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Volume 23

Prospects for Improved Forecasts of Weather and Short-Term Climate Variability on Subseasonal (2 Week to 2 Month) Time Scales

S. Schubert, R. Dole, H. van den Dool, M. Suarez, and D. Waliser

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Prospects for Improved Forecasts of Weather and Short-Term Climate Variability on Subseasonal (2 Week to 2 Month) Time Scales

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Abstract

A workshop was held in April of 2002 that brought together various experts in the Earth Sciences to focus on the subseasonal prediction problem. While substantial advances have occurred over the last few decades in both weather and seasonal prediction, progress in improving predictions on these intermediate time scales (time scales ranging from about two weeks to two months) has been slow. The goals of the workshop were to get an assessment of the "state of the art" in predictive skill on these time scales, to determine the potential sources of "untapped" predictive skill, and to make recommendations for a course of action that will accelerate progress in this area. A remarkable aspect of the workshop was the multi-disciplinary nature of the attendees, consisting of about 100 scientists with specialties in areas that included stratospheric dynamics, hydrology and land surface modeling, the monsoons, the Madden-Julian Oscillation (MJO) and other tropical variability, extratropical variability including extratropical-tropical interactions, coupled atmosphere-ocean-land modeling, weather prediction, seasonal prediction, and various aspects of statistical modeling, analysis, and prediction. This broad range of expertise reflected the wide array of physical processes that are deemed potentially important sources of predictive skill on subseasonal time scales.

One of the key conclusions of the workshop was that there is compelling evidence for predictability at forecast lead times substantially longer than two weeks. Tropical diabatic heating and soil wetness were singled out as particularly important processes affecting predictability on these time scales. Predictability was also linked to various low-frequency atmospheric phenomena such as the annular modes in high latitudes (including their connections to the stratosphere), the Pacific/North American pattern (PNA), and the MJO. The latter, in particular, was highlighted as a key source of untapped predictability in the tropics and subtropics, including the Asian and Australian monsoon regions.

The key recommendations of the workshop are:

a) That a coordinated and systematic analysis of current subseasonal forecast skill be conducted by generating ensembles of 30-day hindcasts for the past 30-50 years with several "frozen" AGCMs. Specific goals include, sampling all seasons, and generating sufficiently large ensembles to estimate the evolution of the probability density function.

b) That a series of workshops be convened focused on modeling the MJO, and that a coordinated multi-nation/multi-model experimental prediction program be developed focused on the MJO.

c) That new satellite observations and new long-term consistent reanalysis data sets be developed for initialization and verification, with high priority given to improvements in estimates of tropical diabatic heating and cloud processes, soil moisture, and surface fluxes (including evaporation over land).

d) That NASA and NOAA develop a collaborative program to coordinate, focus, and support research on predicting subseasonal variability.

Specific steps to implement the above recommendations are: 1) to begin immediately to develop a framework for an experimental MJO prediction program, 2) to convene a follow-up workshop in the spring of 2003 to organize the AGCM hindcast project, and conduct initial meetings on modeling the MJO, and 3) for NASA and NOAA to put out a joint announcement of opportunity within the next year to focus research, modeling and data development efforts on the subseasonal prediction problem.

I. Introduction

"It seems quite plausible from general experience that in any mathematical problem it is easiest to determine the solution for shorter periods, over which the extrapolation parameter is small. The next most difficult problem to solve is that of determining the asymptotic conditions - that is, the conditions that exist over periods for which the extrapolation parameter is very large, say near infinity. Finally, the most difficult is the intermediate range problem, for which the extrapolation parameter is neither very small nor very large. In this case the neglect of either extreme is forbidden. On the basis of these considerations, it follows that there is a perfectly logical approach to any computational treatment of the problem of weather prediction. The approach is to try first short-range forecasts, then long range forecasts of those properties of the circulation that can perpetuate themselves over arbitrarily long periods of time (other things being equal), and only finally to attempt forecast for medium-long time periods which are too long to treat by simple hydrodynamic theory and too short to treat by the general principles of equilibrium theory".

John von Neumann (1955)

Almost a half century after the eminent mathematician, John von Neumann, spoke those words it appears that we are finally ready to tackle the "medium-long" time scale prediction problem. In fact we have, over the last few decades, made important strides in both weather (short time scale) and seasonal/climate (very long time scale) prediction. The critical roles of initial atmospheric conditions in the former, and boundary conditions in the latter, have helped to guide and prioritize research and development, as well as to establish new observing systems targeting these prediction problems.

As surmised by von Neuman, progress in predicting time scales between those of weather and short-term climate (time scales roughly between 15 and 60 days) has been at best modest. The variability on these time scales is rich with well known phenomena such as blocking, the PNA, and the MJO, yet the important mechanisms involved, their predictability, and the ability of current models to simulate them are still in question. Improvements made in predicting these time scales are in many ways an important step in making further progress in weather and climate prediction. For weather, these time scales offer the hope for extending (at least occasionally) the range of useful forecasts of weather and/or weather statistics, while for the seasonal and longer term climate prediction problem they are a key component of the atmospheric "noise" that is a limiting factor in the climate prediction problem.

How predictable is the PNA? How predictable is the MJO? What is the connection between the variations in predictability of weather and the PNA, blocking, the MJO, or various other subseasonal modes? What is the role of the stratosphere? What is the link between subseasonal variability and the

El Nino/Southern Oscillation (ENSO)? Is intraseasonal variability the key to understanding and predicting the interannual variability of the Indian monsoon? How important is ocean coupling to subseasonal prediction? What is the relative contribution of SST and atmospheric initial conditions to the predictability of subseasonal variability on weekly to monthly time scales? Are our models good enough to capture the dominant modes of variability? Are the uncertainties in the predictions dominated by errors in the initial conditions (e.g. the tropics or soil moisture) or deficiencies in the models? These are some of the key issues that need to be addressed for achieving useful long range weather predictions, and for improving and determining the limits of seasonal and longer predictions.

This document summarizes the proceedings of a workshop that was organized to bring together various experts in the field to focus on the subseasonal prediction problem. The basic goal of the workshop was to get an assessment of our current understanding of the above issues, and to determine what we can do to help make progress on the subseasonal prediction problem: this includes necessary advances in models, analysis, theory, and observations.

The workshop was held at the Newton White Mansion in Mitchellville, Maryland on April 16-18, 2002. There were about 100 attendees (see Appendix), with 43 presentations (see abstracts in section VI), including six invited talks. The workshop was jointly sponsored by the NASA Seasonal to Interannual Prediction Project (NSIPP) and the Data Assimilation Office (DAO), with support and funding from the Goddard Earth Sciences Directorate. Additional funding was provided by the Earth Sciences Enterprise at NASA headquarters. The workshop organizing committee consisted of Siegfried Schubert (chair, NASA/DAO and NSIPP), Max Suarez (NSIPP), Randall Dole (NOAA-CIRES Climate Diagnostics Center), Huug van den Dool (NOAA/Climate Prediction Center), and Duane Waliser (SUNY/Institute for Terrestrial and Planetary Atmospheres).

In the following section we present summaries of each session. The overall summary is given in section III, and the recommendations are presented in section IV. The final sections of the document include the list of participants, the agenda of the workshop, and the abstracts (some of them extended) of the talks.

II. Summary of sessions

The workshop was opened with welcoming remarks from Franco Einaudi, the Chief of the Goddard Earth Sciences Directorate. The keynote talk was given by Eugenia Kalnay, Chair of the Department of Meteorology at the University of Maryland, and a leading expert on dynamical extended range prediction. The rest of the workshop was organized into six sessions. Each session began with a 45 minute invited talk, followed by a number of 20 minute contributed presentations. In the following we provide summaries of each session.

The keynote talk by Eugenia Kalnay (see extended abstract) reviewed some of the key areas that provide opportunities for making progress on the subseasonal prediction problem. These opportunities include the use of coupled atmosphere-ocean models to more realistically simulate extratropical atmosphere-ocean feedbacks, improved simulations of the MJO including "interim" empirical/statistical approaches that nudge the GCMs to produce more realistic MJO characteristics, taking better advantage of the history of 15-day ensemble forecasts routinely made by the U.S. National Weather Service, and improved initialization and ensemble methodologies with coupled models. These basic ideas were, in fact, at the core of many of the presentations that followed.

i) Current operational methods and their skill (Chair: Randy Dole)

The session opened with an invited presentation by Huug van den Dool on "Climate Prediction Center (CPC) Operational Methods and Skill in the Day 15 – Day 60 Forecast Range" (see extended abstract). Van den Dool emphasized the great challenges posed by forecasts in the 15-60 day time range. This time scale is intermediate between short-range and long-range forecasts, with the former predominantly determined by initial conditions and the latter by boundary forcing. Forecasting in this time range therefore constitutes a mixed problem in which both initial and boundary conditions are likely to play important roles. Van den Dool described current CPC operational practice, which is to provide a 30-day forecast for U.S. precipitation and temperatures for the U.S. at a lead-time of two weeks; i.e., effectively a forecast for mean conditions over days 15-45. The forecasts are developed through subjective procedures that effectively combine output from both statistical-empirical and numerical model predictions. Predictors include Optimal Climate Normals, Canonical Correlation Analysis, and National Centers for Environmental Prediction (NCEP) model forecasts. When applicable, El Nino – Southern Oscillation composites, soil-moisture state, and potential impacts from the MJO are also considered. Comparisons between monthly and seasonal forecasts show that at present the spatial pattern of the monthly forecast is usually similar to that of the seasonal forecast, with modest positive skill but a somewhat lower signal to noise ratio.

Following the presentation by van den Dool, Frederic Vitart provided an overview of monthly forecasting at the European Center for Medium Range Weather Forecasts (ECMWF, see extended abstract). He described a new monthly forecasting project at ECMWF designed to fill the gap between medium-range forecasting (out to 10 days) and seasonal forecasts. The ECMWF system is based on a 51-member ensemble of coupled ocean-atmosphere model integrations, with the atmospheric component being run at T159L40 resolution, and the oceanic component at a zonal resolution of 1.4 degrees and 29 vertical levels. So far, several monthly forecasts have been performed. Preliminary results suggest that the monthly forecasting system may produce useful forecasts out to week 4, although the model is deficient in simulating a realistic MJO more than 10 days in advance. Plans are to run the experimental system every two weeks for the next few years in order to assess the skill of this coupled model.

Zoltan Toth then described the NCEP Global Ensemble Forecast System and discussed approaches to extending forecasts beyond 16 days. Toth emphasized four issues: 1) This is a combined initial condition-boundary condition problem, as stated previously; 2) that potential predictability in this range is relatively low, but variable in time and space; 3) that a key issue is predicting regime changes; and 4) that the models being used are far from perfect. With regard to each of these issues, he suggested: 1) we need to employ coupled models as part of the prediction strategy; 2) that ensemble prediction methods are essential for enhancing the predictable signal, detecting variations in predictability, and providing probabilistic forecasts; 3) that major regime changes are sometimes well predicted, but case-to-case variations are great, and the extent to which these variations are intrinsic or due to model errors or observational deficiencies is unknown; and 4) that new approaches are needed to correct for the effects of model errors, including biases in both the first and second moments. A critical issue is the lack of adequate variability in the models, which leads to “overconfident” forecasts. It is vital to adjust for this bias in order to improve forecast estimates of probability distributions.

Steve Colucci provided an overview of recent results on ensemble predictions of blocking (see extended abstract). He discussed results of research with the NCEP MRF model, and unpublished work by J. L. Pelly and B.J. Hoskins with the ECMWF model. These studies examined the climatology of blocking over 3-5 year periods. Preliminary results suggest that blocking frequency is underpredicted in both the NCEP and ECMWF model, but that this bias can be at least partially corrected to produce calibrated probabilistic forecasts that extend the range of skillful blocking forecasts.

Arun Kumar discussed the impact of atmospheric initial conditions on monthly-mean model hindcasts with an atmospheric general circulation model (AGCM). The AGCMs were run from atmospheric conditions starting at lead times from 1-4 months in advance. The results suggest that January simulations with a shorter (1 month) lead time have a higher signal-to-noise ratio, especially at higher latitudes, and therefore consideration should be given to using observed initial conditions in this time of year.

The final presentation of the session, given by Thomas Reichler, also examined the role of atmospheric initial conditions on long-range predictability. The study design consisted of running ensemble AGCM predictability experiments with the NCEP seasonal forecasting model at T42L28 resolution from a variety of initial condition (IC) and boundary condition (BC) states, including ENSO and non-ENSO (neutral) years. The basic conclusions were that initial conditions have a noticeable influence on weekly hindcast skill in winter out to weeks 2 to 6, with the effects most pronounced at high latitudes, the middle atmosphere, at lower levels over the Indian Ocean, during active phases of the Antarctic Oscillation (AAO), and when ENSO is weak.

ii) Predictability of extra-tropical "modes" (Chair: Max Suarez)

This session dealt with various aspects of a number of coherent atmospheric teleconnection patterns that have time scales sufficiently long to afford predictability on weekly and longer time scales.

The session began with an invited talk by Mike Wallace about a study on the impact of the Arctic Oscillation (AO) and the PNA on subseasonal variability, carried out by Roberta Quadrelli and Mike

Wallace (see extended abstract). The analysis was based on NCEP/NCAR reanalysis data for DJFM for the period 1958-1999. They examined the variability of 10-day means of sea level pressure, 500mb height and 1000-500mb thickness fields during the extremes in the two polarities of both the AO and PNA. They found that both the AO and the PNA have a substantial impact on the frequency of occurrence of weather often associated with cold air outbreaks in middle latitudes. For the AO, this is characterized by enhanced variability during the low index state (weak sub-polar westerlies).

Mark Baldwin reported on work with Tim Dunkerton that examined the ability to predict the AO using statistical techniques (see extended abstract). They note that the AO is the surface expression of the Northern Annular Mode (NAM): the latter is most persistent at stratospheric levels, peaking in the lowermost stratosphere, where the DJF e-folding time scale exceeds 30 days. They further showed that the persistence of the AO has a strong seasonality with substantially more persistence (e-folding time of 15-20 days) during the winter season when the planetary wave coupling to the stratosphere is strongest. They found a linear relationship between the lower stratospheric NAM and the average AO 10–40 days later, that should make possible predictions of the AO at the 10-40 day range.

Steven Feldstein examined the dynamical mechanisms of the growth and decay of the North Atlantic Oscillation (NAO). The study involved a diagnostic analysis using NCEP/NCAR reanalysis data as well as calculations with a forced, barotropic model. The results showed a life cycle of about two weeks. Both high-frequency (period <10 days) and low-frequency (period >10 days) transient eddy fluxes were found to drive the NAO growth, while the decay of the NAO occurs through both the divergence term and the low-frequency transient eddy fluxes. The results further showed an important difference between the NAO and PNA patterns, in that the NAO lifecycle is dominated by nonlinear processes, whereas the PNA evolution is primarily linear.

Grant Branstator showed examples from the observations and two different model simulations (the NSIPP-1 and NCAR models) of wavetrains that are meridionally confined and zonally-elongated as a result of being trapped within the waveguide of the mean winter Northern Hemisphere jets (see extended abstract). He discussed how these wavetrains are important for the subseasonal prediction problem because they act to connect widely spaced locations around the globe within about a week, they impact the time mean and bandpass eddy statistics, and they effect various other teleconnection patterns such as the NAO and the ENSO response.

Sumant Nigam examined the mature-phase dynamics of PNA variability. He noted that the PNA represents circulation and precipitation variability on both intraseasonal and seasonal time-scales, and that the PNA has sometimes been erroneously associated with ENSO variability as it can be excited during ENSO winters as well. The pattern was simulated with forcing (diagnosed from reanalysis data) using a steady linear primitive equation model. The model results indicated that zonal/eddy coupling and sub- monthly vorticity transients are important in the pattern's generation.

Tim Delsole introduced the concept of an optimal persistence pattern (OPP) as a component of a time-varying field that remains auto-correlated for the longest time lags. He showed how OPPs can be used for isolating persistent patterns in stationary time series, and for detecting trends, discontinuities, and other low-frequency signals in non-stationary time series. The results of his analysis showed, among other things, that the PNA is the most predictable (in a linear sense) atmospheric pattern.

Wilbur Chen examined subseasonal variability and teleconnectivity for various time scales associated with the PNA, NAO and AO using NCEP/NCAR reanalyses for the period 1971-2001 (see extended abstract). He showed that as the timescale increases (7-day, 31-day and 61-day means), the teleconnections not only become stronger and better established, but also much more organized and located in certain preferred regions. He furthered illustrated the sensitivity of the January-March teleconnection patterns to the based point used to define the correlation patterns.

Hyun-Kyung Kim presented work carried out with Wayne Higgins to monitor the PNA, the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), and the Antarctic Oscillation (AAO). Indices of these patterns were developed for the period January 1950 to the present, using the NCEP/NCAR CDAS/Reanalysis. Forecasts of the indices are made by projecting the loading pattern of each mode onto the MRF and ensemble forecast data. The indices and forecasts for the most recent 120 days are posted on the monitoring weather and climate web site of NCEP/CPC and updated daily. (http://www.cpc.ncep.noaa.gov/products/precip/CWlink).

iii-iv) **Predictability of the ISO/MJO** (Chair: Cecile Penland) and **Tropical/ extra-tropical interactions** (Chair: Duane Waliser)

In view of the strong connections between the topics on the ISO/MJO and tropical-extratropical interactions, this section is a synthesis of both sessions III and IV. While the names intraseasonal oscillation (ISO) and MJO are often used interchangeably, it is now becoming common practice to refer to the boreal summer variability as the ISO, while the MJO is a boreal winter or cold season phenomena. For convenience we have chosen not make that distinction here, so that in the following we refer to both phenomena as simply the MJO. Note also that in this section, the references to the speakers appear in parenthesis and usually at the end of the sentence. Invited presentations were made by Duane Waliser (session iii, see extended abstract), and Prashant Sardeshmukh (session iv, see extended abstract).

Tropical intraseasonal variability was shown to interact with and/or influence a wide range of phenomena including local weather in the tropical Indo-Pacific region, onsets and breaks of the Asian-Australian monsoons, persistence extra-tropical circulation anomalies in the Pacific-America sectors, extreme precipitation events along the western United States, the development of tropical storms/hurricanes in the Pacific/Atlantic sectors, and even the initiation of El Nino / La Nina events (Duane Waliser). This latter aspect was even extended to the point that the MJO may help characterize the intrinsic time scale, at least its biennial character of ENSO (William Lau, see extended abstract). Additional influences from the MJO include the modulation of N. Pacific cyclone activity (Mike Chen) and the persistence of the S. America convergence zone (Leila Carvahlo). There is also the indication that an independent intraseasonal oscillation may exist over S. America (Jiayu Zhou, see extended abstract).

A number of presentations (e.g., Prashant Sardeshmukh, Duane Waliser, Ken Sperber) showed that improvements in tropical diabatic heating variability (e.g., MJO, ENSO, other equatorial “waves”) will/should result in enhanced (long-lead and seasonal) forecasting skill in the Tropics as well as mid-latitudes via tropical/extra-tropical teleconnections. For example, one idealized dynamical predictability study showed that with a reasonable GCM representation of the tropical MJO, the expected limit of useful predictability for the MJO might be about 25 days (Duane Waliser). Unfortunately, GCMs in both climate simulation and prediction or numerical weather forecasting settings still exhibit rather poor simulations of MJO variability except for a few isolated cases (Duane Waliser, Ken Sperber, Suranjana Saha). In fact, even the interannual variability of features such as the Asian monsoon appear to be poorly simulated due to the poor representation of intraseasonal variability and its (albeit) only weak dependence on boundary conditions (Ken Sperber). Apart from tropical diabatic heating, one presentation (Klaus Weickmann) noted that atmospheric intraseasonal variability can arise due to the effect of mountain and frictional torques on the adjustment of the atmosphere to stochastically-varying flow over mountains. Thus, to properly account for tropical – extratropical interactions on intraseasonal time scales, it may be important to understand the separate roles and influences from the above stochastically-forced process and from the more deterministic tropical diabatic heating process (i.e. MJO).

One presentation (Prashant Sardeshmukh) showed that forecasts based on a multivariate linear inverse model (LIM) could predict seven-day averages of northern hemisphere stream function at lead times of about three weeks at skills superior to the NCEP Medium-Range Forecast model (MRF). This presentation, along with another (Newman), showed how the above predictability came in large part from an ability to describe the evolution of tropical heating, a phenomenon which is not described well by the MRF. Both presentations emphasized how LIM's prediction skill was tied to the identification of three optimal structures for growth: one dominated by tropical heating, one which combined tropical heating and midlatitude dynamics, and a third dominated by midlatitude dynamics. In addition, it was noted that while the LIM can likely provide useful subseasonal predictions of midlatitude variability, it may be necessary to use non-linear models to provide better estimates of uncertainty – i.e. forecasting forecast skill. Of course, these non-linear models need to represent the strength and variability of tropical heating properly.

Monitoring and forecasting of MJO was discussed in a number of contexts. For example, at least two empirical real-time forecasting schemes appear to be forthcoming (Matthew Wheeler – see extended abstract, Charles Jones, Yan Xue - see extended abstract), in addition to the one that already exists via shallow-water model wave filtering (Matthew Wheeler). These activities can be expected to provide useful real-time MJO forecasts out to 10-20 days lead-time, particularly in the current environment in which no operational model has been shown to do well at simulating/forecasting the MJO. One research group has built an empirical mid-latitude forecasting model based on the canonical relationship between the MJO and mid-latitude anomalies over the Pacific – North American sector (Yan Xue). Such a model (and associated website) is designed to provide an aid for extended range weather and/or short-term climate forecasts. Additional presentations examined the structural variability as well as frequency and propagation characteristics of MJO events (Jones) to better understand the different types MJO events and their associated probabilities for occurrence, including for example how ENSO influences these probabilities (or vice versa). Along these same lines, it was pointed out (Duane Waliser, William Lau) that a number of recent analyses have shown that there is no obvious relation between interannual SST variability in the tropics and the overall activity of the MJO, except that MJO events typically propagate further east during El Nino conditions. However, the analysis from one presentation (William Lau) suggested that the biennial tendency of ENSO may in part be derived from the coupling between the interannual and intraseasonal time scales.

Two presentations (Suranjana Saha, Hilary Spencer – see extended abstract) pointed out specific instances of the extreme sensitivity that the MJO simulation character has on even subtle changes in model parameterization. One of these presentations stressed the need to simulate a correct basic state in a numerical weather prediction model, for both the sake of obtaining an accurate climatology and thus less drift with lead time but also to obtain a better representation of transients that depend on the mean state (Suranjana Saha). In fact, very recent studies have shown that the simulation quality of the MJO can be particularly sensitive to the basic (e.g., low-level zonal wind direction in the Indian/western Pacific Oceans). The other presentation (Hilary Spencer) highlighted the rather significant change in the simulation quality of the MJO simply due to an increase in the vertical resolution (namely in the mid-troposphere). Along somewhat similar lines, it was shown that assimilation of total column water vapor content into the GEOS AGCM can significantly influence the model's representation of the MJO (Man Li Wu – see extended abstract), furthering the suggesting that correct treatment of moist convection and the hydrological cycle are vital to the simulation of the MJO. Another study extended this notion to a completely general framework, pointing out that our analyses and re-analyses data sets are severely hampered by not only a lack of data but also due to incorrect moist physical parameterizations (Arthur Hou – see extended abstract). This study highlighted the improvements that can be gained in these sorts of validating data sets via the assimilation of satellite-based precipitation estimates.

A number of talks stressed the importance of what might have previously been thought of as unimportant details as actually being significant to the subseasonal prediction problem. In one case study, it was shown that the evolution of the seasonal mean circulation over the Pacific North American region was deterministically influenced by subseasonal SST variability (Ben Kirtman). In another case, it was shown that proper simulation of the detailed characteristics of a tropical atmospheric heat anomaly associated with a given El Nino, including the correct partition between basic state and anomaly, were crucial to obtaining a proper mid-latitude teleconnection properties for that given event (Hilary Spencer). Along similar lines, it was shown that distinct sub-seasonal (i.e. monthly) extra-tropical atmospheric signals do occur in response to ENSO and that seasonal averages not only can smear these out but can obscure them entirely (Marty Hoerling).

v) **Role of land surface processes** (Chair: Huug van den Dool)

Randy Koster gave the invited presentation for this session (see extended abstract). There were four additional papers, by Masao Kanamitsu et al. (see extended abstract), Adam Schlosser et al., Paul Dirmeyer and Mike Bosilovich et al. (see extended abstract). To this I will add some comments made by Huug van den Dool in his invited talk about operational methods that relate to the land surface. To paraphrase (and extend slightly) on Koster's list of requirements:

1) Soil moisture needs to have an effect on the atmosphere. This effect has to be quantifiable.
2) Soil moisture needs to have a memory, either through a long autocorrelation (lifetime “on the spot”) or in a more Lagrangian sense as prediction skill where soil moisture anomalies are allowed to evolve and move around.
3) Finally, does realistic soil moisture actually help in the prediction?

Koster et al made several shortcuts and studied “potential predictability” in a model to find “where” soil moisture could make a difference. Different models give, unfortunately, very different estimates of where soil moisture could make a difference. Kanamitsu et al have gone ahead and made a fairly realistic soil moisture data set for 1979-present by manipulating the precipitation that enters the land scheme of the so-called Reanalysis-2. A large focus here is on verification, which leads to a focus on DATA. Model forecasts with and without realistic soil moisture show improved skill in temperature.

The impact on precipitation is unclear. Kanamitsu doubts that we need dynamical models if all we can harvest is the impact on temperature. Van den Dool showed extensively by empirical means how dry (wet) antecedent soil leads to warmer (colder) conditions for the next several months. Such tools are already in place for use in CPC's monthly forecasts and are being relied upon for the warm season. Schlosser showed that the autocorrelation of soil moisture varies from weeks to seasons. He also argued that the beneficial impact of realistic initial soil moisture in a model becomes impossible to find when the model biases overwhelm any small effects we are looking for. The focus here is on a-priori removal of systematic errors. Dirmeyer delineated that the model drift consists of three parts, each with their own time scale. The first is caused by precipitation bias, the second by radiation biases, and the third would be coupling effects. Dirmeyer also raised the question as to whether we should be using model consistent soil moisture or realistic soil moisture. Nearly everybody wanted to know why models have precipitation biases, and what it would take to reduce them. The tracer study by Bosilovich added another perspective to the question about the origin of precipitation in a given area.

Closing comments:

A) Although the effect of soil moisture is expected in “the warm season” it is important year round for a number of reasons: i) There is a warm season somewhere on the planet all the time, and by teleconnection the impacts could be far away, especially when trends in land use over large areas (South East Asia) are considered. ii) Soil moisture calculations need to be done year round and iii) There may be carry over effect from snow cover/depth to soil moisture anomalies.

B) GCMs appear to overdo the impact of soil moisture on for instance the near surface temperature.

C) We need data at the most basic level to verify model results. There appears to be an almost complete lack of evaporation data. Need bright minds to think of measuring (surface) evaporation on a scale larger than a tower here and there.

D) We need to find non-local impacts of soil moisture for this field of scientific endeavor to be really important (over and above simple empirical methods) for forecasts in day15-60 range.

E) What are the causes of large precipitation biases in GCMs, and how to improve the situation?

vi) Link between low frequency and weather/regional phenomena

(Chair: Siegfried Schubert)

This session consisted of a number of talks dealing with various aspects of weather and climate variability and predictability, including diagnostic studies of the errors (both random and systematic) that affect AGCM simulations and forecasts.

The invited presentation was made by Jeff Whitaker on the subject of "Storm Track Prediction" by Jeff Whitaker and Tom Hamill (see extended abstract). The transition between weather and climate prediction was defined to occur at the forecast lead time at which all skill is lost in predicting individual storms. Prediction of weather beyond that transition is based on the assumption that the large scales organize weather to allow predicting the statistics of weather, in particular the short waves that are the major precipitation producers during the cold season.

A number of results were presented from 23 years of three week "reforecasts" for JFM with the MRF model (T62L28) that was operation during the first half of 1998. They found that in the extratropics, the short waves lose skill after 5 days, while the long waves have skill well into week two. The results of a CCA analysis showed that the most predictable pattern for day 10 forecasts is the PNA. A regression analysis further showed a time evolution in which an initial broad anomaly develops in the North Pacific, followed by rapid intensification in the eastern Pacific of a baroclinic wave, followed by downstream propagation. Results for week 2 were quite similar, while the three week averages showed a link to the west Pacific pattern. The above evolution is associated with well-defined storm track shifts. Furthermore, the storm track shifts were more coherent for longer averaging periods (more individual storms). In the second part of the talk, Jeff examined week two quantitative precipitation forecasts (QPFs) with the above forecast model, and based on his analysis of the storm track shifts. The results were based on near real time 15 member ensemble runs at CDC since 1 Dec 2001. The results showed that skillful QPFs in week 2 are possible, but that ensemble bias correction is crucial.

The next talk was given by Yehui Chang on "Extreme weather events and their relationship to low frequency teleconnections" by Y. Chang and S. Schubert (see extended abstract). The presentation described a method for characterizing extremes in daily precipitation over the continental United States using a combination of compositing and linear regression. The results showed that the extremes have both regional and seasonal dependencies. For example, during the cold season, the extremes in precipitation tend to be associated with well-known “large-scale” weather systems, while during the warm season they are associated with more localized convective systems. The results were applied to both the observations and the results from simulations with the NASA/NCAR AGCM run with idealized warm, neutral and cold ENSO SST. The AGCM results and to a lesser extent the observations (1963-1999) showed evidence for a substantial impact of ENSO on the statistics of the extremes events. Preliminary evidence was also presented for impacts of subseasonal modes of variability (e.g. the PNA and the NAO) on the statistics of the extreme events.

J. Shukla presented the results of a study on the “Relationship between the PNA internal pattern and the ENSO-forced pattern: time scales from daily to seasonal”, by David Straus and J. Shukla. The study involved the separation of seasonal mean variability during boreal winter into that forced by SST and that generated internally. The study was based on 30 winters of ensembles of simulations with the COLA AGCM forced with observed SST as well as, long simulations with climatologically varying SST. They distinguish between the ENSO-forced response (or external pattern of variability) and the ‘PNA”-like pattern of internal variability. They found that when these patterns are projected onto pentad data, the probability density function (pdf) obtained for the ENSO pattern is distinct from that of the PNA pattern. They further found that during warm events the PNA pattern has greater chance of having both polarities, while during cold events the ENSO pdf is wider than that of the PNA, and there is enhanced intraseasonal variability.

Rob Black presented a talk on an “Assessment of midlatitude subseasonal variability in NASA/GSFC general circulation models”, by Black, Robinson and McDaniel (see extended abstract). They performed a preliminary assessment of the storm tracks and anomalous weather regimes in AMIP-style integrations of two different models. These consist of the NASA/NCAR AGCM used by the DAO for data assimilation, and the NASA Seasonal-to-Interannual Prediction Project (NSIPP)-1 AGCM used by NSIPP to assess predictability and to carry out predictions on seasonal-to-interannual time scales. The results showed that the models regional patterns of upper tropospheric eddy kinetic energy (EKE) are well represented for both the synoptic and low frequency eddies, and represent an improvement over earlier models. Both models, however, have weaker than observed low frequency and synoptic EKE (by

20-30%). The NSIPP model in particular, has synoptic EKE that is only 64% of the observed values. The authors present a number of diagnostics to attempt to explain the model discrepancies. A diagnosis of the baroclinic and barotropic aspects of the model dynamics shows that the NSIPP model synoptic eddies are experiencing enhanced barotropic energy losses to the mean flow in the jet exit region, while the background baroclinic forcing is closer to the observed values. The authors speculate that the existing deficiencies in the low frequency EKE of both models may be related to the scale interaction between the synoptic and low frequency eddies.

Ming Cai presented a talk on "Diagnostics of Climate Variability and Trend Using Potential Vorticity Maps" by Ming Cai and Eugenia Kalnay. They examined the strong warming trend in high latitudes of the NH during the last 2 decades, and conjectured that changes in extratropical frontal activity may explain part of the much-amplified warming trend in high latitudes. Their diagnostic technique centered on an analysis of potential vorticity surfaces in which they define PV folding zones. The interannual variability of an extratropical PV Folding Index (PVFI) and extreme surface cold and warm events were both shown to have a strong QBO signal. They further showed that the interannual variability of the PVFI is correlated with interannual variability of warm and cold events. An advantage of using the PVFI, over say the AO index is that it measures both mobile and standing parts of polar vortex variability, and is not constrained by "inactive" periods or warmer seasons.

Glen White's talk focused on the systematic errors of the NCEP operational 0-15 day forecasts (see extended abstract). He showed that the systematic errors are similar to the bias in long (multi-year) model simulations, and suggested that improvements in the short-range systematic errors should help to improve the 2 week to two month forecasts. An advantage of focusing on the short-range forecasts is that they should be easier to diagnose, since they occur before nonlinearity dominates the forecast evolution. The analysis addressed, in particular, the systematic errors in the surface fluxes. Glen showed that considerable differences exist between different estimates of air-sea fluxes. Current global forecast systems have problems with cloudiness that produce inaccurate short wave fluxes and problems with moisture that affect long wave fluxes. A key deficiency of current models appears to be in the representation of low-level oceanic stratus clouds.

Mark Helfand presented results from a study of the interannual variability of the United States Great Plains Low-Level Jet (GPLLJ) during May through August (see extended abstract). The results, base on 17 years of GEOS-1 reanalysis data showed that the GPLLJ is one of the most persistent and stable features of the low-level continental flow. The interannual variance was found to have 3 maxima with one over the upper Great Plains, another over Texas, and a third over the western Gulf of Mexico. Mark showed evidence for an intermittent biennial oscillation in the maxima over Texas. Of particular relevance to the subseasonal prediction problem is the finding that the typical duration of the interannual anomalies is on the order of several weeks, with the more southerly maxima having the longest time scales. Further analysis is required to better understand the nature of the biennial oscillation and robustness of the week-to-week coherence of these anomalies.

III. Discussion and Summary

The final discussion session, chaired by J. Shukla, summarized the main findings of the workshop and outline steps that should be taken to make progress on the subseasonal prediction problem. J. Shukla highlighted some of the lessons learned from the numerical weather prediction (NWP) problem. In particular, it was pointed out that much of the improvement in weather forecast skill over the last 30 years has come about because of improvements to the models. It remains to be seen whether this will also be true for the subseasonal prediction problem, though it is already clear that models will have to do many things right (e.g., land, weather, MJO, stratosphere, etc.) to make substantial progress towards the prediction problem throughout the globe. He also outlined a set of baseline forecast experiments that could serve to better assess the status of our current subseasonal prediction capabilities (see below).

The following is a synthesis of the summary session and includes further (post-workshop) summaries and analysis provided by members of the organizing committee. Specific recommendations are given in section IV.

Forecasting on time scales longer than weather but shorter than one season (about 2 weeks to 2 months) is perhaps the most challenging weather/climate forecasting problem we will face in the coming years. This workshop was held in order to take stock of current capabilities, and to examine recent progress in a number of different areas of weather and climate research that offer potentially substantial gains in forecast skill on 2 week to 2 month time scales. The workshop participants, therefore, included scientists from traditionally disparate communities, including researchers with specialties in stratospheric dynamics, hydrology and land surface modeling, the monsoons, the MJO and other tropical variability, extratropical variability including extratropical-tropical interactions, coupled atmosphere-ocean-land modeling, weather prediction, seasonal prediction, and various aspects of statistical modeling, analysis, and prediction.

The key finding of the workshop is that there is compelling evidence for predictive skill at lead times substantially beyond two weeks. It is understood that at these times scales the predictions are largely probabilistic (e.g., phase information about individual storm systems is lost), and that the ultimate goal should be the prediction of the evolution of the probability density function (PDF), thereby bridging both the weather and seasonal forecast problems. The various presentations suggested that we should not expect to find a single dominant source of predictive skill on these time scales. In fact predictive skill will likely come from a host of different phenomena depending on region, season, and time scales of interest. For example, during the boreal winter there is evidence for enhanced predictability in the middle and high latitudes associated with the Arctic Oscillation, the stratosphere, the PNA pattern, and tropical forcing. Evidence for analogous sources of predictability exist in the Southern Hemisphere (e.g., the Antarctic oscillation). The MJO offers the potential for improved forecast skill, especially of the Asian-Australian monsoon. Memory of the soil moisture (and snow melt) offers hope for skillful warm season predictions at lead times beyond two weeks in a number of different continental regions, primarily of surface temperature and to a lesser extent precipitation.

In the following we summarize some of the key unresolved issues and outline specific steps that should help translate the various potential sources of predictability into measurable improvements in forecast skill.

i. Role of tropical heating and the MJO

This is one of the most promising sources of predictability and represents a major opportunity for improvements. Current GCMs do poorly in simulating many aspects of tropical convection and the links to the extratropics, especially the heating associated with the MJO. Simpler (compared with GCMs) linear inverse models (LIMs) show skill at 3 weeks in the extratropics associated with tropical heating, a skill not realized in current GCMs. Statistical and other modeling studies suggest that deficiencies in the ability of GCMs to simulate MJOs are a serious impediment to improving forecasts of subseasonal variability of the Asian-Australian monsoons, the predilection for hurricane formation, and other subseasonal variability including that over the southwestern United States. It was also pointed out that improving the representation of tropical transients in GCMs will likely have a much greater impact on forecasts than improvements in the extratropics, and this will have major impacts on a larger portion of the world's population.

While modeling deficiencies are a major problem in this area, deficiencies in the estimates of tropical heating (both for initial conditions and for model verification) are also important. It is clear that we will need better estimates of tropical heating. Little work has been done to date to address predictability associated with tropical heating on subseasonal time scales using GCMs. How important are the details of the heating fields (how accurately must these be observed) and can we expect to predict these beyond two weeks. LIMs of GCMs offer an important diagnostic tool to address these issues.

Considerable work is needed to better understand the nature and predictability of the tropically forced modes. For example, issues specific to the MJO include, the sensitive of MJO predictability estimates to the GCM, season, ENSO, SST coupling, and mid-latitude variability. How does MJO predictability influence mid-latitude circulation and extreme event predictability? Can we use empirical forecasts of MJO heating and assimilate that into forecast models as a short-term means to improve medium to extended range predictions? The role of subseasonal SST variations not directly coupled to the MJO also requires further study.

ii. Extratropical modes of variability

Annular "modes" provide one of the most promising prospects for skill beyond two weeks in the middle and high latitudes. These modes appear to have long enough time scales and strong enough influences on the surface that memory of the initial conditions can produce useful forecasts at long lead times. For example, the Arctic Oscillation has a strong influence on middle and high latitude surface temperatures.

There is intriguing evidence of stratospheric influence: strength of wintertime stratospheric vortex influences the subsequent tropospheric circulation. Another low frequency pattern that has a substantial impact on the Northern Hemisphere extratropical climate is the PNA pattern. In fact, the PNA was identified as the most predictable of all the extratropical modes examined. Blocking episodes represent another source of predictability, though this is yet-to-be-realized since current models tend to under predict blocking frequency. Still other low frequency teleconnection patterns have been recently discovered in which the tropospheric jets act as wave guides, resulting in zonally elongated wave patterns that link distant parts of the globe. The predictability associated with those modes is yet to be determined.

Key issues that need to be further addressed include the nature of the link of the annular modes to the stratosphere and the signal to noise ratio (i.e. how large is the predictable signal from the stratosphere compared with the total variability). There is a need to better understand the sources of predictability associated with blocking and the PNA (e.g. tropical heating, weather, ENSO). How do the variations in the jets affect predictability associated with the wave guiding mechanism. How well do models reproduce these and other low frequency modes, the interactions with the stratosphere, and interactions with weather/extremes? Does the signal get lost beyond two weeks due to model drift? What is the sensitivity to horizontal and vertical resolution?

iii. Soil moisture and snow

Soil moisture may be very important on subseasonal time scales (perhaps more so even than for the seasonal problem) – consistent with intrinsic time scales of soil moisture anomalies (weeks to one month).

Among the outstanding issues is the fact that LSMs currently do not agree on the strength of interactions between land and atmosphere. Little has been done to address the predictability of snow in current GCMs. Results from current studies suggest strong regional and seasonal dependence (need to pick the right season and the right region).

The availability of land surface data is poor, yet the need is great (especially soil moisture, snow and estimates of evaporation). Can we get evaporation from satellites? We need to consider in predictability studies that soil moisture anomalies move around – this relates to the difference between the predictability time scale and the autocorrelation. Model bias is an issue, especially for rainfall. While soil moisture sensitivity is a summer phenomenon, we need to get the right seasonal cycle, so that snow is important (how that impacts soil moisture in spring). Current results suggest that 80% of the soil moisture effect is on temperature, while the impact on precipitation is still uncertain.

iv. Links with weather and other regional phenomena

Numerous studies have demonstrated that weather or synoptic variability is influenced by (and influences) low frequency variations such as the MJO, the PNA pattern, and blocking. For the subseasonal prediction problem we need to better understand how these interactions affect predictability, and determine those properties (or statistics) of weather that are predictable at lead times beyond which individual storm systems can be predicted. Examples of weather properties that are potentially predictable include changes in storm tracks, changes in regions of preferred hurricane formation, and changes in extreme events. A key issue in addressing these problems concerns the ability of climate models to simulate weather systems. For example, are detailed high-resolution simulations of individual hurricanes needed? Or, is it sufficient to only predict large-scale changes in the factors influencing hurricane formation?

A related issue concerns the resolution that is necessary in climate models to make them useful for addressing predictability on regional scales? Various local climatological features, such as the United States Great Plains Low Level Jet (LLJ), have a profound impact on regional climates, making it unlikely that climate models that do not adequately resolve such phenomena can provide useful predictions on regional scales.

In general, we need to begin to define more stringent quality measures to assess the veracity of model simulations that directly link errors in the models to uncertainties and errors in predictions at longer time scales. Clearly, climate drift plays an important role in that it often exceeds the signal that we are trying to predict. The diurnal cycle is a key example of large systematic errors that are common to most climate models and that likely impact our ability to make useful regional predictions - especially over continents during the warm season.

In addition to reducing systematic errors, useful and reliable regional predictions (and for that matter predictions at all scales) require that models produce realistic variability and show sensitivity to initial conditions. This is necessary so that the spread of ensemble members will provide realistic assessments of forecast uncertainties (more on this below).

v. Methodology and data

A number of suggestions for improving forecast skill at the subseasonal time scale dealt with the application and development of new forecast methodologies. These included the use of atmosphere-ocean coupled models to better simulate the interactions between the atmosphere and ocean, especially in the extratropics. The key argument here is that this should provide more realistic time scales of the atmospheric anomalies. There is also evidence that ocean feedbacks can produce more realistic simulations of the MJO. Another suggestion was to use ocean mixed-layer models: these might provide most of the benefits of a full ocean model, but their use avoids the problems of spin-up and other shocks to the system that often occur when starting up a fully-coupled atmosphere ocean model forecast.

There is a clear need to improve the initialization of coupled atmosphere/land/ocean models in a way that minimizes model shocks and retains the information in the initial conditions. This includes improvements in how one samples from the initial PDF, including uncertainties in the tropical heating and other important forcing mechanisms. Simpler models should be used where possible to help diagnose the full AGCMs. Other uses of simpler (e.g. linear and/or lower order) models include more economical estimates of higher order statistics that could be used, for example, for forecasting forecast skill.

New data sets are needed for both initialization and verification of model forecasts, and for validating models. These include long term comprehensive and consistent reanalysis data sets of the atmosphere, land, surface fluxes, and sea surface temperatures for a host of studies, including hindcast experiments that address issue of model forecast skill and predictability. The reanalysis data sets also need to provide improved diabatic (latent and radiative) heating, precipitation, and clouds to allow better tropical analyses for initialization, as well as to help validate convection schemes. Long term soil moisture, snow and, if possible, evaporation observations are needed for reanalysis, for initializing the land, and improving land surface models. There is also a need for better observations of the diurnal cycle over warm season continents to improve the diurnal cycle of precipitation/convection in GCMs.

IV. Recommendations

The results presented at the workshop suggest that substantial progress on the subseasonal prediction problem will likely be the result of progress in a number of disparate lines of research and development. As such, we believe that it will be crucial that the major climate and weather centers (in particular NASA and NOAA) work together to help coordinate and focus these various efforts. In the following we outline areas of high priority research and make specific recommendations on near term "action items" that we believe are most likely to lead to substantial improvements of predictions on subseasonal time scales.

i. High priority research and development

Tropical heating

- Improvements in the ability of GCMs to simulate the MJO
- Improved satellite estimates of subseasonal variability in tropical heating, especially vertical profiles, and related phenomena such as precipitation and clouds.
- Development of long-term consistent reanalysis data sets with improved representation of the tropics
- Improved initialization and ensemble methodologies
- Determine the role of subseasonal SST variability, and assess the gains in forecast skill from employing coupled atmosphere-ocean models, including models with only mixed layer components
- Develop and exploit simplified models to help diagnose and benchmark the skill of full GCMs
- Improve our understanding of tropical/extratropical interactions

Soil moisture and snow

- Improved model simulations of soil moisture and snow – determine realism of the simulated soil memory
- Improved satellite observations of soil moisture and snow
- Development of long term consistent data sets of soil moisture, evaporation, and snow, including those from global reanalysis systems
- Improve understanding of the coupling between the land surface and atmospheric processes

Extratropical modes of variability

- Improved understanding and simulation of annular modes, and their impact on the surface climate
- Improved understanding of the link to the stratosphere and associated potential predictability in the troposphere
- Improved long-term reanalysis datasets with a well-resolved stratosphere
- Improved understanding of the nature and predictability of various other modes of subseasonal variability such as the PNA, as well as an assessment of how well models are able to capture these modes
- Improved understanding of how subseasonal variability impacts weather and how predictable the impacts are

ii. High priority action items:

a) That a coordinated and systematic analysis of current subseasonal forecast skill be conducted by generating ensembles of 30-day hindcasts for the past 30-50 years with several "frozen" AGCMs. Specific goals include, sampling all seasons, and generating sufficiently large ensembles to estimate the evolution of the probability density function.

b) That a series of workshops be convened focused on modeling the MJO, and that a coordinated multi-nation/multi-model experimental prediction program be developed focused on the MJO.

c) That new satellite observations and new long-term consistent reanalysis data sets be developed for initialization and verification, with high priority given to improvements in estimates of tropical diabatic heating and cloud processes, soil moisture, and surface fluxes (including evaporation over land).
d) That NASA and NOAA develop a collaborative program to coordinate, focus, and support research on predicting subseasonal variability.

Specific steps to implement the above recommendations are: 1) to begin immediately to develop a framework for an experimental MJO prediction program, 2) to convene a follow-up workshop in the spring of 2003 to organize the AGCM hindcast project, and conduct initial meetings on modeling the MJO, and 3) for NASA and NOAA to put out a joint announcement of opportunity within the next year to focus research, modeling and data development efforts on the subseasonal prediction problem.

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01:40	The Relationship Between the Classic PNA Pattern and the ENSO-Forced Pattern on Time Scales from Daily to Seasonal David M. Straus and J. Shukla	158
02:00	Assessment of midlatitude subseasonal variability in NASA/GSFC General Circulation Models. Robert X. Black and Dennis P. Robinson	159
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02:40	Systematic Errors and Surface Fluxes In the NCEP global model Glenn White	164
3:00	Configuration and intraseasonal duration of interannual anomalies of the Great Plains Low Level Jet. Mark Helfand	170
3:20	BREAK	
3:50	**DISCUSSION (Chair: Shukla)**	
5:30	END OF WORKSHOP	