Title

Understanding and predicting seasonal-to-interannual fluctuations in California precipitation using an atmospheric general circulation model

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Abstract

The water supply in California is subject to large variations on a variety of timescales ranging from intraseasonal to decadal. Interannual variations were the focus of the research undertaken in this project. The primary source of water in California is precipitation associated with winter storms originating over the North Pacific Ocean. Thus, the variability in the water supply is ultimately linked to variations in the precipitation. It is known that a significant amount of the interannual variability in precipitation is related to variations in sea surface temperatures (SSTs) in the tropical eastern Pacific Ocean - El Niño and La Niña events. However, the response in California precipitation varies from event to event, in part because the SST anomalies do not evolve in the same way during each event. In addition, extreme events such as the flood of January 1997 can occur even when tropical Pacific SST anomalies are weak, suggesting that mechanisms other than El Niño/La Niña forcing can produce seasonal to interannual variations in California precipitation. The natural variability of the Pacific storm track is one such possible mechanism. These storm track variations can modulate the frequency, strength, and location of landfall of winter storms.

Statement of the Problem

Winter storm systems moving inland from the Pacific Ocean deposit large amounts of precipitation on California and are, therefore, extremely important to the water supply in California. The path which these storms take as they move ashore from the Pacific is known as the Pacific storm track. Variations in the intensity and location of this storm track modulate the frequency, strength, and location of landfall of winter storms. Therefore, seasonal to interannual variations in California water supply are closely related to variations in the Pacific storm track. A better understanding of the physical processes that control storm track variations is essential for successful prediction of such variations.

The Pacific storm track is controlled by the planetary wave component of the atmospheric general circulation. When this component of the general circulation changes, so does the strength and location of the storm track. There are two important processes that can produce such variations. The first process is variations in the "external" forcing at the lower boundary of the atmosphere. Sea surface temperature (SST) anomalies associated with El Niño and La Niña events are the strongest forcing of this type. Although El Niño events are generally associated with wetter than average conditions in California and La Niña events with drier than average conditions, there is no unique El Niño (or La Niña) response in either the Pacific storm track or California precipitation. Furthermore, the influence of SST anomalies in mid-latitudes and other tropical ocean basins may be substantial. For example, recent work (Farrara et al. 2000) had suggested that SST anomalies in the Indian Ocean can have a significant impact on western North America during winter. This raises the question: What is the physical mechanism by which tropical Indian Ocean SST anomalies influence the Pacific storm track? One possibility is that the atmospheric heating anomalies which develop in response to the Indian SST anomalies force changes in the global Walker circulation in the tropics which in turn modify the atmospheric heating anomalies which develop in response to the SST anomalies in the tropical Pacific, and thus the impact of the tropical Pacific SSTs on the Pacific storm track. A second possibility is that the atmospheric heating anomalies which develop in response to the Indian SST anomalies set up a poleward and eastward propagating Rossby wave train which interacts in the region of the Pacific storm track with a corresponding wave train generated in the tropical Pacific. The second process is related to the internal oscillations of the mid-latitude atmospheric flow. In this process, variations in the storm track are produced without any variations in the external forcing. Interactions among different components of the mid-latitude atmosphere, such as wave-mean flow interactions, cause the atmospheric circulation to vacillate between different flow patterns. These natural variations can cause interannual fluctuations in California precipitation even when SST anomalies are weak.

Objectives

A thorough assessment of these two processes is necessary for developing methods to accurately predict short- and long-term fluctuations in California precipitation and was a major objective of the research undertaken. A second major objective of the research was to gain insight into the mechanisms at work when lower boundary forcing (such as El Niño/La Niña) is the dominant factor. It is known that a significant amount of the interannual variability in California precipitation is related to variations SSTs in the tropical eastern Pacific Ocean - El Niño and La Niña events. However, the spatial distribution and intensity of precipitation anomalies varies rather substantially from one event to another. The factors that may contribute to these differences include: i) differences in the intensity, temporal evolution and spatial distribution of the tropical Pacific SST anomalies and, ii) the influence of SST anomalies in mid-latitudes and other tropical ocean basins. To summarize, the primary objectives of the proposed research were: 1) to determine the relative importance of El Niño and La Niña SST anomalies and natural variability on California precipitation and develop an improved capability to predict its interannual variations, and 2) to gain insight into the physical mechanisms responsible for the impact of tropical SST anomalies in the Pacific and Indian Oceans on California precipitation.

Methodology

Since it is impossible to separate the El Niño/La Niña influence from the natural variability using observational data alone, experiments with a numerical model were used as a powerful alternative method of achieving the objectives. To address objective 1) we analyzed AGCM simulations with various prescriptions of observed SSTs and used the AGCM in conjunction with available predictions of SSTs, to make experimental predictions of winter precipitation in California. This is the so-called "two-tier" prediction method in which SSTs predicted using either coupled atmosphere-ocean general circulation models or other methods are taken as the lower boundary forcing for high-resolution AGCM simulations. For each winter during this project we have performed and published on the Web such a "prediction" using SST anomalies for the tropical Pacific predicted by the National Centers for Environmental Prediction (NCEP) coupled GCM.

To address objective 2) our approach consisted of performing ensembles of simulations using a high resolution model configuration (2.5° longitude, 2.0° latitude with 29 layers in the vertical) for the ENSO winter of 1997-98 using various prescriptions of observed SSTs. Ensembles of nine runs each were performed to increase the statistical significance of the results. The nine runs in each ensemble differ slightly in their initial conditions. These results are reported below and in Farrara et al. (2000).

Results

Our results suggest that the natural variability is the dominant factor influencing the intensity and position of the Pacific storm track in years when tropical SST anomalies are relatively weak. For example, significant differences were observed in California winter precipitation during 1999-2000 and 2000-2001 although the extents of SST anomalies (weak) in these two seasons were similar. The results of our prediction exercises for the two winters (for details on the methodology see Appendix A or via the Web at uniblab.atmos.ucla.edu/~vwk206/fcst02.html) showed the influences of these events. For this exercise, we had available predictions of SST for the tropical Pacific Ocean. The SSTs in this region were very similar in these two winters and, therefore, our AGCM-based forecasts were very similar. The unpredictable component, the natural variability, that was unaccounted for in the modeling however was sufficiently large to cause the significantly different precipitation patterns in these two winters.

The response of the extratropical winter circulation to tropical SST anomalies has been analyzed through AGCM two-tier predictions and simulations using the 1997-98 winter as a case study. Ensembles of simulations and predictions were performed using different distributions of SST anomalies as lower boundary conditions. We found that small differences in the structure and evolution of tropical SSTs anomalies in the Pacific can have a substantial impact on the simulated precipitation anomalies in the tropics, but not in California. Neither was there any detectable extratropical signal associated with mid-latitude SST anomalies. The response over the extratropical North Pacific-North American sector, however, was significantly different and more realistic if SST anomalies over the Indian Ocean were included. In addition, there was a significant impact on simulated precipitation anomalies in the western United States when Indian Ocean SST anomalies were considered. The overall skill of the predicted and simulated circulation anomalies in the Pacific-North American region was also evaluated.

The different extratropical responses found in simulations that include Indian Ocean SSTAs compared to those that do not was determined to be due to the linear superposition of a Rossby wave train emanating from the subtropical Indian Ocean region. This conclusion was reached by comparing observed and simulated anomalous Rossby wave sources in the simulations including and excluding Indian Ocean SST anomalies. This was the dominant mechanism of influence; the influence of changes in the global Walker circulation in the tropics which in turn modify the atmospheric heating anomalies which develop in response to the SST anomalies in the tropical Pacific was determined to be small. We have also examined the extratropical response to SST anomalies in terms of their influence on the model's intrinsic modes of intraseasonal variability via a PDF analysis of 700 hPa height anomalies. The results strongly suggest that the model's modes of intrinsic variability are involved in the mean response to SSTs and that the tropical SST anomalies influence the frequency of occurrence of these modes. Furthermore, they suggest that the tropical forcing influences the intensity of the intrinsic modes as well as their frequency of occurrence.

Conclusions

The results of our two-tier predictions suggest that there may be clear limits to our ability to make seasonal forecasts in the absence of strong tropical SST anomalies. When strong SST anomalies are present, it was found that the skill of the two-tier forecasts performed using NCEP SST predictions is comparable to those obtained in simulations using observed SSTs in the Pacific Ocean only, and that, among the simulations, the highest skill was obtained when SST anomalies were included in both the Pacific *and* Indian Ocean basins. The influence of Indian Ocean SSTAs was determined to be due to the linear superposition of a Rossby wave train emanating from the subtropical Indian Ocean region. The results emphasize that successful seasonal forecasts of SST anomalies in the tropical Indian Ocean can contribute significantly to the success of similar forecasts for the extratropics of the Northern Hemisphere during winter. For the exceptional ENSO event of 1997-98 the benefits were clear over the northeast Pacific and western North America. Other work has suggested that concurrent anomalies in the Atlantic contributed a predictable signal over Europe. Operational centers, therefore, are encouraged to provide SST forecasts at least for the entire tropics.

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Farrara, J. D., A. W. Robertson and C. R. Mechoso, 2000: Ensembles of two-tier simulations and predictions of the circulation anomalies during winter 1997-98. *Mon. Wea. Rev.*, **128**, 3589-3604.

Appendix A

The winter of 2001-2002: Forecasts using the UCLA AGCM

a) Motivation

Our eventual ability to predict some fraction of the long-term fluctuations in California's water resources will rest to a large extent on the success of atmospheric general circulation models (AGCMs), which use prescribed sea surface temperatures (SSTs). To be of use in making such predictions, AGCMs must be able to simulate the structure and variability of planetary waves and storm tracks over the western United States, as well as changes in the frequency of occurrence of the predominant weather regimes affecting the region. The largest interannual changes in the atmospheric circulation in the Pacific Basin (tropical and extratropical) are associated with ENSO events in the tropical Pacific. Here, we use the UCLA atmospheric general circulation model in conjunction with SSTs from an ensemble of NCEP coupled atmosphere-ocean GCM forecasts of the SST in the tropical Pacific Ocean to make forecasts of the global circulation and precipitation anomalies for the upcoming winter.

b) Methodology

The version of the UCLA AGCM used is described in Appendix B. The model resolution employed in this study is 2.5 deg. long., 2.0 latitude with 29 layers in the vertical from the Earth's surface to 1 mb. Five control and five "forecast" simulations were performed for two different model versions. The results shown are the average anomalies predicted by this 'multi-model' ensemble of forecast simulations. Each of the simulations is six months long, covering the period October 1 - March 31. The control simulations use monthly climatological SSTs from the GISST dataset (see Appendix B). The "forecast" simulations use the same (climatological) SSTs, EXCEPT in the tropical Pacific (30S - 25N, 120E - 290E) where the SST anomalies for October 2001 - April 2002 from an ensemble of predictions with the NCEP coupled atmosphere-ocean GCM (completed on Aug. 15, 2001) are added to the GISST climatological SSTs. The simulations differ in their initial conditions. The original model initial data is based on observational data for October 1, 1982. The other initial conditions are derived from this original one by adding eight sets of different random perturbations to fields of the model's prognostic variables.

c) The Forecast

The anomalies shown in the plots below are computed by taking the difference between the means (10 member averages) from the "forecast" simulations and those from the control simulations. For November- December precipitation, the most robust anomalies are in the Pacific Northwest (including Northern California and Idaho) - where smaller than normal amounts of precipitation are expected - and all across the southern states from Texas to Florida, where larger than normal amounts of precipitation are predicted (see Figure 1). Temperatures during November and December are forecast to be colder than normal throughout almost the entire country, with the strongest anomalies in Upper Midwest and

Great Lakes region where temperatures are forecast to average 3-4F below normal. On the other hand, temperatures will be only slightly below normal in most of the western U.S., including all of California and Idaho. (see Figure 2). Predicted circulation anomalies in the lower troposphere are consistent with these predicted temperature and precipitation patterns (see Figure 3). During the latter half of the winter (Jan-Mar) drier than normal conditions are expected to continue in the Pacific Northwest (including Idaho) and further develop in the far Northeast, while wetter than normal conditions continue in parts of the South and develop in the Southwest, including southern California. (see Figure 4). Temperatures during January, February and March are forecast to continue to be colder than normal east of the Rocky Mountains, while warmer than normal conditions develop to the West, including all of California, and southwest Idaho. The largest cold anomalies (up to 4F) are found in the Ohio Valley, while the warm anomalies in the West are generally around 1F (see Figure 5). Predicted circulation anomalies in the lower troposphere are consistent with these predicted temperature and precipitation patterns (see Figure 6).

d) Comparison with official NCEP seasonal forecasts for OND 2001 and JFM 2002

The temperature and precipitation anomaly forecasts described in Section 3 can be qualitatively compared with the official NCEP forecasts for Oct-Dec (1.5 month lead) shown in Figure 7 for the precipitation. This figure can be compared with Figure 1, the GCM forecast. The NCEP prediction is for normal amounts of precipitation everywhere except in a region centered on eastern Texas, Oklahoma, Louisiana and Missouri, where above normal amounts are expected. The GCM forecast (Figure 1) suggests above normal precipitation in this area as well although it extends across a wider area of the South. Disagreement between the two is most clear in the Pacific Northwest where the GCM forecast indicates decidedly drier conditions and NCEP predicts normal conditions. Concerning the temperature forecast, the NCEP forecast (see Figure 8) is for above normal temperatures in the desert Southwest and south Florida and normal temperatures everywhere else. The GCM forecast (Figure 2) shows no clearly warmer than normal regions, but indicates somewhat colder than normal weather in the upper Midwest and Northeast. During the latter half of the winter, the NCEP precipitation forecast for Jan-March (see Figure 9; 4.5 month lead) shows above normal amounts across most of the southern states from Texas to northern Florida. This figure can be compared with Figure 4, the GCM forecast. As for the Oct-Dec period, there is broad agreement on the above normal precipitation in the South, but disagreement again in the Pacific Northwest where the GCM continues to indicate below normal precipitation, while the NCEP forecast shows normal amounts. Temperatures during the Jan-Mar period are forecast by NCEP (Figure 10) to be above normal throughout much of the country, especially the Southwest and South. As for the early winter period (Oct-Dec), there is no region that is forecasted by NCEP to have below normal temperatures. This again contrasts with the GCM forecast (see Figure 5) which indicates below normal temperatures east of the Rocky Mountains. There is agreement in the West, where the both the NCEP and GCM forecasts indicate above normal temperatures.

FIGURE CAPTIONS

November-December

Figure 1. Seasonal mean (Nov-Dec 2001) GCM forecast Precipitation Anomaly (mm/day) over North America. The contour interval is 0.5 mm/day. Contours for negative values are dashed.

Figure 2. Seasonal mean (Nov-Dec 2001) GCM forecast Surface Temperature Anomaly (deg F) over North America. The contour interval is 1 deg F. Contours for negative values are dashed.

Figure 3. Seasonal mean (Nov-Dec 2001) GCM forecast 700 mb Geopotential Height Anomaly (meters) over the Northern Hemisphere. The contour interval is 20 meters. Contours for negative values are dashed.

January-March

Figure 4. Seasonal mean (Jan-Mar 2002) GCM forecast Precipitation Anomaly (mm/day) over North America. The contour interval is 0.5 mm/day. Contours for negative values are dashed.

Figure 5. Seasonal mean (Jan-Mar 2002) GCM forecast Surface Temperature Anomaly (deg F) over North America. The contour interval is 1 deg F. Contours for negative values are dashed.

Figure 6. Seasonal mean (Jan-Mar 2002) GCM forecast 700 mb Geopotential Height Anomaly (meters) over the Northern Hemisphere. The contour interval is 20 meters. Contours for negative values are dashed.

NCEP Forecasts

Figure 7. NCEP seasonal mean (Oct-Dec) forecast precipitation anomalies.

Figure 8. NCEP seasonal mean (Oct-Dec) forecast temperature anomalies.

Figure 9. NCEP seasonal mean (Jan-Mar) forecast precipitation anomalies.

Figure 10. NCEP seasonal mean (Jan-Mar) forecast temperature anomalies.

Appendix B

The UCLA Atmospheric General Circulation Model

The UCLA atmospheric GCM is a state of the art grid point model of the global atmosphere extending from the Earth's surface to a height of 50 km. The model predicts the horizontal wind, potential temperature, water vapor mixing ratio, planetary boundary layer (PBL) depth and the surface pressure, as well as the surface temperature and snow depth over land. The horizontal finite differencing of the primitive equations is done on a staggered Arakawa "C" grid and is based on a fourth order version of the scheme of Arakawa and Lamb (1981) that conserves the potential enstrophy and energy when applied to the shallow water equations (Takano and Wurtele 1982). The differencing of the thermodynamic energy and water vapor advection equations is also based on a fourth-order scheme.

The vertical coordinate used is the modified sigma-coordinate of Suarez et al. (1983). In this coordinate, the lowest model layer is the planetary boundary layer. The vertical finite differencing is performed on a Lorenz-type grid following Arakawa and Lamb (1977) above 100 mb and Arakawa and Suarez (1983) below. This differencing is of second order accuracy and is designed to conserve the global mass integrals of potential temperature and total energy for adiabatic, frictionless flows.

For the integration in time of the momentum, thermodynamic energy and water vapor advection equations, a leapfrog time-differencing scheme is used with a Matsuno step regularly inserted. To avoid the use of the extremely short timestep necessary to satisfy the CFL condition near the poles, a longitudinal averaging (which takes the form of a Fourier filter) is performed on selected terms in the prognostic equations to increase the effective longitudinal grid size. The filter acts poleward of 45 degrees latitude and its strength is gradually increased towards the pole by increasing the number of affected zonal wavenumbers and the amount by which they are damped (Arakawa and Lamb 1977). A more localized spatial filter is applied to the predicted PBL depths (Suarez et al. 1983) everywhere. A nonlinear horizontal diffusion of momentum is included following Smagorinsky (1963). The coefficient used is one order of magnitude smaller than that used by Smagorinsky. The diffusion is applied at each timestep, using a forward time differencing scheme. In layers where an unstable stratification develops (potential temperature decreasing with height), we assume that subgrid-scale dry convection occurs and that the prognostic variables (horizontal momentum, potential temperature and water vapor mixing ratio) in the layers involved are mixed completely.

Planetary boundary layer processes are parameterized using the mixed-layer approach of Suarez et al. (1983). In this parameterization, surface fluxes are calculated following the bulk formula proposed by Deardorff (1972). Parameterization of cumulus convection, including its interaction with the PBL, follows Arakawa and Schubert (1974) and Lord et al. (1982), with a relaxed adjustment time scale for the cloud work function as described in Cheng and Arakawa (1994) and Ma et al. (1994). The parameterization of both long and shortwave radiative heating follows Harshvardhan et al. (1987, 1989). The ozone mixing ratios used in the radiation calculations are prescribed as a function of latitude, height and time based on values from a monthly UGAMP climatology (Li and Shine 1995) as used by Kim et al. (1998)

The cloud optical properties are specified following Harshvardhan et al. (1989). This prescription makes a distinction between stratiform clouds and "cumulus anvil"-type clouds.

"Cumulus anvil"-type clouds are assumed to exist at each model layer above 400 mb where the cumulus mass flux is positive; all other clouds are assumed to be stratiform-type clouds. The effects of subgrid-scale orography are included via a gravity wave drag parameterization and envelope orography (Kim and Arakawa 1995, Kim 1996).

The geographical distribution of sea surface temperature is prescribed according to a 31 year (1960-1991) climatology corresponding to the GISST version 2.2 dataset (Rayner et al. 1995); sea ice thickness and extents are prescribed following Alexander and Mobley (1976). Surface albedo and roughness lengths are specified following Dorman and Sellers (1989), in which roughness lengths over land vary according to the vegetation type. Daily values of these surface conditions (as well as sea ice thickness) are determined from the monthly mean values by linear interpolation.

The parallel version of the UCLA AGCM code was designed for distributed memory multiple-instruction-multiple-data (MIMD) computing environments (Wehner et al., 1995). It is based on a two dimensional (longitude-latitude) domain decomposition, message-passing strategy. Subdomains consist of vertical columns from the Earth's surface to the top of the atmosphere. The code is written in standard FORTRAN, including machine-architecture independent directives that are expanded to machine-architecture dependednt source code at pre-processing time. The has been ported to and time in several machines including the SGI/CRAY T3E, SGI/Origin 2000, IBM SP2 as well as DEC and SUN workstation clusters.

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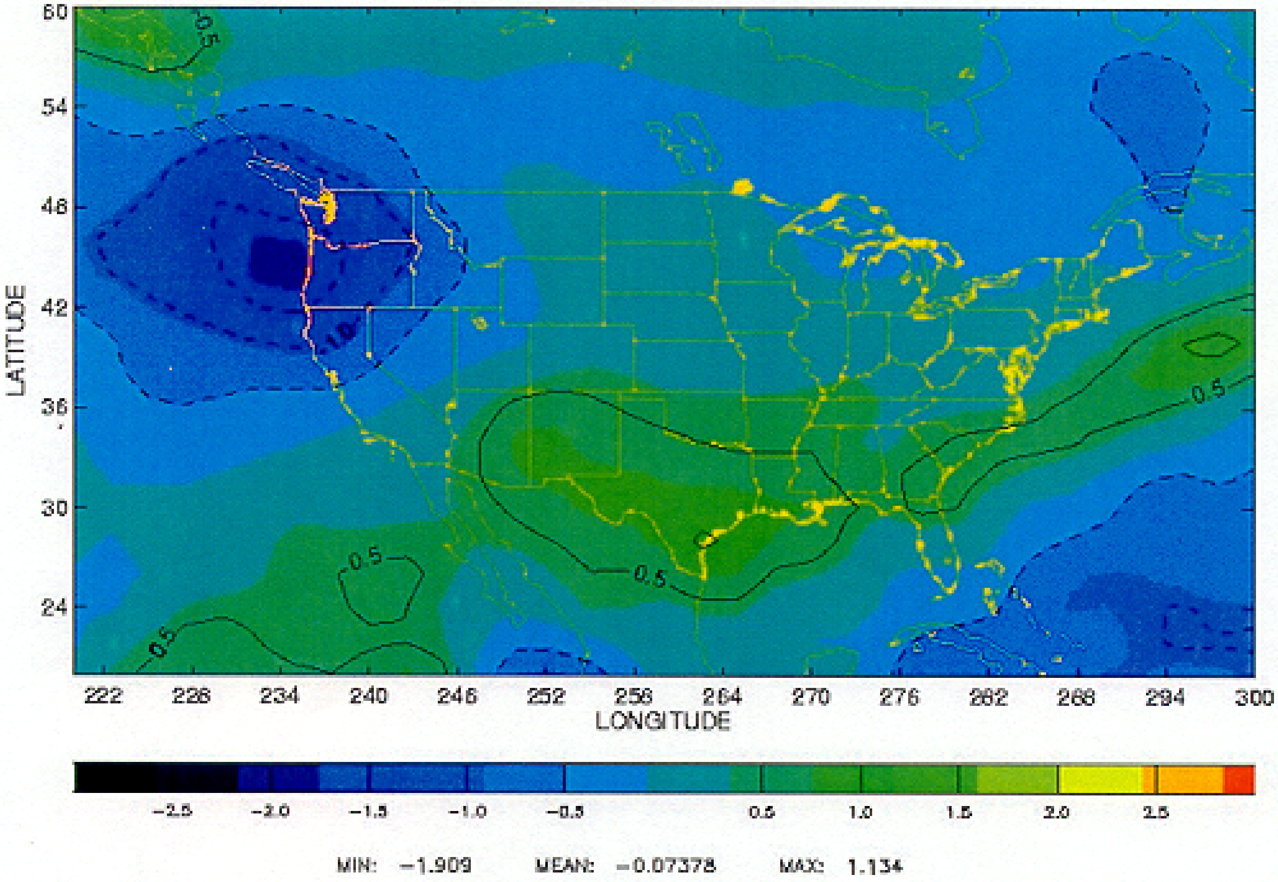
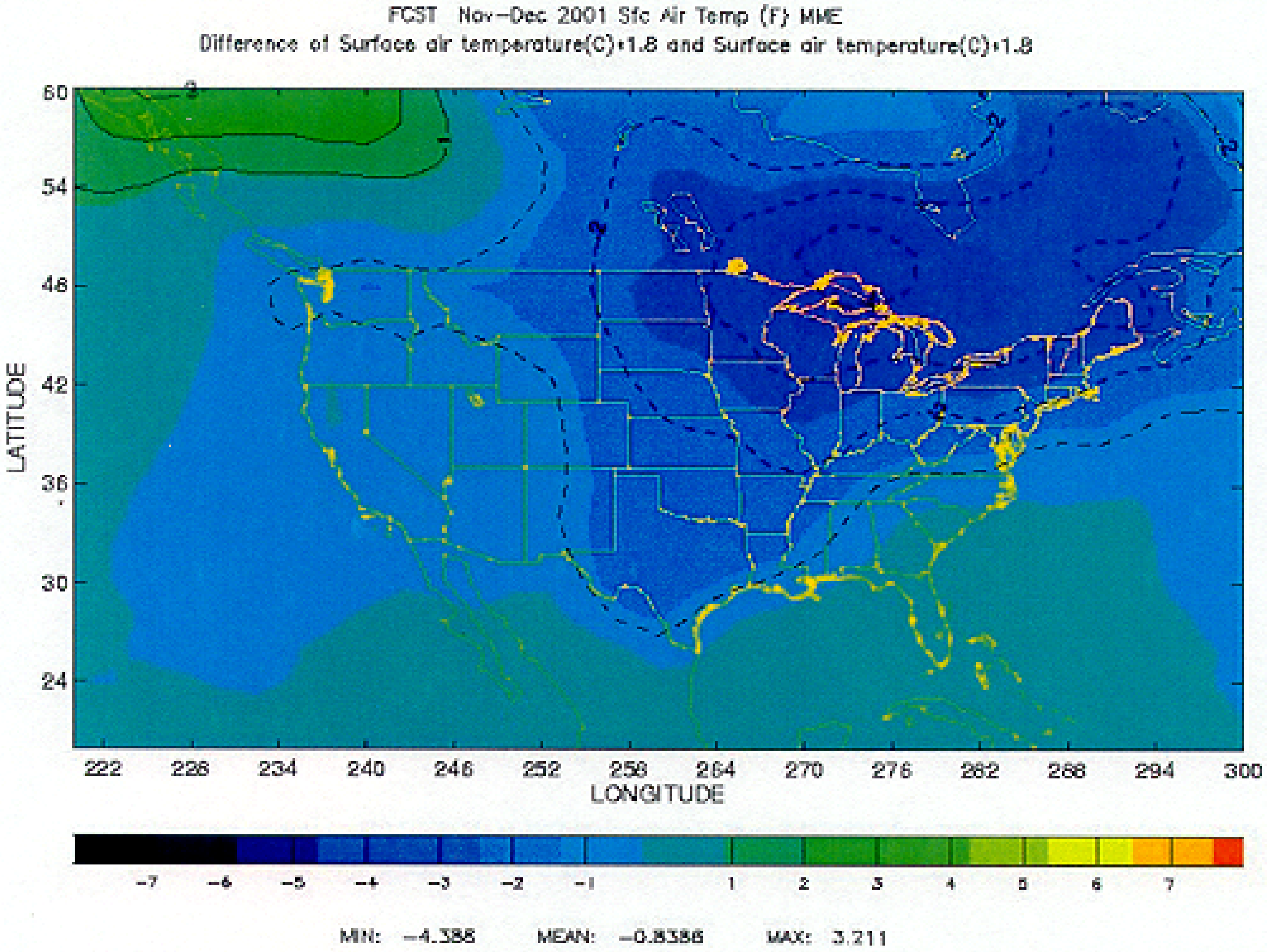

FCST Nov–Dec 2001 Prec Anomaly MME
Difference of Total Precipitation(mm/day) and Total Precipitation(mm/day)


FCST Nov-Dec 2001 Sfc Air Temp (F) MME
Difference of Surface air temperature(C)*1.8 and Surface air temperature(C)*1.8
LATITUDE
60
54
48
42
36
30
24
LONGITUDE
222
228
234
240
246
252
258
264
270
276
282
288
294
300
-7
-6
-5
-4
-3
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-1
1
2
3
4
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MIN: -4.386
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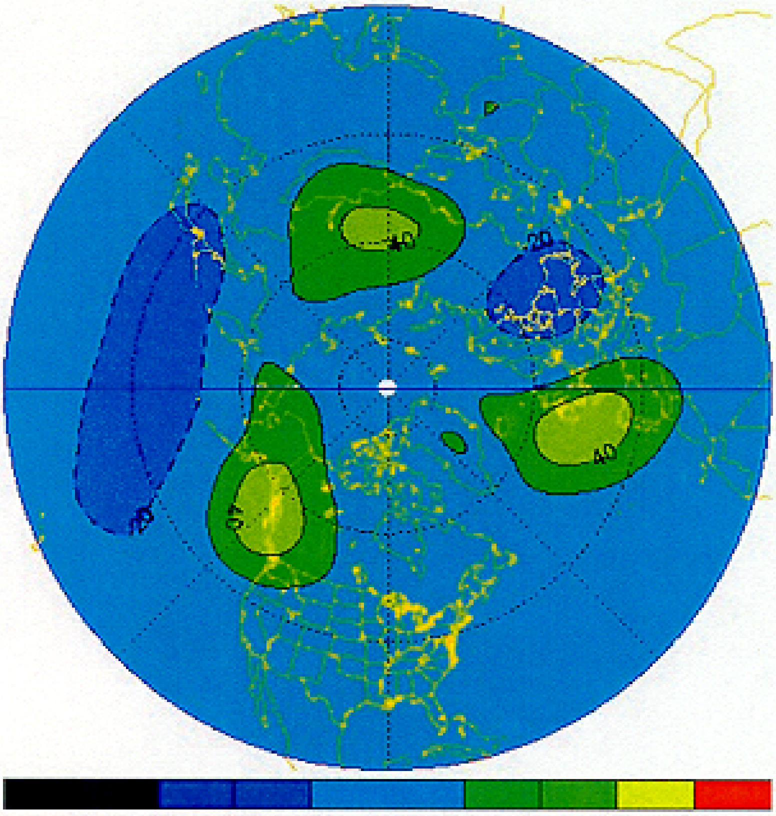
MAX: 3.211



FCST Nov-Dec 2001 700 mb Hgt Anom MME

Difference of geopotential height(m) and geopotential height(m)

Level: 700 mb

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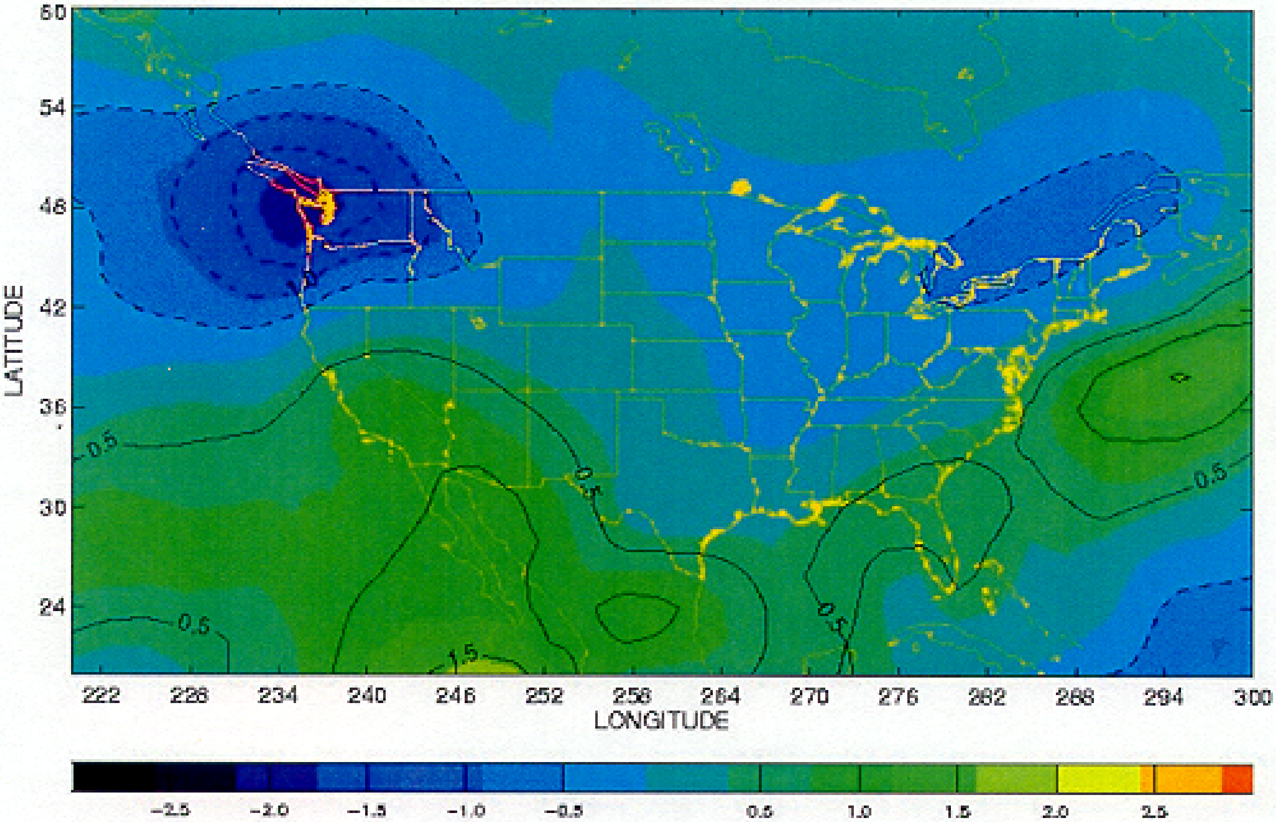


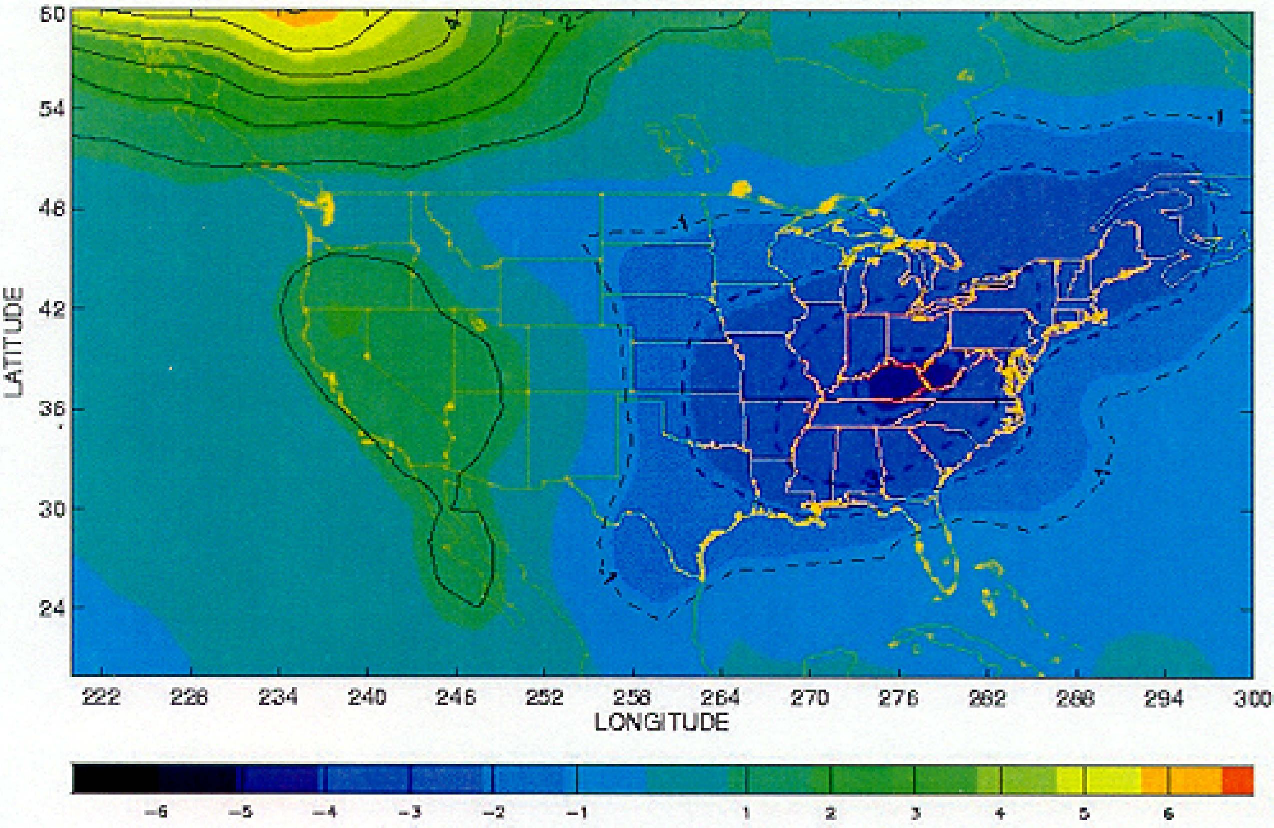
FCST Jan–Mar 2002 Prec Anom MME

Difference of Total Precipitation(mm/day) and Total Precipitation(mm/day)

MIN: −1.942 MEAN: 0.1501 MAX: 1.789

FCST Jan–Mar 2002 Sfc Air Temp (F) MME

Difference of Surface air temperature(C)*1.8 and Surface air temperature(C)*1.8



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Exp. MFx, JFM Mean Yrs 1-5, AGCM 7.0p, 2x2.5,29L, Dynamics variables
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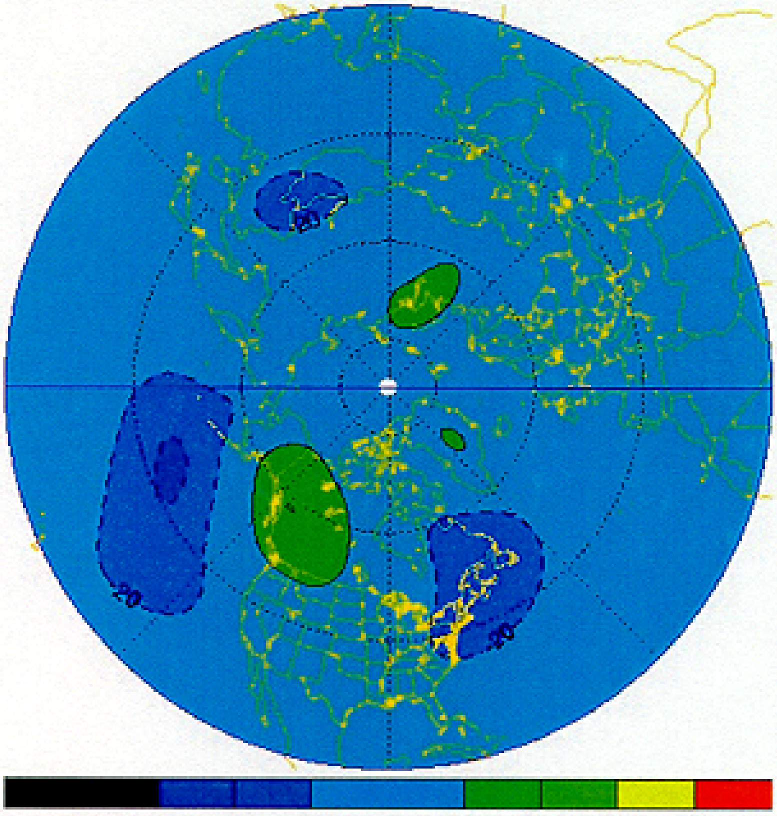
Level: 700 mb



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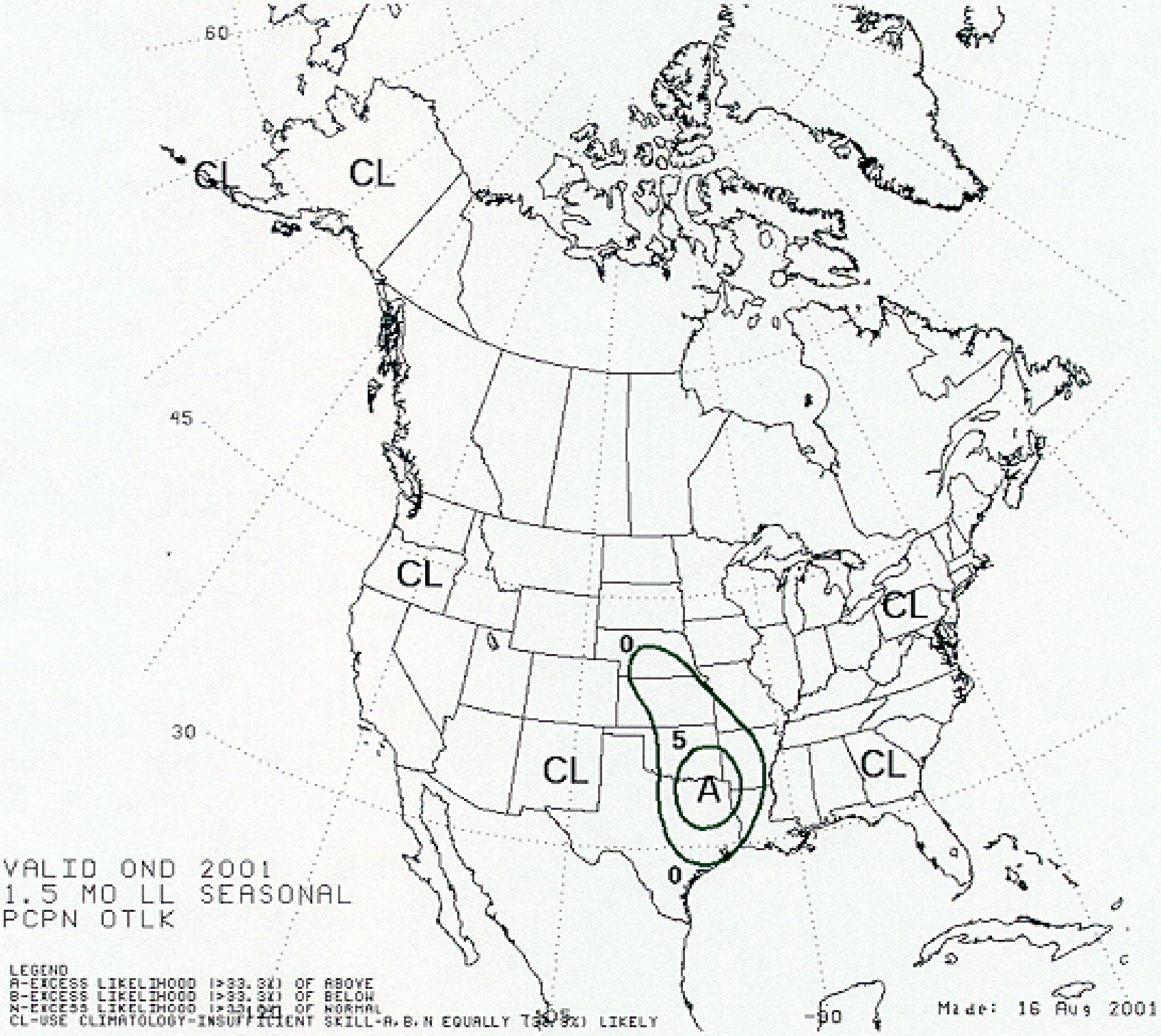
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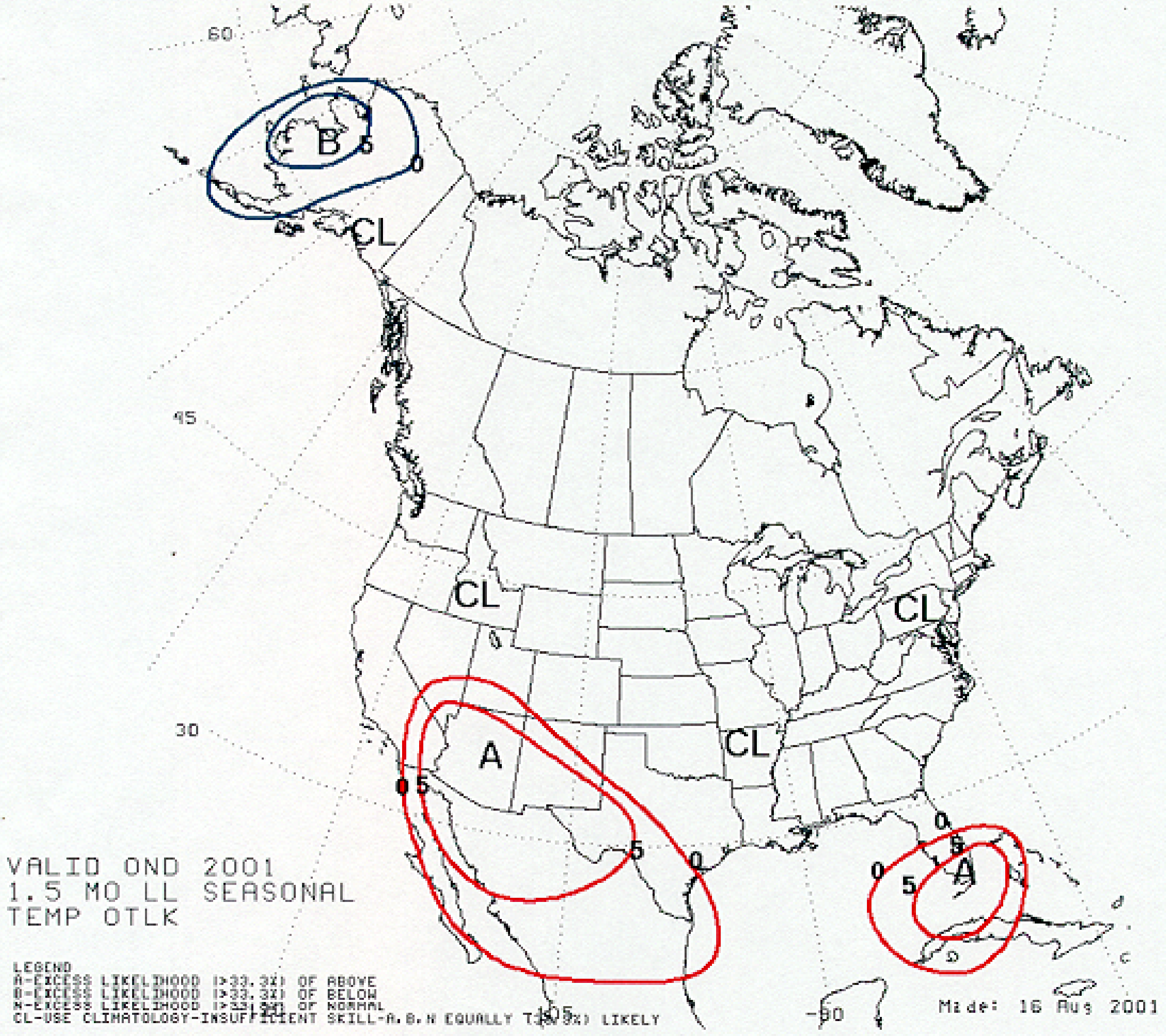
VALID OND 2001
1.5 MO LL SEASONAL
PCPN OTLK
LEGEND
A-EXCESS LIKELIHOOD (>33.3%) OF ABOVE
B-EXCESS LIKELIHOOD (>33.3%) OF BELOW
N-EXCESS LIKELIHOOD (>33.3%) OF NORMAL
CL-USE CLIMATOLOGY-INSUFFICIENT SKILL-A,B,N EQUALLY (33.3%) LIKELY
-105
-90
Made: 16 Aug 2001


60
45
30
-105
-90
B
5
0
CL
CL
CL
CL
A
0
5
5
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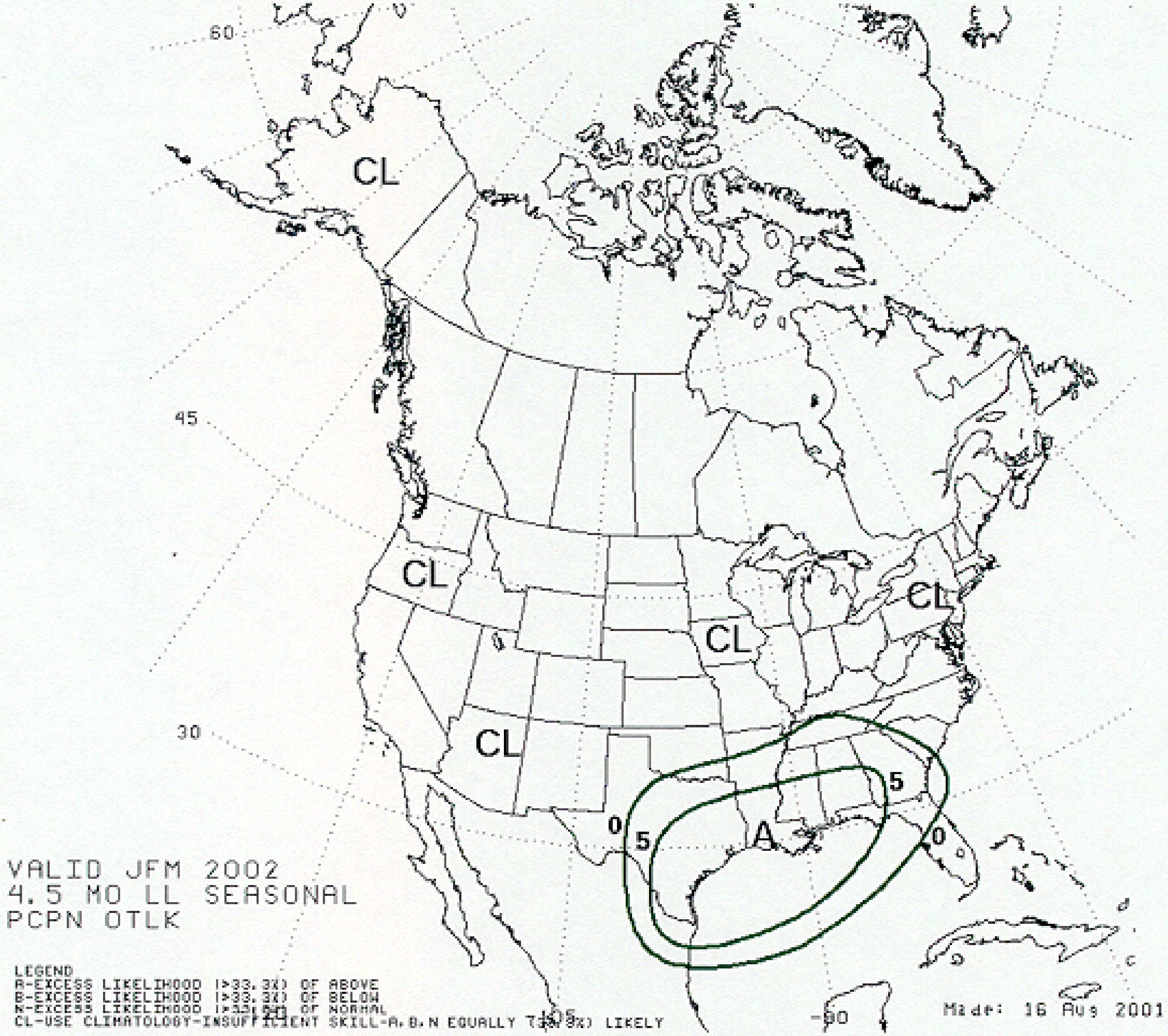
0
5
0
5
A
VALID OND 2001
1.5 MO LL SEASONAL
TEMP OTLK
LEGEND
A-EXCESS LIKELIHOOD (>33.3%) OF ABOVE
B-EXCESS LIKELIHOOD (>33.3%) OF BELOW
N-EXCESS LIKELIHOOD (>33.3%) OF NORMAL
CL-USE CLIMATOLOGY-INSUFFICIENT SKILL-A,B,N EQUALLY (33.3%) LIKELY
Made: 16 Aug 2001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30
CL
CL
CL
CL
CL
A
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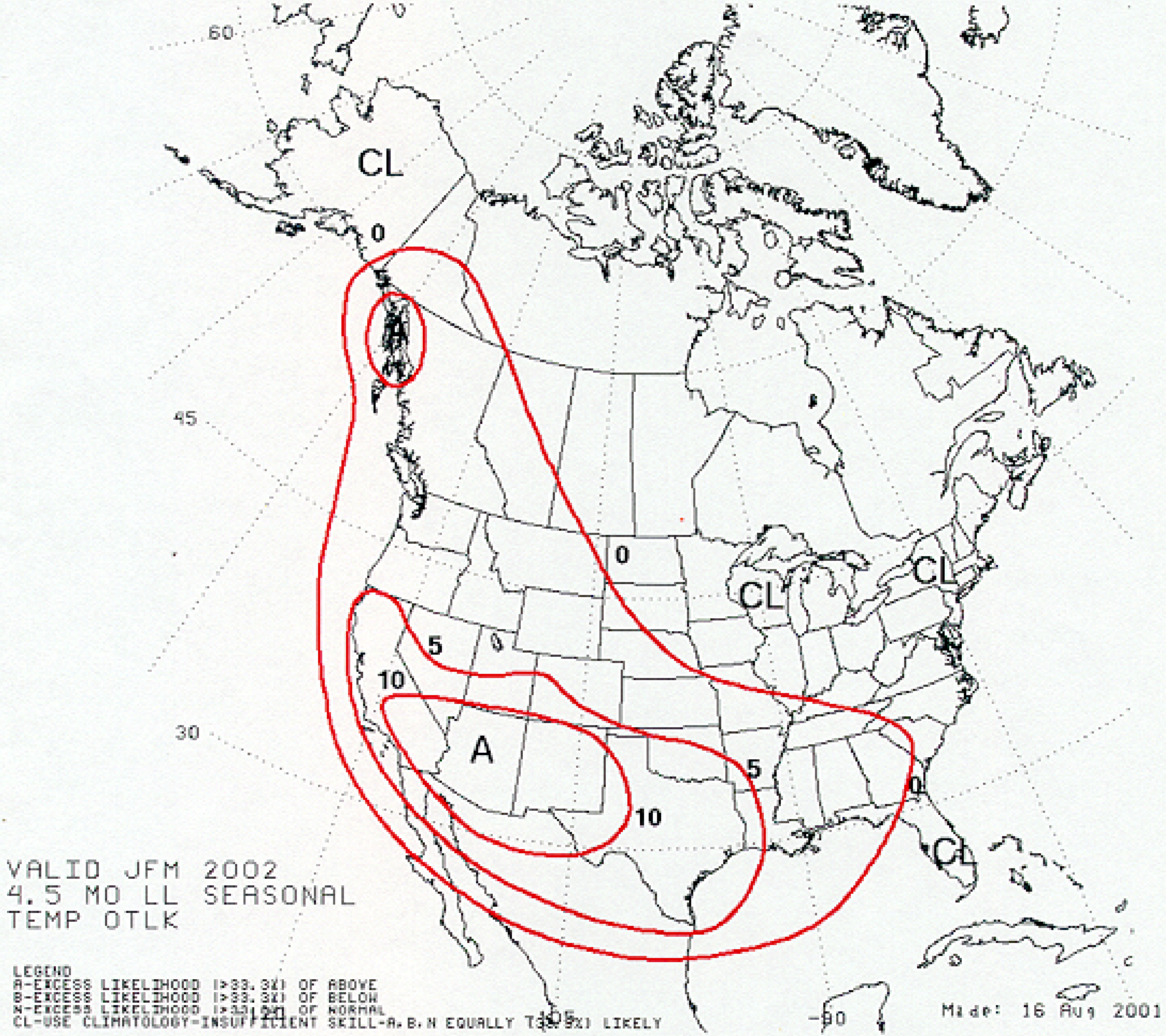
5
5
0
VALID JFM 2002
4.5 MO LL SEASONAL
PCPN OTLK
LEGEND
A-EXCESS LIKELIHOOD (>33.3%) OF ABOVE
B-EXCESS LIKELIHOOD (>33.3%) OF BELOW
N-EXCESS LIKELIHOOD (>33.3%) OF NORMAL
CL-USE CLIMATOLOGY-INSUFFICIENT SKILL-A,B,N EQUALLY (33.3%) LIKELY
-105
-90
Made: 16 Aug 2001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30
120
105
-90
CL
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CL
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CL
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10
A
5
10
0
CL
VALID JFM 2002
4.5 MO LL SEASONAL
TEMP OTLK
LEGEND
A-EXCESS LIKELIHOOD (>33.3%) OF ABOVE
B-EXCESS LIKELIHOOD (>33.3%) OF BELOW
N-EXCESS LIKELIHOOD (>33.3%) OF NORMAL
CL-USE CLIMATOLOGY-INSUFFICIENT SKILL-A,B,N EQUALLY (33.3%) LIKELY
Made: 16 Aug 2001