models to reproduce SST variability globally but only in the tropical Pacific has this been done to any extent.

The only forcing field for which there is a long-term record is that of surface wind. The most widely used record is that prepared at FSU (*Legler and O'Brien*, 1985), for the tropical Pacific covering the last thirty years. Fig. 7 shows the response of one model in the central Pacific, over a 26-year period, together with the observed variability. This is typical of the behaviour found in a broad range of current tropical models. In such integrations, the atmospheric heat exchange, as supported by observations, is assumed to act as a negative feedback on SST anomalies.

Fig. 7 shows that this model is able to reproduce the observed variability rather well, given the many uncertainties in the forcing fields. It must be pointed out that this is a region in which models generally do quite well (correlations ~0.8), and not all regions would be simulated to this accuracy. In general, the coastal region off Ecuador and Peru is difficult to get right (correlations ~0.6), and the western Pacific is also a region where simulations are less accurate. It is not known how much of this can be ascribed to model error, and how much to forcing error.

A concise way of illustrating the ability of models to simulate variability is to calculate Empirical Orthogonal Functions (EOFs). Fig. 8 shows the first EOF of the observed anomalies in SST together with the corresponding EOF from a typical OGCM: the EOF peaks a little too far to the west compared to the observations and explains twice the variance. In most simulations the variability is too equatorially confined, with the variability in the subtropics underestimated. It is not known if this is a model deficiency or a consequence of the heat flux parametrization.

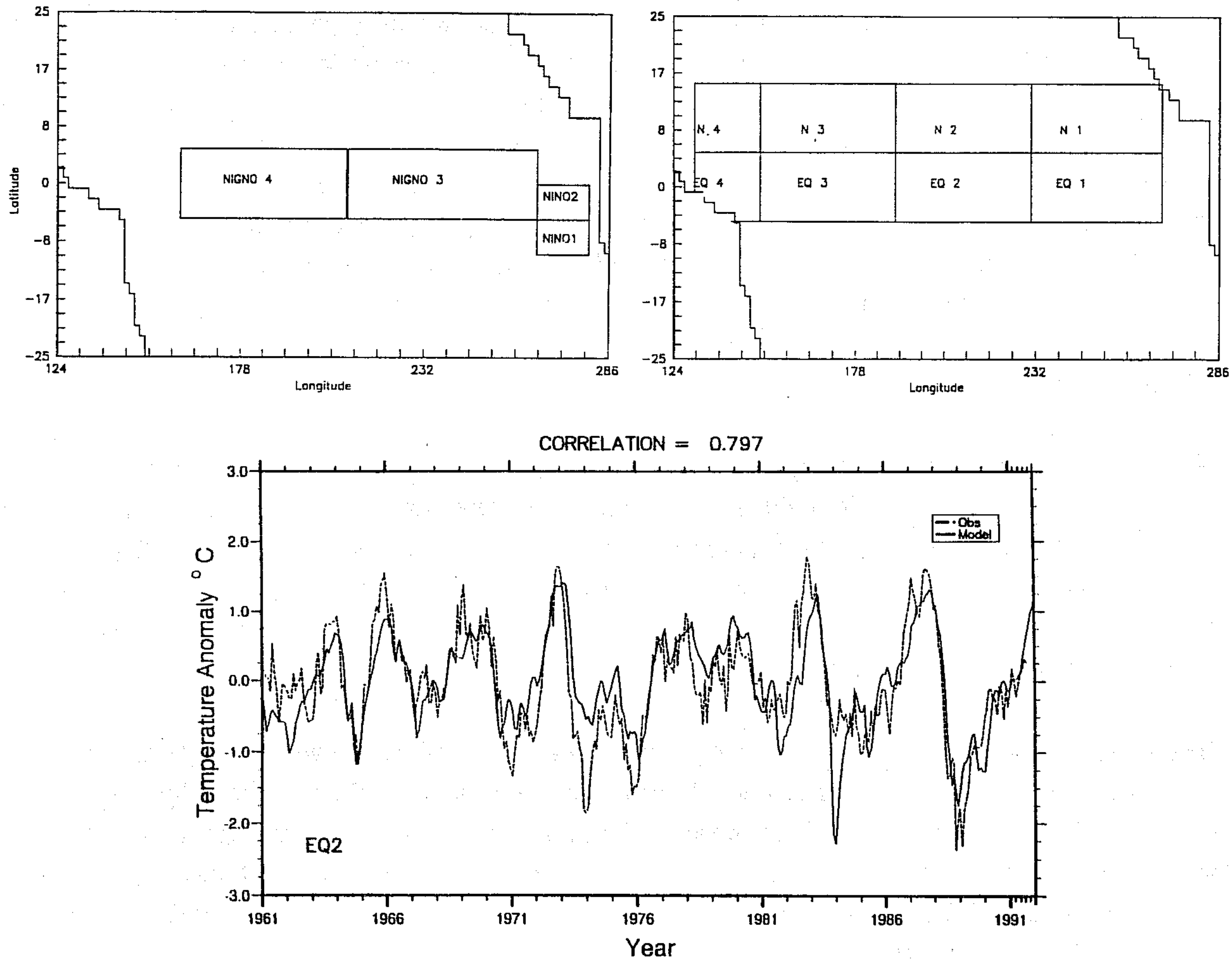
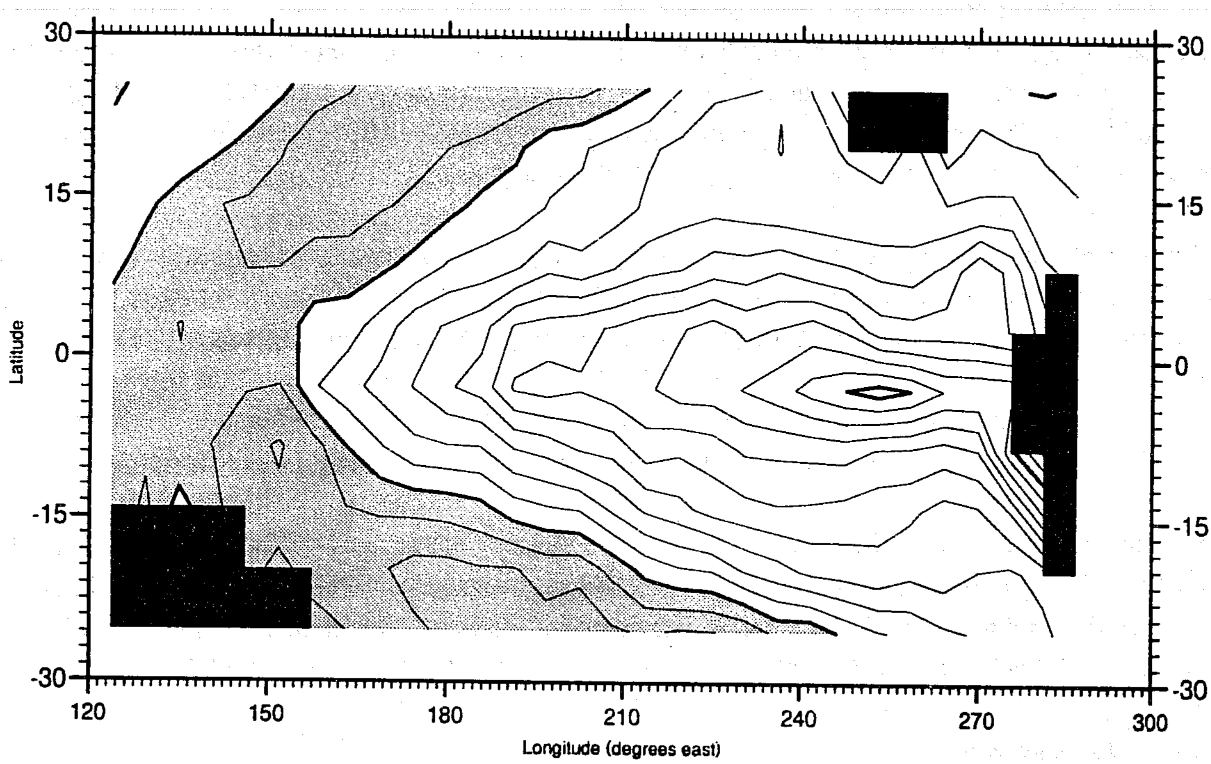
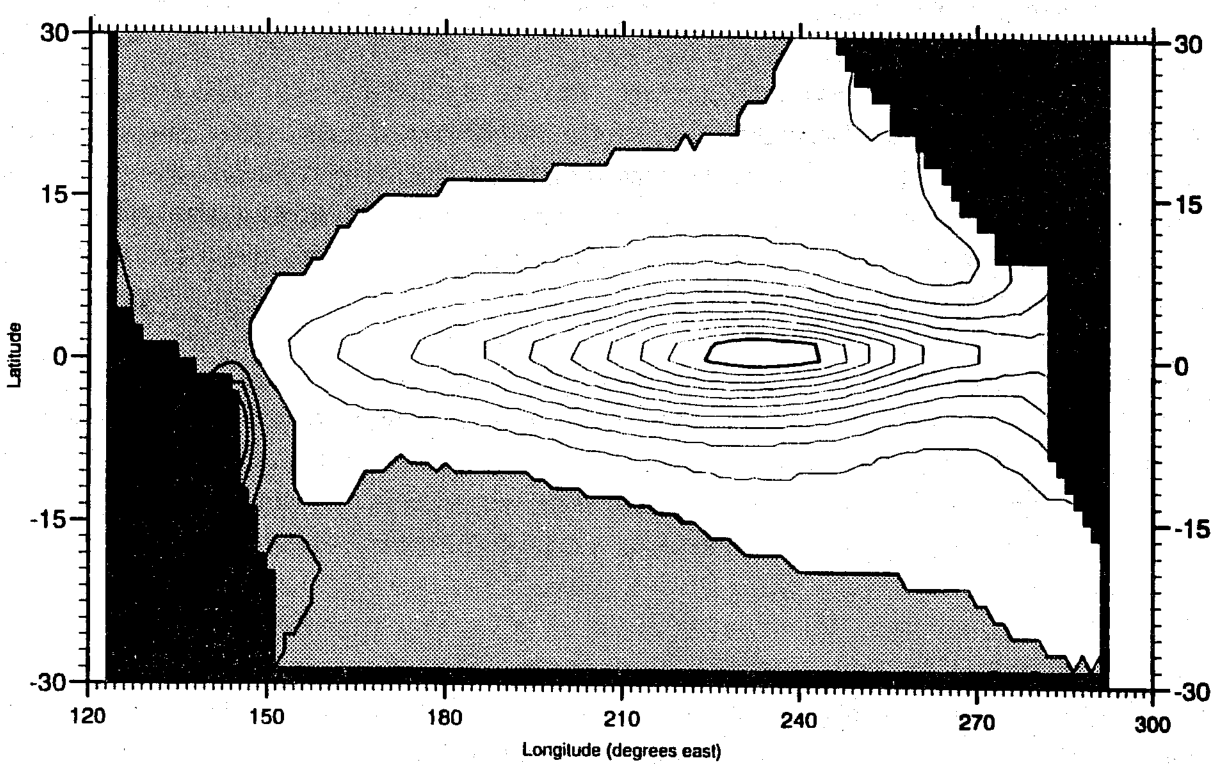


Fig.7 (lower panel) SST anomalies for the region EQ2 over a 30 year period (solid) from the model of *Balmaseda and Anderson* and the observed SST anomalies (dashed). The location of various frequently used regions are indicated in the upper panel.



a) SST (COADS); EOF 1; var=29.7%



b) SST (run WR): EOF 1 ; var=58.1%

Fig.8 First EOF of interannual variability in SST for a) observed, b) the model of Fig. 7.

Ocean models have also been run for limited periods using forcing fields from operational analyses (*Anderson and Carrington*, 1992), but since the quality of the analyses keeps changing, it is hard to draw significant detailed conclusions. Such studies can however be used to assess the gross properties of analyzed forcing fields and to intercompare products from different operational centres. More quantitative tests are needed using forcings from reanalysis projects, or from extended atmospheric integrations with observed SSTs. The Atmospheric Modelling Intercomparison Project (AMIP) experiments, now in progress, provide an opportunity to perform the latter over a 10 year period.

Other tests of ocean models have been made. Of particular relevance is an intercomparison of the seasonal cycle from different ocean models using the best estimate of the fluxes from seasonal cycle climatologies (*Stockdale et al.*, 1992). Over much (but not all of) the tropical Pacific, the best models can simulate the seasonal SST with an uncertainty which can probably be accounted for by errors in the forcing. In other words, these models probably cannot simulate the seasonal cycle better until the forcing fields are improved. Examples of the distribution and size of ocean model errors are shown in Fig. 9 for four different models.

Tests for the other oceans are mixed. The tropical Atlantic interannual and seasonal cycle has been modelled fairly extensively. A substantial tropical Atlantic anomaly occurred in 1984 following the large ENSO in the Pacific in 1982/3: this period has received particular attention by French modellers (see *Reverdin et al.* 1992). Simulations of Indian ocean variability are now being carried out.

2.4.2 *The extra tropics*

In the previous section, it was indicated that the lack of accurate surface flux fields is a serious hindrance to validating ocean models. None the less, there is good evidence that models can reproduce many of the more robust features of tropical Pacific variability, largely because the SST variability results from changes in the wind stress, with the heat flux playing a lesser role. In the extra tropics, this may not be true. The seasonal range of SST is much larger than in the tropics but interannual variations are generally smaller. Much of the seasonal range in SST results from surface heat flux, making simulation of SST more dependent on one of the poorly known fluxes. Further, there is less support in the extratropics for the idea that the atmospheric heat flux acts as a negative feedback. For these reasons, there have been fewer attempts to simulate SST variability than for the tropics.

In a recent study *Luksch et al.*, (1993) have performed a multi-year hindcast integration using the MPI-OGCM for the years 1950 to 1979. They chose to make a heat flux parametrization involving atmospheric advection, equivalent to specifying an atmospheric model, albeit a simple one. In this study the pattern and variability of low frequency SST anomalies was realistic (Fig. 10). The hindcast skill of the model was seasonally dependent, being better in winter, when the mixed layer is deep, than in summer when it is shallow.

In summary, there is an indication that SST changes in the extratropics result from local surface heat exchange as well as from wind-induced effects. However, more experience in simulating extratropical SSTs is needed. Although in some sense the physics and thermodynamics are easier than in the tropics, reproducing midlatitude SST variability may be harder because of the greater importance of net surface heat flux, a poorly-known quantity that is also difficult to predict.

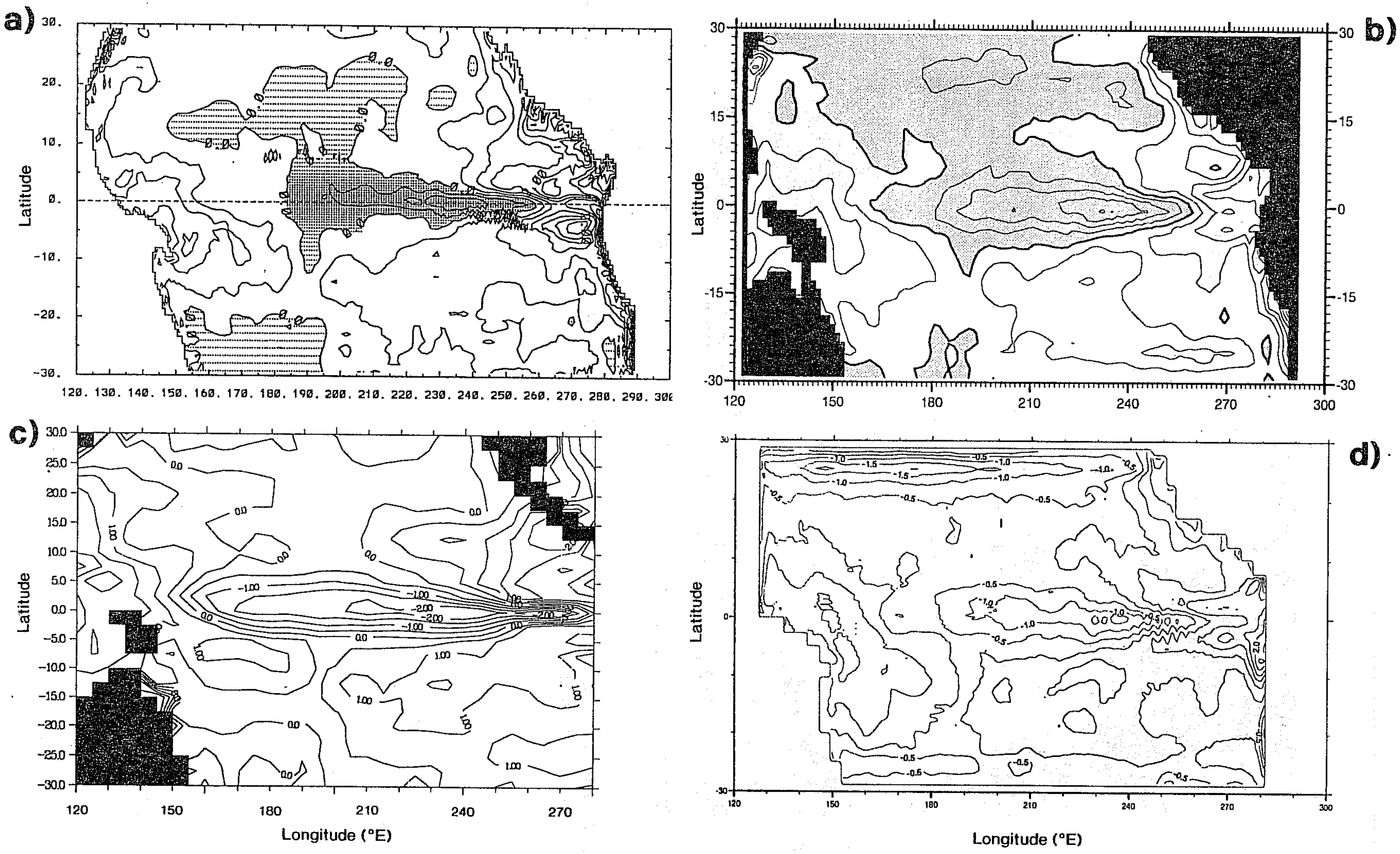


Fig.9 SST error from several ocean GCMs used to simulate the seasonal cycle. From *Stockdale et al.*(1992). Errors are for March, the contour interval is 0.5° C. The models are a) LODYC (Delecluse), b) Cox Bryan (Stockdale), c) MPI (Latif) and d) UKMO (Ineson/Davey).

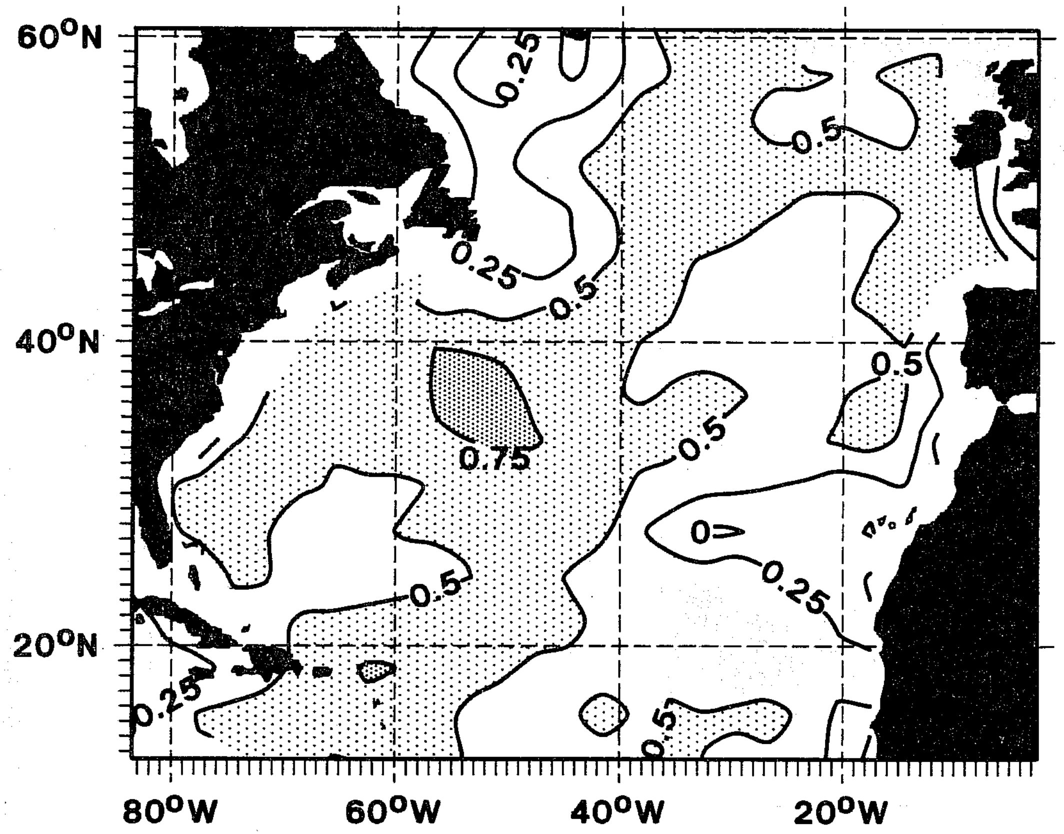


Fig.10 Correlation of observed and simulated SST from a multi-year ocean GCM integration forced with observed winds (Luksch, personal communication).

2.5 Atmosphere-biosphere interaction

Variations in vegetation produce changes in albedo, surface roughness and soil moisture, which in turn produce changes in ground temperature, evaporation and sensible heat flux. These influence the convergence of moisture, and hence convection and rainfall, which in turn alter the soil moisture. The nature and degree of this interaction depends on the character of the dynamical circulation regime where the land surface changes are taking place.

A large number of GCM sensitivity experiments have shown that the simulation and prediction of the seasonal surface temperature and rainfall over land, and of the mean diurnal cycle, are quite sensitive to the specification of the initial land moisture. It will be necessary to develop improved initialization and assimilation procedures to specify the initial land-surface properties and realistic parametrizations of energy and momentum exchanges between the atmosphere and the land surface.

The occurrence of prolonged droughts can be explained, at least in part, by such atmosphere-biosphere interactions. An accurate treatment of atmosphere-land processes is therefore important for prediction of seasonal mean surface temperature and rainfall.

2.6 Coupled model predictions

Coupled models of varying complexity are possible, ranging from fully coupled GCMs to hybrid models in which one component is a GCM but the other not, to intermediate models in which neither is a GCM. To date the most successful forecasts/hindcasts have been made by intermediate models. This is partly because they are run in perturbation mode (i.e. with specified mean climatology) and therefore avoid or restrain climate drift. However, a number of coupled GCMs are being developed and it is anticipated that their skill will ultimately surpass that of the intermediate models.

Fig. 11 shows the correlation between hindcasts of the temperature in NINO3 and the observed SST there, based on a 30-year period obtained from the intermediate model of *Cane and Zebiak* (1987; hereafter CZ) given by the dotted curve. Forecasts are made every month based on the initial state of the ocean. This is in turn obtained using only information on the surface wind. No ocean data are assimilated into the model. Likewise no atmospheric data are used, as the atmosphere is assumed to be in equilibrium with the ocean. As a consequence, whenever SST is known, the atmospheric state is derivable. Only the surface wind is predicted in such a model. Any estimate of rainfall would be indirect, for example, based on correlations between rainfall and SST.

No equivalent comprehensive comparison has been carried out with a coupled GCM, but Fig. 12 shows the results of various predictions using a coupled GCM model for 5 different events. For each event there were 4 forecasts each starting 3 months apart. The correlation of GCM with observed SST is shown in Fig. 11 for the average of the 20 forecasts for comparison with the results from the CZ model, and for other models. Both this and Fig. 12 show that the models have useful predictability out to about 12-15 months before there is a rapid collapse in skill. However, the skill, while high in the early months is not significantly better than persistence. It is only at lead times greater than 3 months that skill of the models is higher. This is partly a function of the initialisation process. Because the model initial state is not obtained from ocean measurements but from the past history of the wind field then the ocean initial state does not match the observed temperatures as well as it could. Hence the correlations of Fig. 11 are not 1 at zero lead.

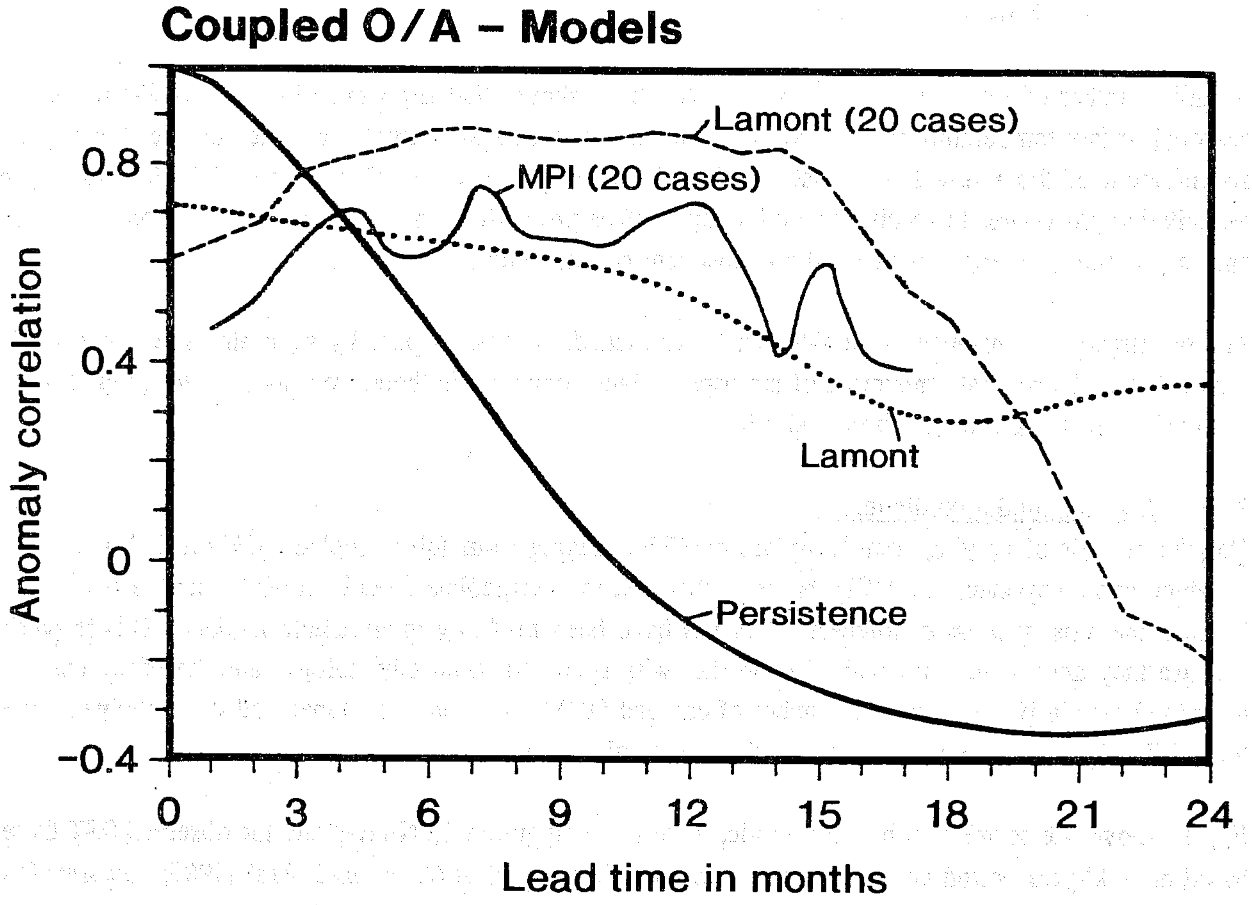


Fig.11 Anomaly correlation of SST in NINO3 region (see Fig. 7) for the 20 hindcasts of Fig. 12 for the MPI GCM (solid) and the Lamont (CZ) model (dashed). In addition the skill over all CZ forecasts for a 30 year period is shown by the dotted curve, and persistence by the solid curve. The model hindcasts do not beat persistence for the first few months. This is partly a reflection of the way models are initialised. From *Latif et al*, 1992.

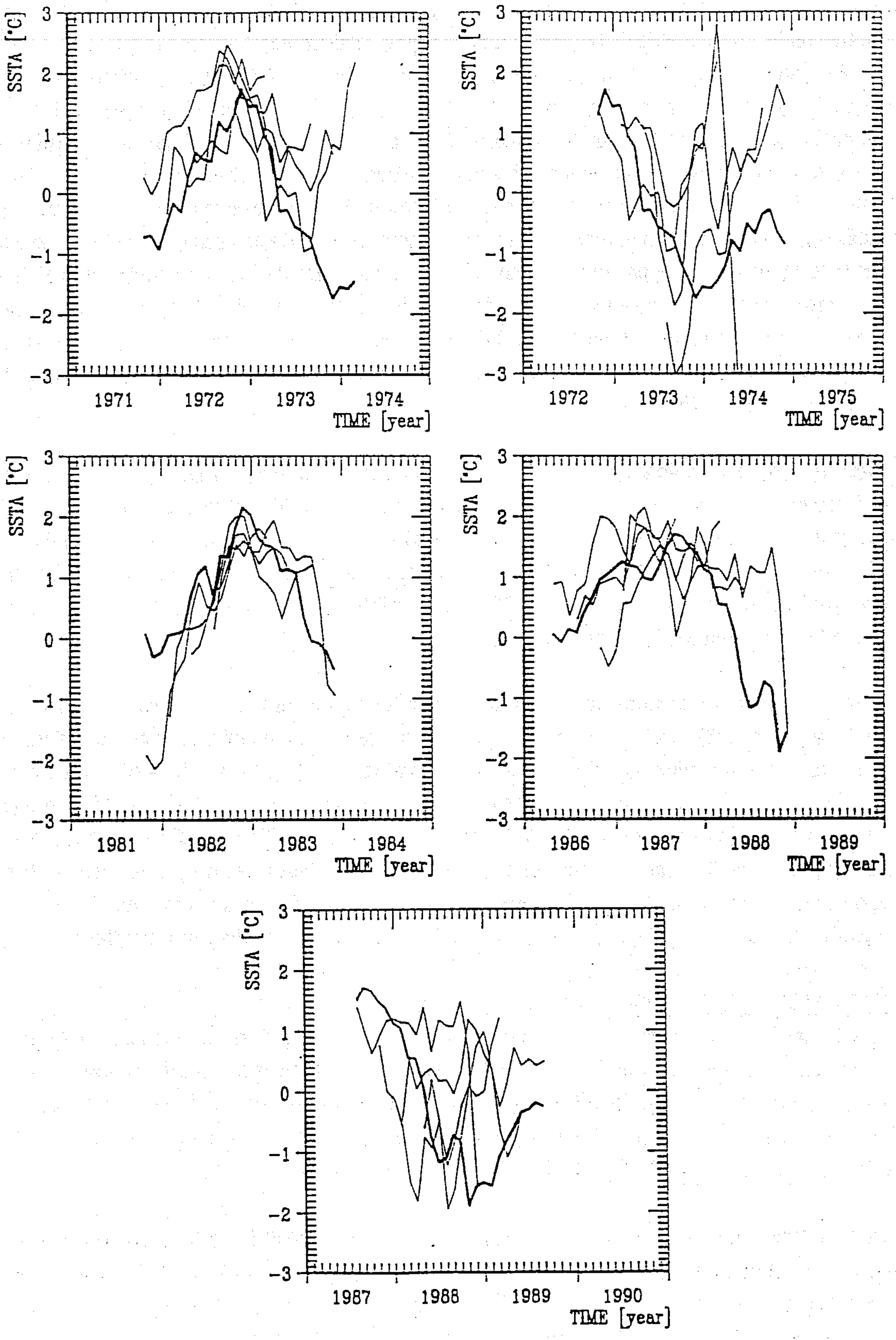


Fig.12 Hindcasts of NINO3 SST for 5 periods using the MPI GCM. The heavy line shows the observed anomalies. For each event there are 4 hindcasts started 3 months apart.

More recently, Leetmaa, Kumar and Ji (personal communication) have used an ocean assimilation scheme to obtain initial states for coupled integrations. Results to date are limited to the years 1984-91 in which there were two realisations of ENSO, but appear encouraging. This forecast scheme is rather comprehensive as it is based on an end to end system. The ocean state from which the hindcast is launched is derived from assimilation of subsurface thermal information as well as SST and the surface wind stress. A high level of dynamical consistency between the analysis and the forecast components is maintained to ensure that the analyzed ocean initial states do not undergo a sudden change at the beginning of the forecast, leading to loss of information. The forecast model consists of comprehensive atmospheric and oceanic models. Considerable effort was expended to tune the physical parametrization schemes in order to obtain sufficiently strong winds to maintain the appropriate ocean subsurface structure during the coupled model forecasts. Even so, the model is not fully coupled as some intervention to the atmospheric momentum and solar heat fluxes is made in order to reduce climate drift. For July initial conditions, skill scores for DJF predictions, of over 0.9 prevail over most of the central and eastern Pacific and are better than the skill scores obtained with a persistence forecast (Fig. 13).

The predictability of the tropical system is a function of the initial state. Fig. 14 shows the skill as a function of season. Forecasts initiated in winter are less skilful than those initiated after spring. This is certainly a function of the sensitivity of the coupled system to error in the initial state. Persistence also has a similar seasonal skill dependence, with correlations of about 0.8 for the first few months, but dropping much more rapidly than the models thereafter. There is possibly also a sensitivity to the phase of the ENSO cycle but this has not been explored properly to date.

In conclusion, it has been demonstrated that predictability to the order of 1 year is possible. Most experience is with the (CZ) model. The model predicts the temperatures of a largish area of the tropical Pacific. This allows a statement of whether ENSO is coming or not and some idea of intensity but does not give a direct prediction of rainfall or other quantities of interest although they could in principle be obtained from correlations between model SST and these quantities. To date, CGCMs have not shown greater skill than intermediate models, but this is probably because they have only very recently been used in prediction mode. Climate drift may be a problem in coupled GCMs and so some may be run in a way which allows perturbation coupling, as in the intermediate models, rather than full coupling.

3. RELATIONSHIP TO MONTHLY PREDICTION

Monthly prediction lies within the time frame of seasonal prediction and in some respects requires use of similar dynamical techniques to seasonal prediction. In particular forecasts on both monthly and seasonal timescales are sensitive to initial conditions and benefit from the use of ensemble techniques. On the monthly timescale the influence of slowly-varying anomalous boundary forcing is weaker than on the seasonal timescale (*Palmer*, 1987, Fig. 12).

In practice this means that a weather forecast for the next month could be quite unskilful, if changes in atmospheric flow on this timescale are dominated by unpredictable patterns of variability; whilst forecasts for the next season could show some skill if these unpredictable internal modes of variability are less dominant (compared with the effects of anomalous boundary conditions) when averaged over the whole season.

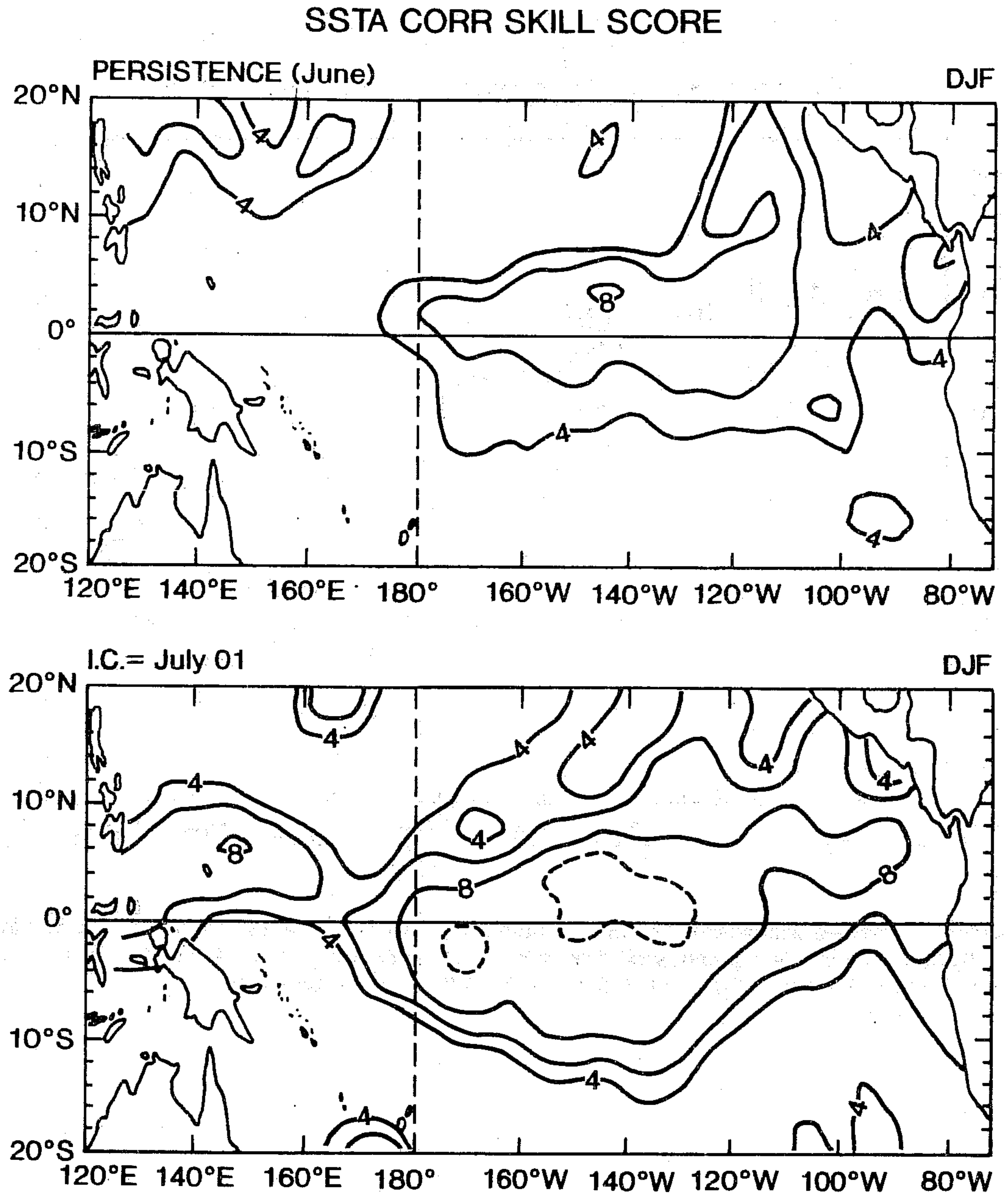


Fig.13 Plot of the correlation of predicted SST with observed in DJF, for the last 6 years. In the lower panel the SST is obtained from the NMC coupled model initialised in July. In the upper panel persistence from June is used. From Kumar, Ji and Leetmaa.

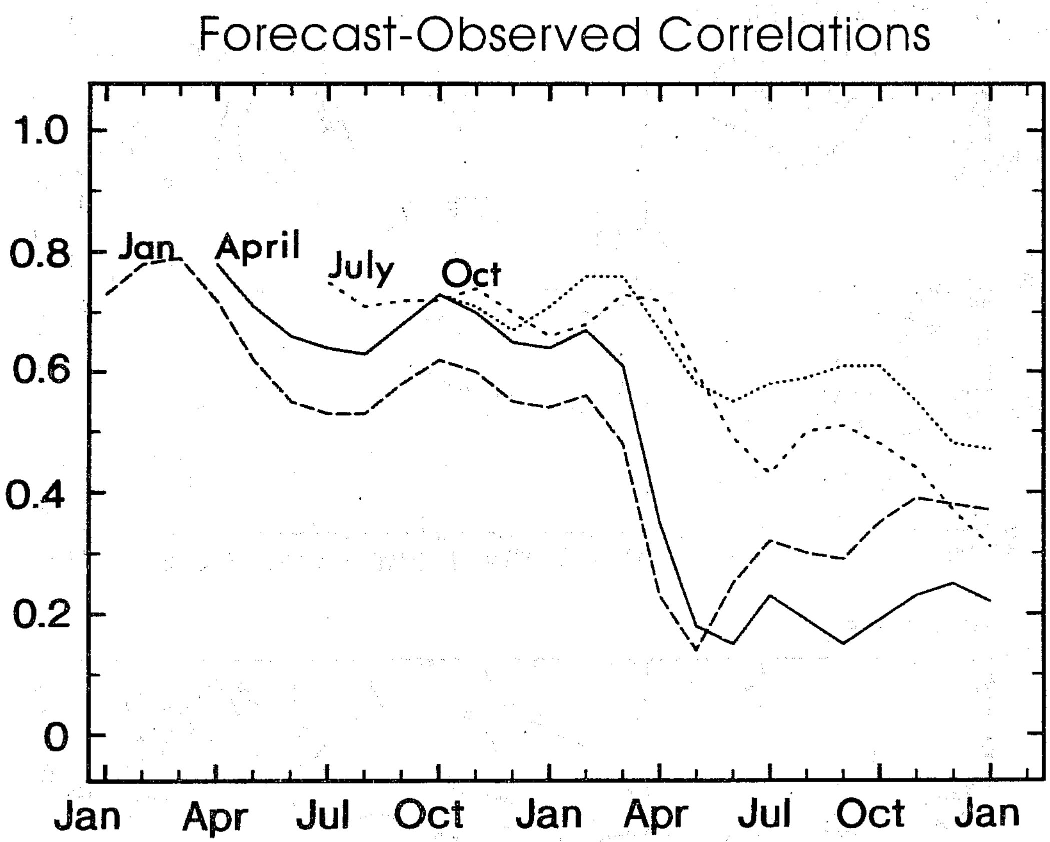


Fig.14 Correlation of observed and hindcast Niño3 SST, from the CZ model. While this figure shows a drop in predicted skill in Spring it is much less pronounced than in some other models. Forecasts initiated in January have the shortest predictive leadtime. Those initiated in April have the longest useful lead.

However, certain internal low-frequency extratropical structures persist or oscillate within monthly timescales possibly giving rise to above-average predictability (*Branstator*, 1987; *Plaut and Vautard*, 1992). As far as can be assessed at present, coupled interactions between ocean and atmosphere are not such a major influence on atmospheric predictability on the monthly timescale. Therefore the monthly prediction problem may be treated as a straightforward extension of the medium-range forecast problem, though arguably it is possible that coupling to 1-D mixed layer ocean dynamics in the extratropics may be beneficial.

3.1 The tropics

In the tropics, the most important mode of variability on the monthly timescale is the Madden-Julian oscillation. Studies from medium-range forecasts at ECMWF (G. Boer, personal communication) indicate that by day 10, skill in predicting the phase and amplitude of the oscillation is generally poor. On the other hand, some successful forecasts over monthly timescales have been made (*Krishnamurti*, 1991). It is likely that skilful prediction of the Madden-Julian oscillation depends critically on the quality of initial analyses in the tropics, particularly in respect to the divergent and associated diabatic heating fields. It is believed that skilful prediction of the Madden-Julian oscillation in the tropics would have some impact on the skill of extended-range forecasts in the extratropics (*Ferranti et al.*, 1991).

From both seasonal GCM integrations with observed SSTs (*Rowell et al.*, 1992), and from empirical model results (S. Hastenrath, personal communication), it appears that little skill has been found in predicting fluctuations in monthly mean fields about a seasonal average.

3.2 Europe

Extratropical prediction on monthly timescales has been the focus of many studies both statistical (e.g. *Folland and Woodcock*, 1986) and dynamical (e.g. *Royer*, 1991). In general, anomaly correlation coefficients from dynamical forecasts for monthly time averages are positive, and better than persistence of either initial conditions, or the anomaly of the previous month. However, the skill of temperature forecasts is small beyond the medium-range, and exhibits a strong case-to-case variability. As far as rainfall is concerned, there is no evidence of any skill with present models beyond day 15. Expectations that useful predictability of large-scale flow arising from memory of the atmospheric initial conditions might only extend to 15 or possible 20 days is consistent with other studies (*Palmer et al.*, 1990).

4. MODELLING NEEDS FOR SEASONAL FORECASTING

4.1 Atmospheric model development and sensitivity studies

Successful seasonal predictions require accurate parametrization of surface fluxes, radiative transfer and convection especially in the tropics. Diagnosis of operational model forecasts and climate integrations suggest that local errors in total heat flux at the surface can exceed 40 W/m^2 even with observed SSTs. Further development of physical parametrizations is therefore required before reliable seasonal forecasts are possible.

Further studies are required to assess potential predictability on the seasonal timescale. With prescribed observed SSTs using ensemble techniques, it will be possible to assess the impact of observed variations in SST on specific seasonal-mean rainfall or circulation anomalies. The impact of SST anomalies in individual oceans can be isolated by further ensemble integrations.

It is unlikely that reliable statistics can be achieved with ensemble sizes less than about 10. Moreover, models must have sufficient horizontal resolution to be able to simulate rainfall and circulation anomalies on the scale of hundreds of kilometres; about T63 resolution might be considered desirable.

More work is required to assess the impact of observed land-surface anomalies on seasonal predictability. One of the difficulties in performing such integrations is the lack of reliable land-surface forcing data. Re-analysis will produce a more homogeneous source of data which could be used to study the impact of specific interannual variations in land surface forcing.

4.2 Ocean model development

The purpose of ocean simulations in this context is to increase understanding of ocean dynamics/ thermodynamics and to improve model parametrization/ formulation. One of the main uncertainties is in the way vertical mixing is parametrized which in turn is not independent of vertical discretisation. Two possible approaches are in use: to split the ocean into fixed depth levels or variable depth layers. (A generalised coordinate system is also possible but not much used). Horizontal resolution should not be a major issue as the incremental cost of having a well-resolved ocean model coupled to an atmospheric GCM is not very large (assuming there is no need to resolve the eddy scale for seasonal forecasts.) It is better to use an ocean GCM and, if necessary, to embed a mixed layer model within it, than to develop a stand alone mixed-layer model. The latter strategy might be adequate for some mid-latitude purposes but not for modelling the tropics. Within Europe, a number of ocean models are in use, of both the level and layer type and a significant amount of experience in running such models and in parametrization exists. Some systematic comparison between ocean models has been carried out. Reanalysed data sets may provide the opportunity for improved forcing in future studies of this type.

Due attention should be given to coupling of the OGCM to the atmospheric model. *Janssen and Kattenberg* (1992) have shown that heat flux errors can be reduced significantly by including a suitable mixed layer model in the OGCM. They also found a clear relation between the mixed layer formulation and the dynamical behaviour of the ocean model. Attention should also be paid to the possible role of surface waves. Recently, it was found that waves can have a significant effect on the momentum flux. (*Janssen*, 1989, 1991). Simulations by *Weber et al.* (1992) indicate that this effect may be parametrized in coarse resolution runs. Whether this result can be generalised is still under investigation. The WAM model, a reliable global ocean wave model is operational at ECMWF, and will be used to further investigate the effect of waves on the momentum flux.

In coupled integrations the ocean state is of paramount importance. Some work has been done to asses the growth of error in the coupled system for both tropical and extratropical regions. *Blumenthal* (1991) found the most rapidly growing modes of the CZ model. *Miller* (1991) has considered the error growth in midlatitudes using a QG ocean model coupled to a two-layer atmosphere. He found that it was better to use the observed SST anomaly than climatology but that persisting the anomaly was as good as using the predicted SST. This latter result indicates the likely difficulty in predicting mid-latitude SST, alluded to earlier.

4.3 Data assimilation requirements

In the initial phases of hindcast experimentation it will be possible to create initial ocean states without the benefit of ocean data assimilation. Given the availability of re-analyzed products, a convenient and fruitful method would be to spin up the ocean surface layers to an observed state using "analyzed" fluxes and wind stresses from the reanalysis datasets over a period of a couple of years or so preceding the initial date of interest. However this is unlikely to be adequate in the longer term and a proper ocean analysis system is required.

More generally, an initial ocean-atmosphere dataset is best produced using all available information, in both atmosphere and ocean. The development of a 4-dimensional variational data assimilation technique would appear most suitable for this purpose. Extension of this for the seasonal problem requires construction of a forward and adjoint tangent coupled model. Development of such coupled tangent models will be useful for the study of predictability on seasonal timescales.

The WAM model can be used to assimilate satellite observations of the sea surface. Joint assimilation of all wind and wave observations (conventional and satellite) will be useful for the initialisation of a coupled run.

4.4 Ensemble integration techniques

From coupled integration studies performed so far, seasonal predictive skill appears to depend considerably on such factors as the time of year and the state of ENSO when predictions are initialised. Moreover, because of the internal dynamics of the atmosphere, there is no unique determinate response to some prescribed SST anomaly field. These results suggest that seasonal prediction is best thought of as an attempt to estimate the probability distribution of forecast states of the atmosphere and ocean.

Research is already well developed to reformulate the medium-range forecast problem from forecasting a unique deterministic state, to predicting a probability distribution of states. In the medium range, it is believed that such a distribution arises primarily because of uncertainties in initial state. For seasonal prediction, uncertainties in the parametrization of physical and dynamical processes in the atmosphere and ocean may also contribute significantly to the overall forecast probability distribution function. (Even when climate modelling has reached the stage when climate simulations are of reasonable verisimilitude, one cannot assume that there will be one unique choice of parametrization schemes that is associated with smallest systematic error.)

Ensemble prediction is a way to estimate the probability distribution of forecast states through a finite sample of deterministic integrations. For seasonal prediction, it will be necessary to construct the ensembles both from sets of initial conditions each equally consistent with the available initial data, and from ensembles of models, whose climates are each equally consistent with the available climate data.

Methods of calculation of the most effective initial perturbations for seasonal prediction may be just as complex as they can be for medium-range forecasting. It may be possible, for example, to use a tangent model of the coupled system to estimate singular vectors optimised for a season. If a tangent model has been developed for ocean-atmosphere data assimilation, then such vectors can, in principle, be calculated. Much research would be needed to study the practicality of using such types of perturbations, and to compare with simpler methods such as time-lagged techniques where forecasts are run from consecutive analyses.

There is a simple approach to the problem of perturbing model physics, provided seasonal prediction experiments with ensembles of forecasts are being made with different models. By taking a grand ensemble from all individual ensembles, and estimating forecast probability distributions from this total ensemble, perturbations in both initial state and model formulation can be taken into account. Moreover, with, for example, three or four different forecast centres contributing, a total ensemble size of $0(10^2)$ may be feasible in the future. From such an ensemble, reliable probability forecasts including cluster analyses of forecast states should be feasible on the seasonal timescale.

To give a simple example of the type of probabilistic analysis possible with ensemble forecasts, Fig. 15 shows the probability estimate of 850 mb temperature from the ensembles whose mean difference was shown in Fig. 7. Fig. 15a shows the probability that the MAM 1987 - MAM 1989 850 mb temperature over Europe is less than zero, whilst Fig. 15b shows the probability that it is greater than zero. The verifying field was shown in Fig. 7b. Such a probabilistic analysis is considerably more useful and informative than is possible from an ensemble averaged quantity.

A probabilistic forecast of tropical rainfall, based on 9-member ensembles for JJA 1987 and 1988, is shown in Fig. 16. (1987 was a drought year, relative to 1988 over sub-Saharan Africa and India). The maps show that Indian rainfall is less predictable than African.

5. THE BENEFITS OF DEVELOPING A SEASONAL-TIMESCALE FORECAST CAPABILITY

5.1 Predictions of seasonal circulation and rainfall for Europe

Whilst there can be little doubt of the economic importance of a totally skilful deterministic seasonal prediction capability, it must be recognised that a seasonal-timescale prediction, especially in extratropical regions such as Europe will take the form of a probability distribution function for forecast variables such as temperature or rainfall. Only in exceptional circumstances will such distributions have a sharp unimodal peak, and in many cases the difference from a climatological probability distribution may be small. Whilst there are already customers (e.g. some European energy companies) that have the capability to make direct use of products in which a range of forecast alternatives are specified with varying probability, the economic impact of such probability predictions has not been quantified.

The potential benefit of skilful seasonal predictions for developed countries in the extratropics has been most comprehensively discussed in the context of the United States economy. For example, according to *O'Brien* (1992), the potential savings in the U.S. for the agriculture sector of the economy is $0.5-1.1 billion dollars over 10 years, even assuming a forecast accuracy of only 60%. The potential economic benefits to the energy industry and to agriculture are also discussed in *Livezey* (1990) and *Sonka et al.* (1987) and references therein. In Europe an assessment has been made of the value of deterministic monthly forecasts of regional UK temperature and rainfall to UK industry (*Harrison et al.*, 1992). Positive benefit appeared to have been gained by most companies involved in the practical trial. However, no comparable studies have been made for the seasonal timescale.

5.2 Prediction of seasonal circulation and rainfall for developing countries receiving European aid

One of the most thorough assessments of the potential of seasonal rainfall forecasts to the developing world was made by *Hulme et al.* (1991) for the sub-Saharan region. They concluded that such a forecast capability has a potentially important contribution to make to food security and natural resource management.

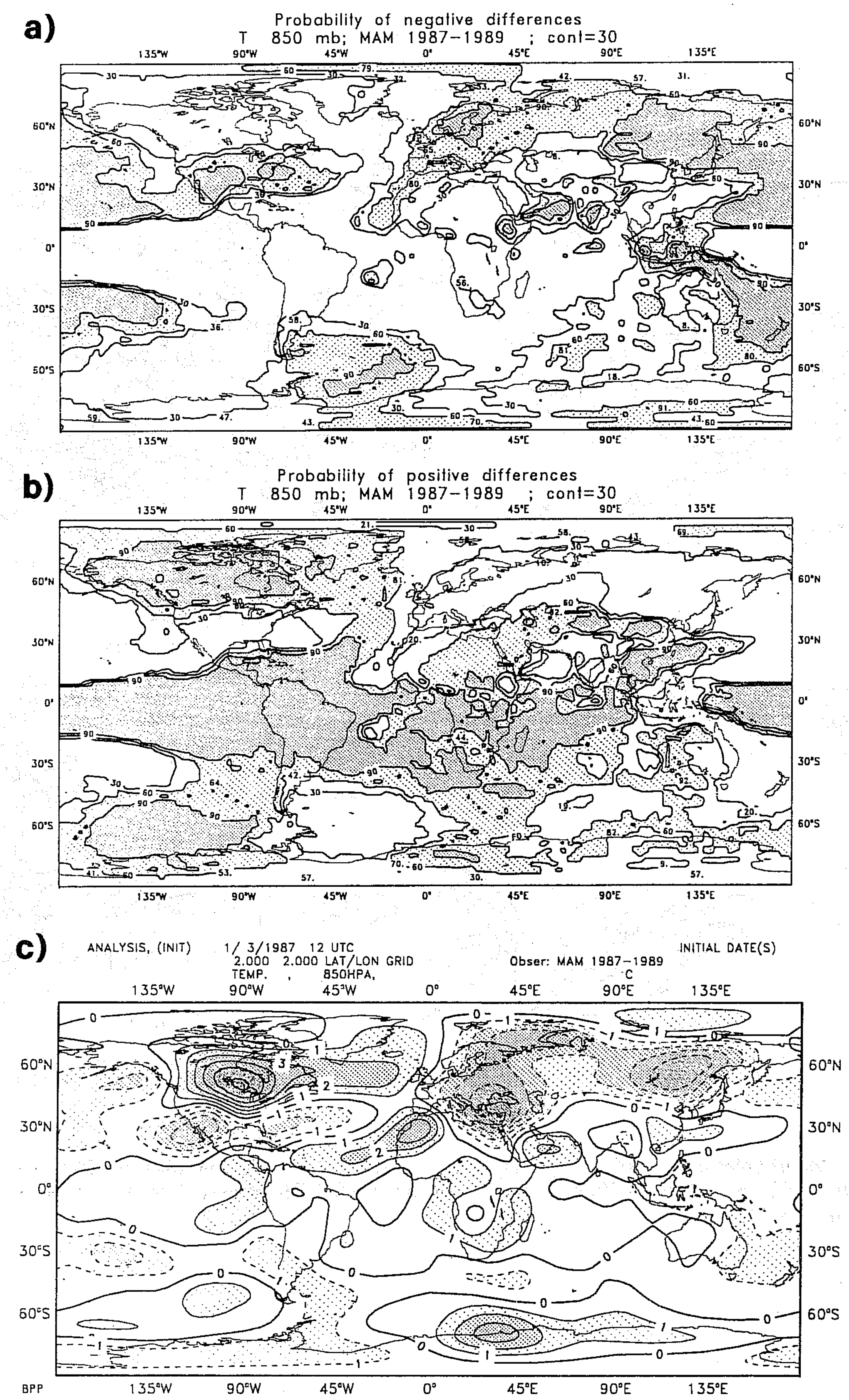


Fig.15 Probability estimates of 850 mb temperature difference based on 9-member ensembles of 120-day integrations with observed SST. MAM 1987-MAM 1989. Probability (%) that temperature difference is a) negative, b) positive, c) verification. Contours for a), b) - 30%, 60%, 90%.

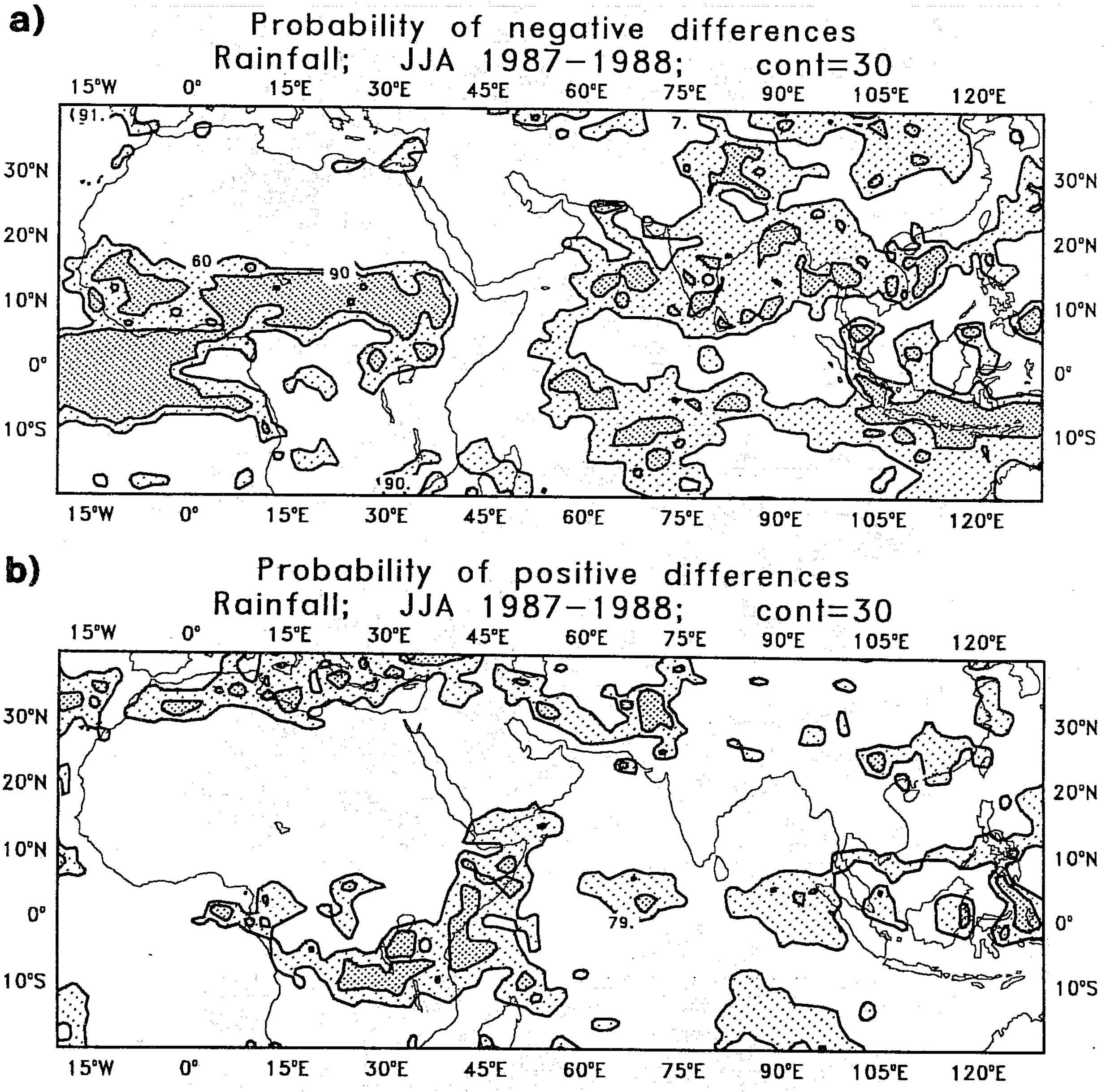


Fig.16 Probability estimates of rainfall over parts of the tropics based on 9-member ensembles of 120-day integrations with observed SST. JJA 1987-JJA 1988. Probability (%) that rainfall difference is a) negative, b) positive. Contours are 60% and 90%.

However, they warn that the lack of infrastructure to inform and support local communities currently limits the potential value of such forecasts.

In other areas of the tropics, seasonal forecasts are already making a significant impact on the national economy. In Peru, for example, an assessment of the likelihood of a warm or cold phase of El Niño guides government decisions as to whether to plant dry crops such as cotton, or a more water responsive plant such as rice. Substantial increases in agricultural yields have resulted from such guidance. Forecasts of wet season rainfall, made locally and by the UK Met Office, are now used in real time in North East Brazil.

As discussed above, it is likely that the output from a coupled ocean-atmosphere prediction scheme, even for tropical regions, would be an estimate of the forecast probability distribution of a meteorological variable such as rainfall. In order for these forecasts to be useful to farmers, they must be used as input for agro-econometric models which can finally arrive at a recommended course of e.g. crop planting. Such models must take into account the expected skill of the forecast and the cost benefit ratio of different courses of action. Little work has been done in this area.

5.3 An assessment of low-frequency variability and its sensitivity to physical parametrizations. Feedback to numerical weather prediction and climate modelling

Medium-range forecasting is concerned primarily with the prediction of changes to the circulation of the atmosphere, on timescales up to 10 days or so. Systematic errors in the representation of such circulations limit the skill of the forecast. Tracing the origin of misrepresentation of physical processes that give rise to such systematic error is often difficult, and a variety of techniques is required to determine confidently the source of some error. In this respect, sensitivity experiments made by integrating the forecast model over seasonal timescales are a convenient and often illuminating way of analysing systematic errors. Indeed, diagnosis of systematic error in the simulated occurence of low-frequency variability associated for example with blocking or weather-regime transitions cannot be readily made without such extended integrations.

Miller et al. (1992) documented an example of where analysis of seasonal timescale sensitivity experiments with idealised SST anomalies led to a revision in the operational ECMWF model with demonstrable improvements to the medium range. Such a revision was concerned with the representation of latent-heat fluxes in low-wind speed conditions. More recently it has been found from seasonal-timescale experimentation that the ability to simulate North Pacific blocking frequency is particularly sensitive to the specification of SST near Indonesia. This has stimulated further work on the parametrization of gustiness in the ECMWF operational model.

The ability to represent correctly such heat fluxes is crucial in simulating modes of low-frequency variability such as El Niño in coupled models; it is also important for the development of synoptic events on medium-range timescales (e.g. cold-air outbreaks, or intense cyclogenesis). Indeed, most parametrizations used in coupled GCMs and NWP models are critical to successful simulations on the short and medium range, seasonal and longer term climatic timescales. For example, systematic errors in cloud representation will influence both prediction of landsurface maximum temperatures over timescales of a day and of warm-pool sea surface temperature over timescales of a season. Representation of cloud has also been found to be a crucial factor in the sensitivity of climate models (*IPCC*, 1992). The representation of small-scale orography will influence both the prediction of the mean zonal wind on seasonal and longer timescales, and the development of an individual depression and its attendant rainfall on the daily timescale. In particular, coupled model integrations provide a strong constraint on surface fluxes which are otherwise not well known.

The ability to analyse a potential error in a physical process from more than one timescale, i.e. using different "angles of attack" can be invaluable in its correction (*Hollingsworth*, 1993).

5.4 Provision of consistent global ocean/atmosphere analyses for the climate community

The climate community has made great use of global operational atmospheric analyses. The ability to diagnose interannual and other variability with a consistent analysis of ocean and atmosphere will be a particularly appealing extension of such a service. A seasonal forecast facility with a comprehensive atmosphere/ocean analysis procedure would provide global internally-consistent assimilated fields of atmospheric and oceanic variables, which are synthesised from all available in-situ and satellite data. The importance of this activity for climate research has been discussed at length by the US National Academy of Sciences (*Johnson et al.*, 1991). The European investment in meteorological and oceanographic satellites more than justifies such an effort. NMC is moving swiftly to provide this resource for US scientists. There is no comparable effort in Europe.

6. ENHANCED OPPORTUNITIES FOR SCIENTIFIC COLLABORATION WITH MODELLING GROUPS IN EUROPE AND ELSEWHERE

Research into seasonal variability and its underlying physical mechanisms and prediction, provides a meeting ground for scientists from weather prediction and climate institutes. The development of improved data assimilation schemes and of comprehensive validation techniques and data sets can provide valuable information for the entire research community including scientists studying processes and fundamental mechanisms thought to be relevant to short, medium and long-range forecasting. Development of physical parametrizations for climate research and weather prediction are also in many respects complementary. The seasonal timescale is an excellent test bed for verifying the adequacy of such parametrization schemes. Development of ocean circulation models is already at an advanced stage in many climate research institutes. The testing of different formulations of ocean models, coupled to atmospheric models can act to stimulate collaborative activity amongst modelling groups within Europe. As a "spin-off" of such collaboration, a more thorough understanding of some of the persistent systematic errors can be expected.

As discussed above, the most rational approach to ensemble prediction on seasonal timescales is through multiple integrations with perturbations to physical parametrizations, as well as perturbations to initial conditions. The development of different formulations of such parametrizations within Europe is therefore of potential benefit for this type of work. Research activities related to seasonal prediction at European Institutes are outlined in the appendix.

7. RELATIONSHIP TO RELEVANT INTERNATIONAL PROGRAMMES

Considerable effort is now being expanded internationally on various projects, which are relevant to seasonal prediction, mainly sponsored by WCRP. Most important of these is TOGA, the Tropical Ocean Global Atmosphere experiment, which has provided the rationale for the development of an operational near-real-time observational system mainly for the tropical Pacific Ocean, and a focus for seasonal prediction related to ENSO. Although TOGA will formally come to an end in December 1994, plans are already well advanced for a follow-on programme GOALS (Global Ocean Atmosphere Land System), which has many of the same objectives as TOGA but extends the remit to include consideration of the higher latitude ocean and to assess the importance of land processes. In turn it is likely that GOALS will be a component of CLIVAR, an experiment to consider climate variability on timescales from a season to a century.

Support for the maintenance and extension of the observational data system will come partly from research experiments such as TOGA and CLIVAR/GOALS, but also from GCOS, the Global Climate Observing System (supported by UNEP, IOC, ICSU, WMO).

The Intergovernmental TOGA Board has called for a proposal for a seasonal prediction facility, IRICP (International Research Institute for Climate Prediction). This initiative has also provided strong support for the maintenance and development of the observing system.

A major atmospheric model intercomparison AMIP is in progress to help assess the ability of atmospheric models to simulate atmospheric variability over a ten year period (1979 to 1988) when forced with prescribed SST's. By intercomparing model results and comparing to analyses, it is anticipated that the strengths and weaknesses of the various models will be assessed.

Since seasonal predictions from GCMs will rely on accurate simulation of the hydrological cycle, results from the Global Energy and Water Cycle Experiment (GEWEX) will be of great relevance.

Although the WOCE, World Ocean Circulation Experiment generally addresses different timescales to those relevant to seasonal prediction, some components, for example those related to flux studies, to upper ocean processes and to satellite altimetry, are relevant.

8. SUMMARY

Extended-range prediction beyond the average limit of predictability of individual synoptic weather systems rests on the following premises: that there are large-scale components of the atmospheric general circulation with an intrinsically longer predictability time than that of individual synoptic weather patterns, that during some periods, the predictability of the atmosphere is significantly longer than average, and finally that lower boundary forcing which evolves on a much slower timescale than that of weather, can impart significant predictability on atmospheric development.

Within the monthly timeframe, internal variability appears to dominate the effects of variability of slowly evolving lower boundary forcing. Studies of atmospheric variations on timescales between about 2 weeks and a month have suggested only very limited predictability, with the possible exception of the Madden-Julian oscillation in the tropics.

The impact of lower boundary conditions becomes particularly relevant on the seasonal timescale. This document has suggested that seasonal forecasting is an exciting scientific issue with considerable practical importance. There are good grounds to expect significant progress in the foreseeable future, especially for variability of equatorial origin, but which can influence the atmosphere well removed from its place of origin. The International Scientific Steering Group for TOGA (Tropical Ocean Global Atmosphere, a component of WCRP) has advised that the time is now ripe to develop seasonal climate prediction activities. The USA is now moving rapidly to develop a prediction facility (*Moura*, 1992). No comparable initiative presently exists in Europe, although Europe has extensive expertise in all the areas needed to develop such a capability. What is needed is a collaborative framework. Seasonal prediction represents a special opportunity for collaborative European research, tackling a challenging problem of immense human importance and with good expectations of success.

APPENDICES

APPENDIX A: RESEARCH ACTIVITIES RELATED TO SEASONAL PREDICTION AT EUROPEAN INSTITUTES

1. RESEARCH AT UNIVERSITY OF BOLOGNA

The Atmospheric Dynamics Group of Bologna University (ADGB) is heavily involved in diagnostics of low-frequency variability, blocking and weather regimes both in observations and in long integrations of climate models. This activity is carried out within the frameworks of both the CEC EPOCH Programme (C21C Project) and the WGNE AMIP Programme (Sub-project "Blocking"). ADGB is prepared and willing to extend such diagnostic activities to both research and experimental pre-operational trial integrations on both monthly and seasonal timescales which should be produced at ECMWF as a result of such activities.

The Regional Weather Service at Bologna would also be very interested in any experimental, operational or pre-operational long-range forecasts produced at ECMWF. It is also conceivable that the Italian National Weather Service (SMAM), the National Electricity Board (ENEC-CRTN) and many other Regional Weather Services might also show interest in such products.

2. WORK ON MONTHLY AND SEASONAL FORECASTING AT KNMI

Most research at KNMI is concerned with climate and climate change. An important objective is to obtain a better understanding of the coupled atmosphere-ocean system, with some emphasis on aspects of air/sea interaction and flux estimation. Several ocean models have been developed and implemented. Recent work by *Allaart and Kattenberg* (1990) and *Sterl* (1992) concentrated on improving the heat flux description in Tropical and Atlantic ocean models. Also the coupling between physics (mixed layer model, mixing) and dynamics (volume and heat transport, etc) has been studied. *Burgers* (1992a,b) participated in the Koerber project (MPIM-ECMWF-KNMI, Latif et al., investigating the forecasting potential with a coupled ocean-atmosphere model). He contributed by tuning the HOPE model and its coupling to the atmospheric model.

This type of work will be continued. In addition, statistical analysis methods obtain growing attention (Verbeet, Weber; mainly because of KNMI's interest in the analysis of decadal variability). It is expected that these methods could also be applied to seasonal variability.

KNMI took part in several model intercomparisons, such as the coupled model intercomparison (*Neelin et al.*, 1992) and the TOGA model intercomparison (*Stockdale et al.*, 1992).

3. MONTHLY AND SEASONAL FORECASTING AT MÉTÉO-FRANCE/CNRM

Though it is not its main centre of interest, the climate modelling section of the Centre National de Recherches Météorologiques (CNRM) has some activity and plans in long-range forecasting.

A sample of 40 independent winter forecasts has been generated with a frozen version of the "Emeraude" spectral model (T42, 20 vertical levels). "Emeraude" has been used (in T79, 15 levels) for operational short-range forecast at METEO-FRANCE from 1984 to 1992. Each forecast of this sample consists of 5 lagged integrations of 45 days each. This sample has been used to study the mean skill at different ranges, the potential predictability, the skill predictability, and the impact of ensemble averaging and of systematic error correction. We are currently studying a simple model of the forecast error growth, and the formulation of probability forecasts.

Our plans are to generate a similar sample with the "Arpege-IFS" model (T42, 30 vertical levels, cycle 9). We intend to generate 10 winter and 10 summer forecasts, each forecast consisting of 3 lagged integrations of 60 days each. The impact of the ensemble size on the estimates of the model spread will be studied separately in "perfect model" experiments.

Another part of our activity is not motivated by the monthly and seasonal forecasting, but has some connections with it, as far as the potential predictability is concerned. We participate in the AMIP experiment, and intend to repeat it with various horizontal resolutions (T21, T42, T79 and T106). In the framework of the French climate community model, we are developing two coupled ocean-atmosphere models (tropical Pacific and global ocean).

4. SEASONAL PREDICTABILITY: RESEARCH PLANS AT LMD

Although the boundary forcing of the atmosphere is slowly varying, the long-term predictability in the mid-latitude is poor, simply because the internal variability is highly nonlinear and is of much higher amplitude than the forced variability, which is not the case in the tropics. Nevertheless, regularities such as weather regimes, on timescales of 10-30 days, or low-frequency oscillations with periods between 30 and 90 days do exist in the atmosphere, showing that at least some variables remember initial conditions. Presumably weather regimes are difficult to forecast in the long term since their onset and breaks depend crucially on the unpredictable transient fluctuations, but their probability of occurrence has been shown to depend strongly on the phase of low-frequency oscillations. Weather regimes and low-frequency oscillations act as two coupled systems with different timescales, in such a way that the second system represents a slowly-varying environment to the first one.

These regularities leave us with the hope that, independently of the boundary forcing, the mid-latitude atmosphere has long-term predictability. Some modes of variability are highly predictable, some others are not. A major problem is to develop a technique allowing the separation of those modes. The multi-channel singular spectrum analysis (MSSA) is a good candidate, since it is easy to use, and provides adaptive filters for analysing a signal which may contain regular oscillations, chaotic components and stochastic noise.

The projects contain three parts:

4.1 Analysis of the free and forced variability

Seven integrations of the LMD general circulation model with observed SSTs have been performed over the period 1970-1989, with perturbed initial conditions, providing a reasonable ensemble of 7 realisations of the atmosphere for a given boundary forcing. The separation between forced and free variability is therefore analysed by performing statistics on ensemble or time averages. Preliminary results show that the realisations are close to each other in the tropics but no resemblance at all is found in the mid-latitudes. These integrations also provide a bench for testing significance of statistical techniques such as PCA, weather regime identification.

4.2 Diagnostics of the forecast variability

In order to forecast correctly weather regimes, general circulation models must represent correctly their interactions with the transient baroclinic fluctuations. Also, these models must forecast the low-frequency oscillations. In order to assess the skill of a model in the two cases, error diagnostics are fundamental. For the interaction between weather regimes and transients, we propose to use isentropic potential vorticity (IPV) diagnostics, such as already developed at LMD. Essentially these diagnostics consist of the estimation of composite IPV fluxes during weather regime episodes, and the comparison with the ones obtained from a 25-year set of multi-level IPV maps calculated recently. The composites could be calculated from different regimes' definitions. For the skill of low-frequency oscillations predictions, MSSA seems a quite adequate tool. It is important to know whether GCMs are at least as good as statistical techniques in forecasting those modes. We are now ready to analyse any GCM experiment.

4.3 Empirical or semi-empirical seasonal predictions

MSSA is a powerful tool for expanding the atmosphere's variables into predictable and unpredictable components. We shall test the ability of linear statistical models to forecast each component. The expected result is that oscillating components will be very well forecast, probably better than a GCM would do. Such models have already proven to be very skilful, in the cases of the prediction of the global surface temperature (predictability > 4 years), the southern oscillation index (predictability > 3 years), or the latitude-banded vertically-averaged angular momentum (predictability > 1 month). For non-averaged maps the skill is not as good. The limits of such an approach will be tested. A natural extension of this analysis is that if GCMs do not forecast the predictable components of the flow better than statistical models, it would be possible to drive these GCM forecasts with prescribed predictable components forecast by statistical models. We shall investigate this possibility.

5. MODELLING AT UKMO RELEVANT TO SEASONAL AND MONTHLY PREDICTION

5.1 Work aimed at ENSO prediction

The AGCM is the standard climate version of the UKMO global Unified Atmospheric model: L19 (hybrid sigma and p) 3.75 long x 2.5 lat finite difference B-grid. Physics includes e.g. cloud water and ice, canopy water, multi-layer soil and a penetrative mass flux convection scheme.

The OGCM is a derivative of the Cox model with salinity included, but with the barotropic mode omitted. The domain is for the Tropical Pacific (30N-30S, with open boundaries), high resolution (1°/3 latitude interval near equator increasing to 1° at N and S boundaries, 1.5° longitude decreasing to about 0.5° near E and W boundaries) with 16 levels in the vertical. The eddy viscosity is variable with a minimum value of 2×10^7 cm^2s^{-1}. Two forms of vertical mixing are included - Pacanowski-Philander and Kraus-Turner vertical mixing.

Work recently completed includes simulation of the ocean climatology with 0.75 Hellerman stress and an ocean simulation 1961-90 with forcing of amplitude 0.75 x 1.535 x FSU pseudostress. A Haney-type surface heat flux with Oberhuber Q and dQ/dT (weakened by 0.3 factor for perturbations from model climatology) has been used. Results are typical of similar OGCM experiments: the cold tongue is too cold in climatology, the SST anomaly correlation for the interannual simulation for the region nino3 is 0.7. In progress are hindcasts with OGCM + an empirical atmosphere derived from simulation and coupled GCM trials. A full 1° x 1° (approx) global ocean with higher resolution tropics is in development.

An ocean data assimilation system based on an optimal interpolation (Lorenc analysis/correction method) scheme is being developed by the UKMO FOAM (Forecasting Ocean Atmosphere Model) group, which includes an automated quality control stage. The first version uses temperature and salinity data; altimeter etc. data to be included in later versions of the scheme. The scheme is not yet implemented for the tropical Pacific ocean model, but this is intended.

An Indian OGCM was used with NWP and climatological surface fluxes for simulation of the period 1987-1990, but this has not yet been adapted for the new unified system of operation.

Work has also been carried out on a reduced physics, 2 active layer tropical Pacific ocean model with the wind-forced circulation decoupled from thermodynamic variations. Empirical, linear equilibrium, and moist time dependent atmospheres have been tested. Hindcasts are in progress.

5.2 Empirical seasonal forecasts

Empirical seasonal forecasts for the Sahel and NE Brazil regions have shown very good skill since commencement in 1986, and issue of these will continue. The forecasts are of rainfall, based on SST data, and are made using multiple linear regression and linear discriminant analysis (see *Ward and Folland*, 1991 for details).

5.3 Future work on seasonal predictability

A new phase of research, partly designed to study seasonal predictability, (not prediction) is starting called "Climate of the Twentieth Century", funded by CEC. This will study seasonal variability and climate variability using observations and one or more versions of the Unified Atmospheric model. Initial work will focus on the periods 1904-13 and 1949-1991, especially in the 1960s. The overall aim is to determine the extent to which SST (and sea ice) are in mutual equilibrium on timescales from a season to several decades. The model is being forced by the new Global Sea Ice and Sea Surface Temperature Data Set (GISST) (*Parker et al.*, 1993). The prime focus will be on the extratropical North Atlantic and Europe followed by Tropical Africa, the summer Asian monsoon and the Australasian/SPCZ region. Collaboration is expected with several groups. There will be an input to AMIP. A key aim is to determine whether the model skilfully distinguishes the relatively-blocked decade of the North Atlantic winters of the 1960s from the more westerly winters in the early twentieth century. If this is achieved, can the atmospheric mechanisms be identified? If skill is shown on the decadal timescale, at what smaller timescale does skill disappear? Are some extreme seasons particularly predictable, such as the extreme blocked season 1962-63? *Rowntree* (1976) produced evidence of the influence of SST in the 1962-63 winter and suggested a mechanism. An ensemble of runs has just started for 1904-13 and the 1960s with extra integrations (just begun) for 1962-63. Different atmospheric starting conditions and versions of the model are being used. At a later stage, continuous runs are planned from 1871-now, when the CRAY computer has been upgraded. In addition, runs of the Unified Model forced with the AMIP SST data set are being made and will be similarly analysed.

To assess useful predictability, comparisons with observations are needed (comparisons between runs from different starting conditions or runs using different models, without recourse to observations, are also useful). Attempts are being made to upgrade a range of historic data sets. A new gridded historic monthly rainfall dataset, extending back to 1890, has been obtained from the Climatic Research Unit, University of East Anglia. We also hope to contribute to and benefit from reanalyses, such as the proposed NMC reanalysis extending back to 1958. Attempts are also being made to improve surface wind and atmospheric pressure data back to the late nineteenth century. GISST could also be markedly improved over time. For the future, other areas (e.g. SE Asia, Mexico/Caribbean) will be investigated using results from UKMO 20 C climate AGCM integrations, combined with historical precipitation observations. Empirical hindcasts for selected areas, with dynamical modelling are expected to follow, using the models described above.

5.4 Current projects in monthly forecasting

Group work remains focused on the problems of practical provision of forecasts on ranges to 30 days, with current concern directed to providing time-mean temperature and rainfall predictions for the UK on scales of 1 to 5, 6 to 15 and 16 to 30 days. An on-going operational programme supplies deterministic predictions to a number of UK customers on a commercial basis. Customers appear to be satisfied in general with the quality of the predictions. A critical assessment of the quality of the predictions over the last ten years, and the contributions towards this quality from the different forecast techniques, is underway.

Empirical techniques are still in use alongside ensemble predictions, but no further development of these empirical techniques is envisaged. Compared with the model previously used, the unified model exhibits larger and more realistic variability at low frequencies (≥ 6 days). Results from ensembles with this model can only be expressed within a probabilistic framework: we are transferring the project from its historical deterministic base to a probabilistic framework. To this end we will be undertaking further studies of the performance of the fixed version of unified model, once available, on time scales to 30 days using ensembles generated both from our lagged-average system and from the optimal singular value perturbations developed at ECMWF. The work will include an assessment of the regime dependency of model performance. We are also planning to continue with the NCAR intercomparison project once our model is available.

6. EXTENDED-RANGE PREDICTIONS AT DWD

30 day forecasts based on analogue methods have been issued twice a month until June 1990. A similar scheme is still in operation for the eastern parts of Germany (former GDR).

At present, the development of a new scheme for monthly predictions, based on ensemble forecasts with our global model, is under consideration. A final decision has not yet been taken.

7. ACTIVITIES AT MPI (HAMBURG) RELATED TO SEASONAL FORECASTING

Activities at MPI related to seasonal forecasting include uncoupled and coupled modelling studies. A hierarchy of models of different complexity is applied.

The atmospheric general circulation model at MPI is ECHAM (*Roeckner et al.*, 1992). It is generally used by several climate modelling groups and is available as a Climate Community Model at DKRZ (German Climate Computing Centre). The present version ECHAM3 has been run at T42 resolution in several multi-year integrations with the objective to explore the role of SST-boundary conditions and the prospect of long-term predictability. Some of these experiments have been run as part of AMIP (Atmospheric Model Intercomparison Project). In order to obtain an indication of the predictability of the atmosphere on seasonal and longer time-scales, the T42 was run several times with identical boundary forcing but with different initial conditions. The tropical behaviour of earlier versions of ECHAM at T21 resolution was investigated by *Latif et al.* (1991) and *Barnett et al.* (1991) who investigated a 20 year run with observed global SSTs.

Similar runs with climatological SSTs and anomalous SSTs in specific regions only (tropics only, midlatitudes only) were also conducted with the T21 version.

The standard ocean model for the investigation of seasonal predictability is HOPE (Hamburg Ocean Primitive Equation), which is an ocean general circulation model (OGCM) formulated on prescribed levels (Wolff and Meier-Reimer, 1993). Earlier cycles of HOPE were run in an uncoupled mode in a variety of studies to investigate the interannual variability in different regions of the world ocean. *Latif et al.* (1985) and *Latif* (1987) applied HOPE to the simulation of low-frequency variability in the tropical Pacific. *Villwock et al.* (1993) used HOPE to study the interannual variability in the tropical Indian Ocean circulation. *Luksch et al.* (1991) and *Luksch and Storch* (1992) used HOPE to study the interannual variability in the North Atlantic. All these studies indicate that low-frequency variability in sea surface temperature (SST) can be simulated realistically when boundary conditions are prescribed from observations. Additionally, suitable data assimilation techniques are currently under development.

Coupled modelling focusing on seasonal predictability is done mostly with ECHO (ECHAM coupled to HOPE). An earlier version of ECHO was run for 26 years in order to study the interannual variability in the tropics (*Latif et al.*, 1993a). Coupling was restricted to the region 30° N to 30° S for this purpose. Overall, ECHO simulated realistically the interannual variability in the tropics, although it exhibited significant climate drift. In particular, ECHO simulated an irregular ENSO (El Niño/Southern Oscillation) cycle, with a preferred timescale of about three years. Furthermore, the impact of tropical SST anomalies on the atmospheric circulation in midlatitudes was simulated realistically. This version of ECHO was also used in an ensemble of ENSO prediction experiments (*Latif et al.*, 1993b). ECHO showed skill in predicting tropical Pacific SST up to lead times of about one year.

The latest version of ECHO includes also air-sea interactions in mid-latitudes, the coupling domain extending from 60° N to 60° S. Preliminary results indicate that the climate drift could be reduced considerably in this cycle. It is planned to apply this version to classical predictability experiments in order to gain more insight into the potential predictability of the climate system in mid-latitudes. A similar coupled model was established recently at ECMWF, in which the atmospheric component (ECHAM) was replaced by a low-order version of the ECMWF forecasting model. It is also planned to use an alternative coupled model at MPI to study seasonal predictability, in which an OGCM formulated in ispycnic coordinates (*Oberhuber*, 1992) will be coupled to ECHAM.

8. RESEARCH ACTIVITIES AT THE DANISH METEOROLOGICAL INSTITUTE

The Danish Meteorological Institute (DMI) is the organisation responsible for weather forecasting in Denmark, Greenland and the Faroes. In order to carry out these tasks a continuous adaptation of new methods is very important. The Research and Development Department is responsible for this. The department has about 50 employees and at present about 20 researchers work in the area of numerical modelling. DMI has been a participant in the international HIRLAM project since it began in 1985. The main objective of this project was to develop a High Resolution Limited Area Model (HIRLAM) and data-assimilation system. This system has been an important and successful vehicle for operational short term weather forecasting. For medium range, European Centre for Medium-Range Weather Forecasts (ECMWF) is the main source of information.

DMI has no operational activities on longer time scales, but the institute is involved in climate modelling. A global modelling project was established at DMI in cooperation with the Geophysical Institute at the University of Copenhagen (GIUC) when reasonable computer resources became available in 1985. A Danish climate model has been developed based on a version of the spectral model developed at ECMWF. The research activities are carried out in cooperation with other institutions and DMI participate in the major European initiative "The climate of the 21st century" which is partly funded by the EEC.

In this context DMI is studying the extra-tropical Northern Hemisphere climate variability on time-scales from weeks to seasons in both observations and in GCM experiments with the Danish climate model. Persistent anomalies of localised nature like blocking as well as the largest scale flow patterns are identified by the use of objective identification methods like pattern correlation analysis and blocking indices. Different parametrization formulations may affect the results. For this reason several different model configurations are used in the study. A major goal is to investigate the impact of different horizontal and vertical resolutions on the model's ability to simulate persistent anomalies. Simulations will be carried out with different horizontal resolutions for extended periods. Also, a number of different vertical resolutions will be considered and the impact on the troposphere due to increased vertical resolution in the stratosphere will be investigated.

An interesting new application of the HIRLAM model is the development of a regional climate model. This special version of HIRLAM can be integrated over long time spans provided reasonable boundary conditions are supplied. The goal of the project is to use HIRLAM nested into a global climate model which is applied with rather coarse resolution. HIRLAM is then used as a high resolution model giving detailed information on a limited area such as Europe. This research is carried out in cooperation with the Max Planck Institute für Meteorologie in Hamburg, and it is now possible to apply the physical parametrization from the German model ECHAM in HIRLAM. Initially, it was only considered to use this version of HIRLAM in connection with climate studies. However, it has turned out that, when used with analysed boundary conditions, such very extended simulations provide a valuable tool for testing the physical parametrization routines.

DMI is also contributing in the area of atmospheric dynamics. A hybrid isentropic coordinate scheme has been developed. The scheme is energy and angular momentum conserving and has a smooth transition between terrain-following levels near the surface, and purely isentropic levels at the tropopause. The new scheme will be implemented and tested in a climate model (either ECHAM or the Danish climate model) and the behaviour will be carefully validated. The change of vertical coordinate in the model formulation will most likely influence a number of parametrizations in the model. The horizontal diffusion will certainly have to be reconsidered in view of the fact that the advection in the model atmosphere will be handled on surfaces closer to streamlines. Similarly, both gravity wave drag and vertical diffusion need reassessment in order to improve the performance of the model.

DMI is also carrying out sensitivity experiments with the GCM in order to investigate the influence of the external forcing from anomalous sea surface temperatures. Such experiments are done in order to contribute to the understanding of the ocean's influence on atmospheric variability. These studies include the AMIP experiment which is the simulation of a ten year period with prescribed climatological SSTs and a 10 year period simulated with the prescription of observed SSTs. These long-term integrations have become feasible with the computer facility at DMI, and the results will be made available for analysis to scientists at other institutes.

For several years DMI has been involved in several areas of research concerning the ozone question. The possibility of forecasting ozone concentration has been addressed and this involves the generation of a proper initial ozone field. Another important issue is the possible impact on climate of ozone depletion. This problem has been tentatively investigated with the Danish climate model. However, this model has an inadequate vertical structure for this problem and important radiative processes are not included with sufficient accuracy. Due to this it has been decided to replace the present Danish climate model with a more modern model. Among several possibilities a cooperation with Météo-France on application of their model ARPEGE has been initiated.

Quite recently DMI was selected as the focal point for a major climate research effort to be initiated by the Nordic countries and funded by the Nordic Council of Ministers. This project, starting in 1993, has participation from all the Nordic countries. The scope of the project is to increase the level of knowledge concerning the interaction between clouds and radiation.

9. LONG-RANGE FORECASTING RESEARCH (METEOROLOGISCHES INSTITUT UNIVERSITÄT HAMBURG)

Research on long-range forecasting has been concentrated on the following subjects and is likely to continue in collaboration with other research groups.

9.1 Dynamical systems analysis

Nonlinear methods of analysis have been applied to model and observational data to estimate intrinsic predictability and degrees of freedom as part of the static and dynamic properties of attractors of chaotic systems.

9.2 Climate anomalies in Europe

Phenomenological aspects of European weather regimes are analysed to evaluate the cross-Atlantic stormtrack variability (and its response on distant El Niño-Southern Oscillation forcing) and to determine the dynamical implications applying transient and stationary eddy-mean flow diagnostic.

9.3 Combination of forecasting techniques

Error minimizing forecast techniques have been analysed and applied showing both in theory and praxis that a combination forecast can improve, in the average, the accuracy of the independent individual predictions comprising the combination.

10. SWEDISH METEOROLOGICAL AND HYDROLOGICAL INSTITUTE (SMHI)

Activities include:

a) Development of parametrization schemes within the HIRLAM project that will also be tested in climate models.
b) Research on weather regimes, structural organization of baroclinic waves and statistical equilibration.
c) Empirical forecasting on the seasonal timescale.
d) Cost-benefit studies of the value of monthly and seasonal forecasts.

11. COUPLED MODELLING WORK AT OXFORD UNIVERSITY

To date coupled models have been used to illustrate mechanisms leading to ENSO-type oscillations. The first model showed the role of planetary/Kelvin waves in setting timescales, the second the role of local coupling in generating eastward propagating instabilities.

A variety of ocean models is in use ranging from two layer to multi-level, coupled to atmospheric models, trained to extract only the coherent large-scale structure of the SST field in deriving the associated wind fields. The atmospheric component is thus much simpler than that of an AGCM, but the coupled models developed have useful predictive (hindcast) skill, which fully comprehensive coupled GCM's must aim to beat.

Some work has been done on data assimilation using successive correction and variational techniques, the latter in models of reduced physics.

APPENDIX B: PARTICIPANTS

Workshop on Monthly and Seasonal Forecasting
ECMWF, Reading, UK, 7-9 December 1992

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