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FORECAST GUIDANCE OF SIGNIFICANT WEATHER EVENTS IN SACRAMENTO AREA USING HISTORICAL ANALOGS

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Abstract

A procedure for identifying key features of significant weather events is presented and then applied to a specific locale.
The significant weather events are gathered into homogeneous groups, and for each of them maps are created. Each map refers to a specific meteorological variable and time at or prior to the beginning of the studied event. Significance testing, using the non-parametric resampling method called "Bootstrap", is performed for these maps to highlight potentially unusual areas linked to the event at hand.
Analyzing these results allows a better understanding of how significant events happen and provides key features for forecasters to note thus providing new guidance for forecasters.
This method has been applied to the Sacramento area Sacramento (Central California, U.S.A.) for four types of severe events: long duration dense fog, heavy rain, heat wave and hard freeze.

Note

A set of webpages have been developed to present those maps with features which pass a strict significance test. These may be accessed by going to R. Grotjahn's home page at
http://www-atm.ucdavis.edu/~grotjahn
and following links to the "Forecast Analogs" pages.
A CD-Rom is available to complement this report. It contains all the results: NetCDF files and significant map plots. It contains also this report and the Appendices (in color). All the programs developed are present too.

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Introduction

Significant meteorological events are still very challenging to forecast. Most events have an impact upon public safety or business operations and are therefore highly valuable to forecast with accuracy. Meteorological forecast models have dramatically improved over the last twenty years but such events are often not well predicted in advance.

An original method to improve the forecast of such events had been elaborated in the National Weather Service Office in Sacramento, California, USA. For every type of severe event, synthesis (composite) maps were calculated, showing the mean or typical fields. A forecaster was then able to characterize these events. However this original study relies basically only on direct analysis of mean fields, which can lead to incorrect conclusions.

The main contribution of this new study is to have a new and outstanding statistical approach, allowing a small number of cases to be studied. It emphasizes objective identification of potentially unusual areas on analog composite weather maps that are linked to the event at hand. The significance of the synthesis map is also assessed. Moreover the number of synthesis maps has been greatly increased, which allows a comprehensive synoptic analysis.

First, this document presents the initial study from the National Weather Service and the improvements explored. Several statistical and technical points are also discussed.

The second part is an accurate description of the method used. It starts with a crucial point, to define several types of events that gather homogeneous occurrences. That is required to have a useful statistical approach. Then the statistical analysis of the mean maps is described.

The third and last part shows the results obtained while using this method for the Sacramento area for four types of severe events: long duration dense fog, heavy rain, heat wave and hard freeze.

PART I : Background

CLIMATE OF SACRAMENTO, CA.

Figure I.1 : relief of California
(cf. Appendix I.1 for better quality)

Several geographic features influence the weather experienced in Sacramento. The latitude of Sacramento is similar to Washington DC and Lisbon (38.5 North). To the West lies the Pacific Ocean and a coastal mountain range, while to the East lie higher mountains of the Sierra Nevada. Sacramento lies in the nearly flat Central Valley between these two mountain ranges (cf. Fig. I.1).

The Sacramento River is the primary river draining the Northern part of the Central Valley. The river flows into San Francisco Bay through a gap in the coastal range. This gap allows intrusions of marine air during "sea breeze" events. The city of Sacramento is located approximately 90 miles (~140 km) north and east of San Francisco. The Sierra Nevada peaks are only 70 miles (~110 km) east, and the Pacific coast 80 miles (~130 km) west.

1. MAIN CHARACTERISTICS

The low-land climate of the Sacramento area is as follows. Further details can be found in Masters-Bevan (1998) a technical note by the National Weather Service Forecast Office in Sacramento (NWSFOS)

Weather is usually mild and sunny all year round. Annual precipitation is ~400 mm. About half the annual total falls during a "rainy season" from November to March. The prevailing winds in Sacramento are northerly or southerly, due to the north-south orientation of the valley (cf Fig. I.1).

Winter storms are modified by the surrounding mountains, which act partly as a shield but also set up convergence zones. Heavy rain occasionally occurs in the Valley. Due to the warm, maritime nature of most winter storms, heavy snow frequently occurs in the Sierra Nevada. Such events can lead to flooding in the Sacramento River drainage. Snow is extremely rare in Sacramento and falls in such small amounts that it is not considered as a climatic feature. Fog can be common after fall storms have wetted the Valley floor; the denser fog occurs mainly in December and January. The fog often disappears by late morning, but sometimes lasts for several days.

Summer days are usually warm to hot, dry, and cloudless. Nights are often much cooler and pleasant thanks to a sea breeze from the San Francisco Bay (and proceeding across the Sacramento river delta; hence the local name of "delta breeze"). However heat waves may occur, with several very hot days in a row without cooling breezes from the delta. These high temperatures are reached with very low relative humidities. Thunderstorms seldom occur; they occur mainly during the transition seasons when a upper level "cut-off" low passes over the region.

2. FORECAST CHALLENGES

California has the biggest agricultural activity of any state in the USA, and the Sacramento Valley plays a very important role in this production, with a great variety of crops. Therefore the first challenge for the National Weather Service is to forecast accurately disastrous meteorological conditions for the farmers, such as freezing and heavy rain.

The former can be due to radiational cooling, and in this case farmers can contemplate some measures to avoid damage to their crops because the cold layer above the ground is very thin and so is easily mixed with the warmer upper layer (using large fans, for instance). Freezing can also be the consequence of cold air advection, with a cold layer from mid-levels to surface. Such an event leads to more important damages because farmers do not have measures to mitigate the hazard.

Heavy rain affects agricultural production too, because it may induce flooding along the Sacramento River and many tributaries. Floods may damage crops and infrastructure as well as prevent equipment from being used. The Sacramento Valley is so flat that flooding events may become a general threat, with the spread of water to inhabited areas. To avoid that, several bypasses are placed along the river to allow flooding first of unpopulated areas, mainly agricultural fields.

Another crucial event for the numerous Sacramento area inhabitants is dense fog. The large population of the Sacramento metropolitan area, large cities to the east and west, and major cross-continent thoroughfares (Interstate highways 5 and 80) lead to heavy traffic. Summer heat waves are another event with wide consequences. The persistence of very dry and very hot weather for several days affect each activity in the valley, from workers to tourists, and is even sometimes a threat to inhabitants' health

I.B. Staudenmaier study

1. Study presentation

The first study of significant meteorological events in the Sacramento area was Staudenmaier (1995). The basic aim of his study was to help familiarize forecasters at the Sacramento National Weather Service Forecast Office (NWFSOS) with the synoptic features associated with these significant events. Indeed, new forecasters need to be aware of the significant weather conditions they might have to forecast, while the more experienced ones may benefit from a summary of those events which are, by definition, rare.

The first step of this study was a classification of these events. Eight groups were defined: northerly winds, southwest winds, southeast winds, heavy rain, hard freeze, long duration dense fog, summer heat wave and delta breeze. These groups have been defined with the criteria recapitulated in Table I.1.

Table I.1 : significant weather events and their criteria

Events	Criteria
Wind (all type)	Sustained winds over 25 mph with gusts of, or above, 40 mph.
Heavy rain	3 inches of rain over a two to three day period, and not due solely to convection.
Hard freeze	Cold air advection ahead of an arctic area of high pressure.
Long duration dense fog	Dense fog reported for over a week
Heat wave	Maximum temperature over 100 degrees Fahrenheit reached for at least three days, with a maximum day over 105 degrees.
Delta breeze	Not precisely defined. Criteria on wind speed and direction, along with temperature decrease.

The second step was to find out all the dates corresponding to each occurrence of the event. The dates were found from the historical records in the Sacramento area; these include the records of one station in Downtown Sacramento and two others at the surrounding airports: Executive and Sacramento International fields.

Once these dates were found, the basic idea was to obtain a general view and understanding of each event. Staudenmaier averaged all the fields relative to the dates of occurrence, for several variables. Thus, he obtained for each event and each variable an average field, called a composite map.

Staudenmaier's maps were formed using the geopotential height (850, 700 and 500 hPa) and sea level pressure. The geographical area encompasses North America, except Alaska, and a small part of the two oceans.

Then Staudenmaier discussed what the typical and unusual conditions are for each event, according to these composite maps. He tried to explain the dynamics behind each type of event, with a precise description of the fields over the western continental U.S.A.

The dates have been reanalyzed twice since the first study; the last reanalysis included dates until 1994. In this last study, composite maps were formed for the updated dates of the events, and composite maps corresponding to the situation 12 and 24 hours before each event were plotted too.

A summary of the results of the original study is presented in part III, just before the results obtained in this new study.

I.C. Overview of improvements explored

Staudenmaier's study was a first step towards a better understanding of Sacramento significant weather events. His study can be improved to obtain a more comprehensive and accurate picture of the large-scale weather and to assess the importance of meteorological conditions prior to these events. The analysis of such results should lead to better forecast guidance in this region.

To achieve these goals two main improvements are emphasized: to use a broader range of data, and to establish the statistical reliability of the results.

1. More variables

The original study did not take into account the evolution of the meteorological fields before the start of these events. The last study made a step towards this direction, but it was very slight: composite maps were created for the beginning of each event, 12h before and 24h before.
Since the aim of studying these events is to improve their forecast, it is important to examine the evolution of meteorological fields prior to the events. To study a period of three days seems to be the minimum, and the geographical area studied must be expanded accordingly. Moreover, a large area is necessary to display a synoptic view of the situation, and to check if some events that occur in the Sacramento area can be linked to remote conditions.

Staudenmaier's study, and the following ones, constructed composite maps only for: geopotential heights at three levels, and sea level pressure. A more exhaustive collection of meteorological variables would be very useful to have a better and more global view of each situation. Moreover, taking into account several levels, from the surface to the tropopause, should also increase dramatically the quality of the significant event description.

2. Statistical assessment

The understanding of each event is improved by increasing the input data, yet a deeper understanding is gained from a comprehensive and accurate statistical analysis.

a) Aims

A composite map is one way to summarize several occurrences of a similar event, by averaging the corresponding fields together. This leads to what we can call a typical field, standing for of idealized occurrence.

Such maps are very informative, but they must be analyzed with care. The basic idea is to find the regions of a map that are linked with the event at hand. It is easy to anticipate that between all the occurrences of an event, some patterns in some regions may be similar, whereas in some other areas the constituent fields may be quite different. These similar areas, which could be labeled "active zones", may provide keys to explain the dynamics of an event. Active areas present in different fields and during different times create together the signature of an event, the way it is built and thus the way it could be forecasted.

In the previous studies it had been supposed that the entire field was linked to the event. This assumption might have been justified because the data were limited in space and time, but it cannot be assumed for this study that increases greatly the geographical area and the period prior to the events.

Once areas linked to the studied event are determined, they have to be analyzed. Previously a forecaster judged how unusual were the composite maps, relying on his/her own experience for this region. Such analysis can be inadequate because an averaged field may hide several disparities between the occurrences, and may have been biased by the small size of the occurrence sample used to create the composite maps. Moreover, this approach is very subjective; the conclusions depend on the forecaster.

Therefore, other tools are needed to analyze correctly composite maps. A powerful approach is to quantify how similar the occurrences are for one type of event. This approach would provide a way to know, for instance, if a trough seen on composite maps is present on the great majority of occurrences. Similarly, the approach may distinguish if the values of a field over California are close from one occurrence to one other, though not unusual.

These two considerations lead to the use of a new approach in parallel with the calculation of composite maps.

b) Method

The following approach was developed to help analyzing composite maps.

Each gridpoint value on a composite map is the average of several values whose distribution is known. The composite drawn from the significant events is labeled the "target composite". Data from the target group may be compared to the climatological average and variance. An average and a dispersion estimate can be calculated from randomly selected samples drawn from the historical record. From these data a significance test can be performed on the values for the target composite. Consequently, for each grid point mean value, we can know if it comes from a distribution with unusually high (low) average or unusually high (low) dispersion.

This simple method is very powerful because it achieves the two aims described above: it locates the significant areas, i.e. the "unusual" ones linked to the event at hand and it describes how similar the occurrences are, similar accordingly to average or dispersion estimates.

These two estimates, although basic, are very useful to analyze several meteorological fields together for forecast purposes.

I.D. Data choice

The first step to obtain reliable results is to use high quality data. The choice of the data is discussed first, followed by a presentation concerning the quality of the original dataset chosen. The third part describes in more detail the dataset actually used in this study.

1. WHY DATA FROM REANALYSIS, AND WHICH ONE?

To perform this study, a large dataset is needed. It should include analysis maps from a forecast model, for numerous variables and during a long period of time. These maps can be obtained in two ways: from an archive of real time analyses or from reanalysis projects.

The goal of a reanalysis project is to produce a record of global analyses of atmospheric fields for a long period of time, and the data obtained present some advantages compared to the real time data. First, these analyses are performed with a frozen data assimilation system during all the record, which eliminates all the artificial climate jumps due to changes in the data assimilation system. Another advantage of the reanalysis, compared to analyses from real time data, is that the observational database is as exhaustive as possible, including the observations available later than feasible for operational data. Moreover, the observation quality control is better than for operational data. Thus reanalysis data have better homogeneity and quality.

Two major reanalyses were available: one from the European Center for Medium Weather Forecasting (ECMWF), and another one from a joint project between the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The advantages of each of them are discussed below.

The first quality of a reanalysis is its length, and upon this consideration the NCEP/NCAR Reanalysis is much better than the ECMWF. The former goes from 1948 to 1999, while the latter covers a fifteen-year period, from 1979 to 1993. The differences between the two data assimilation schemes push in the same way: 3D-VAR against 1D-VAR. However, the ECMWF reanalysis has a strong advantage concerning its resolution, T106 (equivalent to latitude/longitude intends of 1.125 degree), compared to the other reanalysis (T62, equivalent to latitude/longitude intends of 2.5 degrees).

The NCEP/NCAR Reanalysis has some other advantages, such as its exhaustive dataset of observations, the fact that its model had been used as a real-time forecasting one (it was implemented in January 1995 at the NCEP), and the ease to obtain its data over the internet.

All this led us to choose the NCEP/NCAR reanalysis data in this study.

2. NCEP REANALYSIS QUALITY

a) Different categories of variables

The model output variables have been classified into several categories, according to the relative influence of the observational data and the model data upon the gridded variable (Kalnay et al, 1996). The A class gathers the most reliable variables, the ones which are strongly influenced by the observations (e.g., pressure level temperature). The B letter designates variables that are still influenced by some observational data, but the model has also a great influence on their value (e.g., pressure level humidity). A variable is in the C category when no observations influence it directly, hence its value is derived from the model fields and it is less reliable than B variables (e.g., precipitation rate).

All the variables used here are drawn from classes A and B, in order to obtain more reliable results. The class of the variable will be noted when analyzing the results.

b) Impact of observation changes

The aim of a reanalysis project is to create analyses for a long period with the best of both quality and continuity of input data. However, one of these two is emphasized by the choice of the observational data. On the first hand, one can choose to keep the same observational network during all the period, which leads to the best continuity. It means that only the oldest kind of observation is used. On the other hand one can choose to take into account as many observations as the assimilation system can accommodate. This allows the use of observational improvements that happened during the reanalysis period, such as the introduction of satellites or the widespread availability of aircraft data. Thus this approach produces the best analysis for any specific time. Its disadvantage is that changes in the observational network have been found to produce spurious changes in some of the time series.

The NCEP/NCAR Reanalysis uses the second option, and several studies have been made to assess the influence of new observational data, mainly the introduction of satellite and aircraft data (Kalnay et al, 1996; Ebisuzaki and Chelliah, 1998). The consequences are not as important as one could have feared, but they do exist, mainly before the seventies.

It is not clear yet what differences the changes in observational network could have made on instantaneous fields, but this study emphasizes first the quality of the data used. Hence this study will focus only on the period 1979-1999.

This 20-year period can seem short for the study of severe events, and can appear also very close to the 15-year period of the ECMWF Reanalysis. Yet this choice is the best compromise between the longest period of study and the more reliable data.

3. DATASET USED

The NCEP/NCAR Reanalysis dataset offers plenty of parameters, but many of them have been rejected for this study, as being non-instantaneous fields or the less reliable ones (category C). The final choice of the parameters was done in cooperation with the NWSFOS staff, in order to target fields commonly used in daily forecasting. Although, some other fields less widely used were elected in order to have the more general view of the situation (c.f. Table I.2).

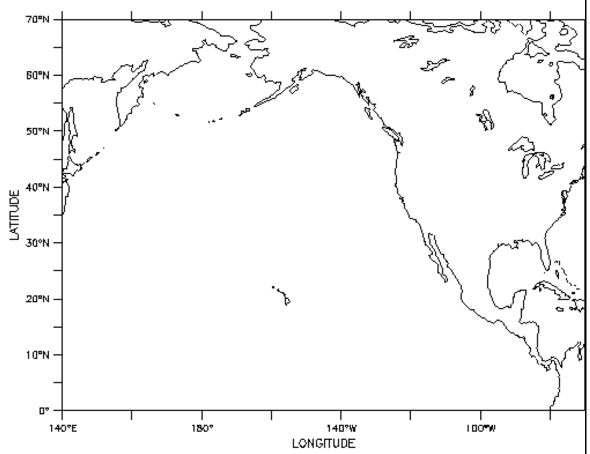

Figure I.2: area studied

The geographical area studied has been enlarged from the one used in Staudenmaier's study to capture synoptic situations upstream at times prior to the onset of the event. The domain was increased northwards, westwards and southwards, to encompass now the U.S.A., Canada and the majority of the North Pacific (cf. Fig. I.2). The original dataset from the NCEP Reanalysis covers the whole globe, so it has been subsampled (cf. Table I.2).

The pressure level variables are originally available on seventeen levels. Only four of them have been kept, 850, 700, 500 and 300 hPa, to sample the different troposphere layers. The tropopause data are available via separate variables.

The frequency of the data has been reduced from four times a day to twice daily by storing only the 00Z and 12Z data. This choice was a balance between computation time and temporal accuracy. However, if further studies were needed, the twice-daily data could be easily replaced by the original ones.

Table I.2 : Summary of the studied fields

Pressure Level Data		
Common features: 17 original pressure levels (except humidity), 4 were consulted (300, 500, 700 and 850 hPa).		
Variable name (abbreviation)	Units	Category
Air temperature (air)	degrees K	A
Geopotential height (hgt)	m	A
Relative humidity (rhum)	%	B
Specific humidity (shum)	kg/kg	B
Omega (omega)	Pascal/s	B
Zonal component of wind (uwnd)	m/s	A
Meridional component of wind (vwnd)	m/s	A
Surface Data		
Common features : one level, surface or near the surface (0.995 sigma level)		
Variable name	Units	Category
Air temperature (surf_Tair)	degrees K	B
Omega (surf_omega)	Pascal/s	B
Potential temperature (surf_pot_temp)	degrees K	B
Relative humidity (surf_rhum)	%	B
Sea level pressure (slp)	Pascal	A
Zonal component of wind (surf_uwnd)	m/s	B
Meridional component of wind (surf_vwnd)	m/s	B
Tropopause Data		
Common features : one level : tropopause		
Variable name	Units	Category
Air temperature (trop_Tair)	degrees K	A
Pressure (trop_pres)	Pascal	A
Common features of the dataset used (*original values*) :		
Grid resolution and gridpoint number 2.5-degree longitude x 2.5-degree latitude grid with 61x29 points (*144x73*)		
Area covered 70N-0N and 140E-290E (*90N-90S and 0E-357.5E*)		
Time length 1/1/1978 to 31/12/1999 (*1/1/1958 to present*)		
Data frequency Output every 6 hours (*12*)		
Type of field Instantaneous values		

I.E. Statistical theory

As stated previously, a statistical approach is needed to assess objectively each composite map; it identifies which areas are significant and how the meteorological pattern is similar through all the occurrences. This similarity can be assessed by the estimation of how unusual is a given estimate (either average or variability) calculated from the target group of occurrences.

Next, a short overview of the theory of statistical significance is presented; then a discussion about the statistical choices made in this study follows.

1. Introduction and definitions

The first step of statistical significance is to define a test statistic. The two basic test statistics chosen in this study are an average estimate and a variation ("dispersion") estimate. As noted previously, both are very useful in the analysis of meteorological fields, and they are simple, hence fast, to calculate. However, more sophisticated test statistics are feasible.

The null hypothesis to test underlying statistical significance is simply that the observed target group "test" statistic is exactly the same as the population value it is drawn from, the alternative hypothesis is simply that the null hypothesis is not true. This leads to the construction of confidence intervals.

The null distribution, i.e. the sampling distribution of the test statistic under the null hypothesis, is obtained in a way that is specific to the method chosen to assess the significance. While using a parametric test, such as the "Student's t test", the null distribution is a theoretical one, whereas it is an empirical one if using a resampling method.

Finally the observed value of the test statistic is compared to the null distribution, to know if the null hypothesis can be rejected or not.

2. Which method?

First, the average and the dispersion estimates chosen for this study are respectively the mean and the standard deviation. They are quick to calculate, and relevant to the small size of the samples studied.

Second, the method used to assess the significance should be chosen. The well-known Student's t test may seem appropriate: it examines the null hypothesis that an observed sample mean has been drawn from a population characterized by some previously specified mean. From this the variance significance can be tested too. This test is a parametric one, with the following basic hypothesis: the sample must be sufficiently large that its sampling distribution is Gaussian.
The main disadvantage is that only mean and variance can be used as test statistics, thus the use of another test statistic implies the implementation of a new method. That is why this

parametric approach has been rejected in favor of a more general method with better evolution possibilities: the bootstrap.

The bootstrap method is more precisely a resampling test, a computer-based method for assigning measures of accuracy to statistical estimates (Efron and Tibshirani, 1993). The idea behind the bootstrap is very simple, and goes back at least two centuries; however it has only been recently developed because it requires modern computer power.

The basic idea is to build up a collection of artificial data groups of the same size as the target group. In this study, the target group is a group of dates corresponding to the occurrences of a type of event, and the artificial data groups are groups of the same number of dates, but these ones are randomly picked in the dataset.

Then the test statistic of interest is computed for each artificial group. This procedure results in as many artificial values of the test statistics as there are artificially generated data groups. Taken together, these values constitute an estimated null distribution against which the test statistics computed from the target group are compared.

A non-parametric resampling test has two major advantages. The first is that no assumptions regarding an underlying theoretical distribution for the data are necessary. The second is that **any** statistic, so long as it can be computed from the data, can form the basis of the test. Consequently, the use of a new test statistic requires just the implementation of the test algorithm, not of a whole new method.

The bootstrap has been used in several climatic studies in the past few years (Gershunov and Barnett,1998a,b; Matthews and Kiladis, 1999).

I.F. Technical tools

This section describes very briefly the different tools used during this project: tools for the transfer and the storage of the data, and tools relevant to data manipulation.

1. Data access tools

The ratio between the sizes of the studied and original datasets was very low (cf. Table I.2); for instance, the process of subsampling on space and time of the original files reduced the size of pressure level files by 98%.

The first approach to get the data was to use DODS (Distributed Oceanographic Data System), a software package that helps users provide and access data over the net. Although DODS was originally designed and developed by oceanographers and computer scientists for oceanographic data, there is nothing in the design of DODS that constrains its use to oceanography. Among many others, its main advantage for this work was to allow subsampling of a dataset before its transfer. Therefore to get the data via the Internet would have been easy and quick. However the data wanted from the NCEP reanalysis were not available yet on a DODS server.

Even without this useful tool, the data had to be obtained online, because a customizable procedure was needed compared to the other ways (e.g., CD by mail), and even faster thanks to a high-speed Internet connection. The only large database online at the time (February 2000) is available via the Climate Diagnostics Center (CDC) and is stored in NetCDF (Network Common Data Form) files. (URL: http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml)

The actual method to get the relevant data was first downloading then subsampled. This process has been automated and it is described in Appendix I.2. Firstly, an automated ftp is launched and downloads one file from the ftp site of interest. When the transfer is completed, the relevant data are extracted from this file (cf. next section) into a new one. Then the original file is erased and another one is transferred, etc. This process allowed transferring 60 Gbytes in 315 files easily and without human action.

Magneto-optical disks were used to store the datasets. Their capacity is about 520 Mbytes on each side, and three of them have been used to store the files obtained from extraction, totaling almost 2 Gbytes.

2. Data manipulation tools

As seen above, data are stored in NetCDF files. The NetCDF interface allows one to create, access, and share array-oriented data in a form that is self-describing and portable. "Self-describing" means that a dataset includes information defining the data it contains. "Portable" means that the data in a dataset is represented in a form that can be accessed by different computers.

NetCDF data can be easily accessed and manipulated by software. The ones in use at the LAWR department are Ferret and GrADS. They can be used to plot data directly, but some derived fields can be computed and saved too.

However, these integrated tools were not powerful enough. The initial subsampling of the files in order to save only the relevant data required a complex extraction, both on longitude/latitude and on time. And above all the development of the statistical method to analyze the composite maps was too complex to avoid using a programming language.

Fortunately NetCDF data can be manipulated easily with a Fortran90 interface. An I/O library callable from Fortran allows creating, accessing, and managing NetCDF files through several functions. This method has been used for all the manipulations of NetCDF data.

The subsampling of the original data, described in Appendix I.2, took advantage of the powerful extraction functions provided by the NetCDF library, and of creation functions that make personalized data files.

This library has been particularly useful for the statistical significance program: all data accesses and storage were done simply and clearly.

PART II : DESCRIPTION OF THE METHOD

EVENT CHOICE

The quality of the final results depends greatly on the care taken to search for and classify the occurrences. Indeed, a severe event must have a precise or at least quantitative definition, in order to gather similar situations without bias. Moreover, precise dates of occurrences are needed in case a given variable must be stratified by time of day.

1. NEW CLASSIFICATION

The first step was to choose which events to study. The focus is on those events with major consequences in the life and the economy in the Sacramento area, and for which forecast improvements could be gained. Such events include: hard freeze, heavy rain, long duration dense fog and heat wave.

As long as the statistical significance assessment is an automatic process, the different categories of events should be as homogeneous as possible. The definitions used were derived from Staudenmaier's definitions, with some improvements to reach a better homogeneity.

The main worry was to minimize imprecise starting times (offsets) between the occurrences of a same event to obtain the most reliable mean fields. In the previous studies each occurrence was stored as a single date, either the beginning of or the climax of one. In this study each occurrence has been described more accurately accordingly to the type of event; for instance, for each occurrence of heat wave, the start and the end dates, the day of the maximal temperature, the maximal temperature and the average of the maximal temperature during this period are stored. This amount of information makes a human review of each group possible, at each stage of the project. Moreover this data can be more easily shared with other people, even if they work with different criteria.

The following criteria have not been defined arbitrarily, but in accordance with the experience of forecasters at the NWSFOS and with the climatological records during the 20-year period of the study.

a) Hard freeze:

This event was difficult to express with a precise definition. Ours differs from the one used by Staudenmaier (1995). The definition chosen was: **a two-day -or more- period, during which the minimum temperature is less than 30 degrees Fahrenheit (-1 degree Celsius). Moreover this cooling must not be due solely to radiation. The latter criterion was approximated by the proxy condition that the subsequent maximum temperature be under 50 F (10 C).** This situation, which combines length and strength, is the worst for the Sacramento Valley farmers because they cannot easily mitigate against it.

b) Heavy rain:

This event had been previously defined as a two or three day period with more than 3 inches (76.2 mm) of rain, not due only to convection. This definition does not make clear if, for instance, a thirty hour period split on three days is taken into account or not.
The criteria have been redefined to clarity, and a bit relaxed to suit the relatively short period of the study. The new definition is: **a rainfall event not due only to convection, that lasts at least 24 hours in a row, with either a total of rain superior to 2.5 inches (63.5 mm) or an activity superior to 2 inches per day (50.8 mm per day)**.

c) Long duration dense fog:

The actual definition of this event is: **a five -or more- day period during which dense fog, i.e. visibility under a quarter mile (approximately 400 m), is reported at least once a day**. The definition used by Staudenmaier was the same except for the length -seven days.

d) Heat wave:

This event has not been redefined: **at least three consecutive days during which the daily maximal temperatures are above 100 degrees Fahrenheit (38 degrees Celsius), and with at least one of them above 105 degrees Fahrenheit (40.5 degrees Celsius)**.

2. NEW DATES

The new definitions required a search for event dates from the beginning of the data record. For heat wave events only the occurrence dates between 1994 and 1999 needed to be searched because the definition of this group remained the same. Nonetheless, some differences appear between the dates found by Staudenmaier (1995) and in the two updates that followed. Consequently, even for this event, it was not clear how reliable were the dates found previously.

So, for each type of event, the dates were sought from scratch, in order to have both a more exhaustive and a more reliable list of occurrence dates for the 1979-1999 period.
This task was automated as much as possible, using climatological database access software available at the NWSFOS The data of two different stations in Sacramento County were available through this software: the Executive Airport and Downtown Sacramento.

Here are the methods used to find the occurrence dates for each event.

a) Hard freeze:

The climatological software can find directly consecutive days whose minimum temperature is under a specified value. In order to represent the agricultural threat conveyed by this event, only the data from the Executive Airport have been used.

The main problem was to eliminate the dates due to radiation cooling without analyzing each situation. This had been done by using the maximal temperature: radiation cooling is likely to be followed by radiation heating, so only the dates with maximum temperatures under 50 degrees Fahrenheit (10 degrees Celsius) have been kept as hard freeze occurrences.

b) Heat wave:

The first step of this method is the same as the previous one: consecutive days whose maximal temperature is above a specified value are found with the software. Then this list of dates must be analyzed with another one, corresponding to the days when the maximal temperature reached or exceeded 105 degrees.

These dates were established for each of the two stations. While each station has specific dates, only the common ones have been used to assure consistency.

c) Heavy rain:

To find these dates, the data available both via the software and in the paper archives have been used. An automatic search was used to find roughly some periods that could be nominated as heavy rain events. For instance, highest precipitation days and some consecutive rainy day periods of different lengths and different activity were searched with the software. Once this first job was done, all of these dates were studied more precisely with the actual observations. Next the rainfalls due only to convection were removed, and the beginning and the end of each rainfall period were established within a one-hour precision. Finally all the dates were assessed according to the criteria of a heavy rain event.
These occurrences are the only ones not defined as a 'several day' period, but as a 'several hour' period. While for the other types of events all the first day data are gathered, at 00Z then at 12Z, in this case it is the data corresponding to the hour of beginning that must be gathered. Thus the exact hour of the start is very useful to minimize offset between each occurrence: an occurrence that started at 3 p.m. was represented by the previous 00Z fields, whereas an occurrence that started at 9 p.m. was represented by the following 12Z fields.

d) Long duration dense fog :

The visibility is not available via the climatological software, so the long fog dates had to be found manually in the archives. As soon as dense fog is reported for one hour, it becomes the significant weather pattern for that day. Thus only the monthly weather summary has to be checked for each year, from November to February.

Appendix II.1 presents, for each severe event studied, its definition, and all the data recorded for each occurrence. All the information gathered could be very useful for further studies with different criteria. It must be noticed that all the dates and hours are in local time (GMT minus nine hours), whereas meteorological data are archived using GMT.

II.B. Statistical assessment: basic algorithm

The conceptual idea underlying the Bootstrap method has been presented in I.E. Now its implementation will be described in a general presentation of the significance-testing program. First the initial parameters will be discussed, because they influence many aspects of the program behavior. Then the general algorithm will be presented, and its two main parts will be described more deeply: the elaboration of the null distribution by resampling and the comparison between the occurrence test value and the null distribution.

1. Initial parameters

Before making each significance test, several parameters must be specified. Some are necessary just to describe the input dataset, while others control some parts of the algorithm. A comprehensive list of them is presented in Appendix II.2. Here are the most important ones:

- *Occurrence dates*: at least one group of **n** dates must be specified; it is the studied sample whose significance will be computed.
Typically several groups of **n** dates are given, the first one standing for the beginning of the severe event (**n** dates corresponding to the beginning of each occurrence). The others represent the evolution prior to the event (for instance 2 groups of **n** dates corresponding to 24h and 48h before the event).
Of course the number of dates in each group must be the same, i.e. no data are missing. There are neither restrictions on the number of occurrences nor on the length of the period studied (number of groups).
Once again it must be emphasized that these dates must be as homogeneous as possible in order to have the most accurate and, consequently, useful results.

- *Data used*: The study of severe events would not be satisfactory if performed without seasonal stratification. Indeed each severe event happens only during a three or four month period, and so the use of the other months to assess the significance will bias the results. That is why the months relevant to the severe event studied must be specified. Then the length of the study period must be defined by two dates, its beginning and its end.
The final dataset used for the statistical significance is the addition of all the relevant months (consecutive or not) for all the consecutive years defined by the start and end years. Of course this dataset must contain all the event occurrences dates, even the ones prior to the event.

- *Variable*: one –and only one- variable must be chosen for the test. Several parameters relative to this choice must be specified, as for instance how many levels it has.

- *Test statistics*: they are the tests of interest, as the mean or the standard deviation, whose significance is to be assessed; up to six different ones can be specified.

- *Significance levels*: these are the different levels used to assess the significance of the target test statistic; up to six different levels can be specified.

- *Replacement*: there are two different ways to perform the Bootstrap: with or without replacement. In the case of Bootstrap with replacement, the dates among each random sample are not necessarily all different, while without replacement all dates among the same random sample must be different.

2. ALGORITHM

The following algorithm (cf. Figure II.1) gives an overview of how the statistical assessment works and what are the different loops on the different parameters.

The first part is only data extraction, in order to work only with data relevant to the event studied, and requires little computer time. The second step, explained in B.3, requires a lot of computer time because a null distribution is created for each grid point. One should be aware that this time increases with the number of grid points and mainly with the number of random samples. Once these null distributions are created, the assessment of the significance of the different occurrence date groups, explained in B.4, is pretty fast; for instance, there is virtually no difference in time between using two or eight dates in advance of an event.

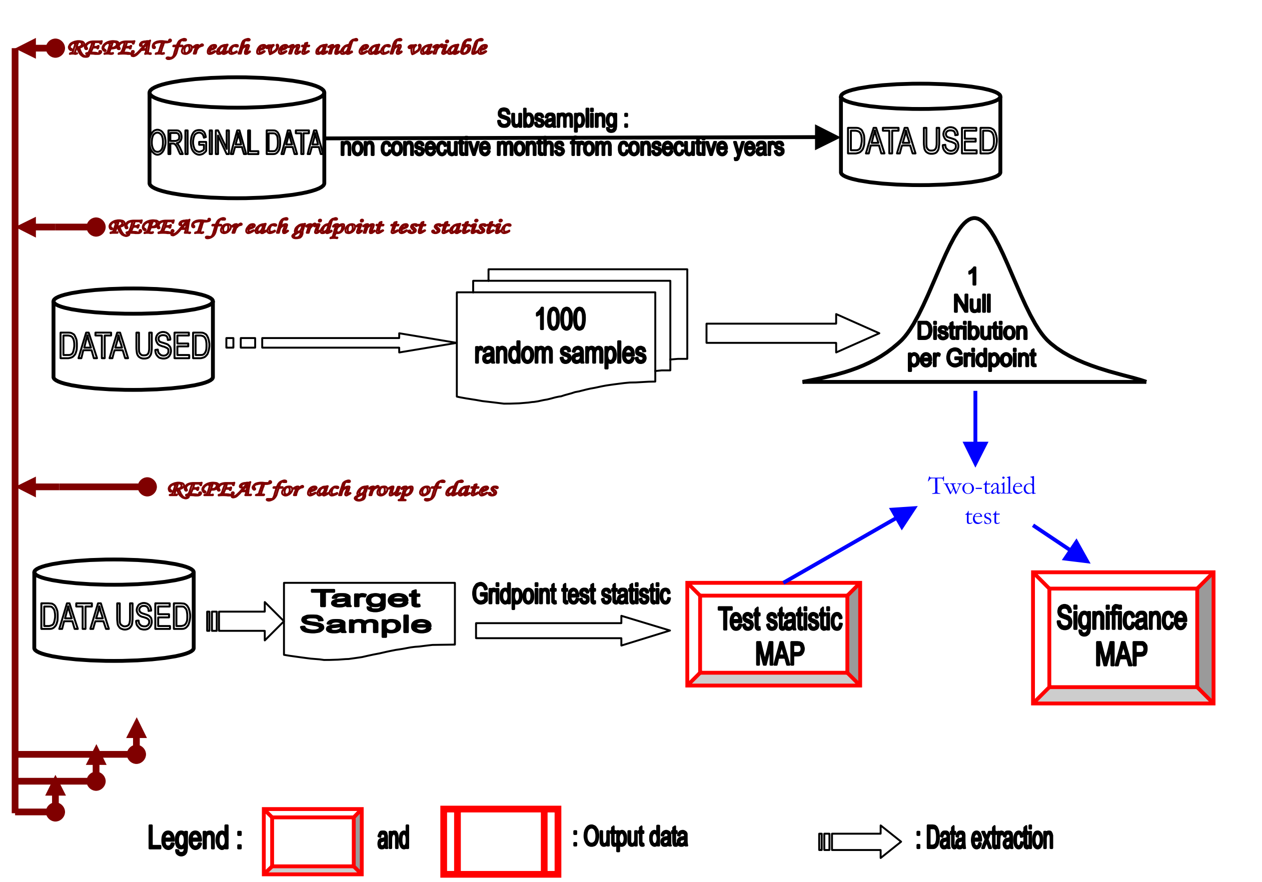

Figure II.1 : basic algorithm

3. ELABORATION OF NULL DISTRIBUTION

The different steps to create a null distribution using a resampling method are: 1. generate random numbers; 2. create random samples from them; 3. perform a test statistic on them.

The random number generation is done using the Fortran Uniform [0,1] Random Number Generator. Given a starting point number (seed), this generator produces a list of random numbers $(RN_i)_i$ issued from the uniform distribution within the range $0 \leq RNi < 1$. The seed for the first sample is automatically generated from the current date and time, while for the other samples the seed is taken from the previous random list.

Supposing we study N occurrences of a severe event, we want to generate P (typically P=1000) random samples of size N. The data used for this event gather M different dates.
The easiest way to achieve this goal is to generate P random lists of size N, and to associate each random number to a date among the M available. One way to do that association is to rank the M available dates, and to link the random number RN_i with the date d, $1 \leq d \leq M$, according to the formula $d = INT[M * RN_i + 1]$, in which INT stands for the truncation of fractions. It must be noticed that different random numbers might be represented by the same date.

Consequently, using the Bootstrap with replacement generates P random lists of size N, while using the Bootstrap without replacement generates P random lists of size N', N'>N and N' large enough to contain at least N numbers that are associated with N different dates. This program uses an empirical value of N' for which no problems have ever been found: N' equals 20*N.

Finally we have P random samples of size N, i.e. P random groups of N maps chosen from the M dates of the used data. Then on each sample a grid point test statistic is performed, and the P results of this test create, for each grid point, the null distribution against which the test statistic performed on the studied sample is compared. In this program the tests available are the mean or the standard deviation: given a group of maps they return respectively a mean or a standard deviation map, calculated grid point by grid point.
An example of null distribution is shown on figure II.2.

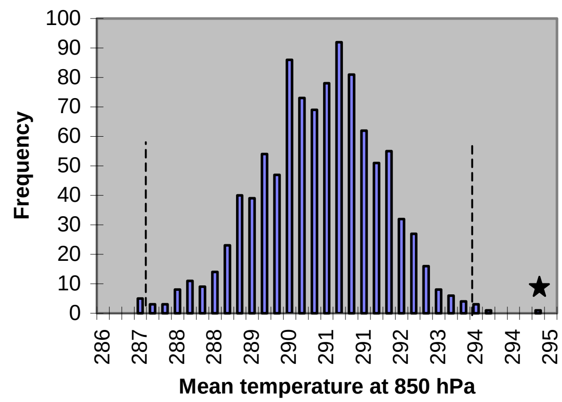

Figure II.2: example of null distribution.

This null distribution was generated while assessing the significance of the 850 hPa mean temperature for heat wave events.

This histogram refers to the grid point closest to Sacramento, and gathers 1000 random samples. The occurrence value has been added and is shown by a star. **99% of the values stand between the two dashed lines**.

4. Significance testing: Bootstrap Confidence Intervals

Once a null distribution is obtained for a gridpoint, confidence intervals have to be determined. They were defined with the intuitive percentile method. The (1-α)% confidence region is delimited by two values out of the P forming the null distribution: the $(P^* \alpha /200)^{th}$ and the $(N^*(1- \alpha)/200)^{th}$ ones.

If the value corresponding to the occurrences is outside this zone, the hypothesis is rejected and therefore this value is called significant.

An example of this method is shown on figure II.2: the occurrence value lies in the upper 0.5% zone of the histogram, therefore it is significant at the 99% level.

Once composite maps are created, their mean or standard deviation significance is assessed grid point by grid point. The program assesses the significance for every level specified (up to 6), and the final significance will be the highest significance value of α, or 0. Therefore a test statistic significance map is created, with at every grid point a value of significance: α if the value of this grid point was found significant at the α level (α maximum) on the right tail of the distribution, - α if it is on the left tail, 0 if it was not significant even at the lowest level. For instance, the value stored in the example of the figure II.2 is +99.

II.C. Statistical assessment: enhancements

The algorithm previously presented is already able to produce good results, but several enhancements have been provided. The aim of the first of them is to increase the quality of the composite maps, while the other ones seek a more powerful statistical analysis.

1. Anomalies

The composite maps and the statistical treatment described before are performed on the usual 'total' fields. This choice has been made to suit the forecast aim of the project, by working on fields easily available and usable at the NWS.

The problem with these total fields is that their values are not comparable all year long. Thus the statistical assessment was performed using only the three or four months where the great majority of the occurrences of a given type of event took place.

However, the use of anomaly fields is a way to be sure that the results are not biased or hidden by the length of the studied period. This should give more precise composite maps, though they are less useful for direct forecasting analysis, hence we can hope that the following statistical analysis may find similar results for total and anomaly fields.

An option that deals with anomaly fields had been implemented in order to check if the anomaly results are more accurate or not. The anomalies have been defined using the daily long-term mean fields derived from the NCEP Reanalysis; these values are thirty-year daily averages, and are available for all the pressure level variables.

2. Double null distribution

This enhancement is the consequence of a simple statement: all the events studied, except heavy rain, are defined as unusual days. Therefore each group of occurrence dates is composed only by either 00Z or 12Z data: the group corresponding to the beginning of an event will gather for instance only 00Z data to represent the situation just before the event day.

However the null distribution is constructed from samples built by randomly picking dates among the data record used, thus the ratio between the 00Z and 12Z dates that basically form the *null* distribution is unknown. In fact we can expect that roughly half are 00Z data for a large number of random samples. Then it is easy to figure out how that sampling biases results concerning variables having daily oscillation, as do the surface ones.

For an example, consider the mean surface temperature corresponding to the beginning of the event. If all the occurrences are taken, for instance, at 12Z, then the majority of the grid points will be assessed as unusually low, because they are compared to both 12Z and 00Z times[1]. On the contrary, the composite map twelve hours before would be assessed as unusually high.

[1] This result is correct for California, because the model time 12Z corresponds to 3 a.m. in local time.

The case of heavy rain is a bit more complicated because on every group of occurrence dates 12Z and 00Z data are mixed. If the ratio between 12Z and 00Z is not near 1 over 2, the results could be biased the same way as shown before. In fact the case of heavy rain in Sacramento area was very similar to the other events, because all but two dates (out of fifteen) are in phase, i.e. referring to the same model time.

An option that builds two null distributions with frozen ratios has been implemented which is simple and at the same time adapted to the majority of events. The distributions are elaborated by randomly picking only 12Z or 00Z dates. This leads to two null distributions, one relative to the "day" (12Z) and one to the "night" (00Z). This option is vital for air temperature or surface variables, but it can also be used for all the other ones.

The figure II.3 shows clearly the huge difference this option makes on some variables. A mean of 12Z, or 00Z, would be virtually always significant if compared only to one distribution made with day and night values.

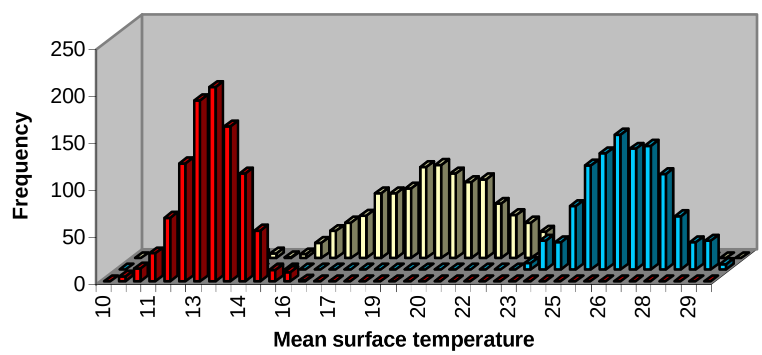

Figure II.3: double null distribution against simple one.

These three null distributions were generated while assessing the significance of the surface mean temperature for heat wave events. These histograms use the grid point closest to Sacramento and incorporate 1000 random samples. The background one is made from both 12Z and 00Z values. The two others contain only 12Z (foreground one) or 00Z (middle one) values.

3. Statistical assessment of the maps: global significance

All the tests of significance described up to this point are performed grid point by grid point. That means that the significance of each map by itself is unknown. One can think that as long as each test has the confidence level α, so has the whole map. However this problem, known as the multiplicity problem, is not that simple.

An analogy with a die is easier to understand: a map with one hundred independent grid points, each of them assessed at 5%, can be associated with one hundred rolls of a 20-sided die. If the map were significant at 5%, it would mean that the probability for a random map to have five or more significant grid points is 5%. This probability is the same as the one to obtain five or more times the face 1 while rolling one hundred times a 20 sided die. This probability calculation, well known to statistics students, has an actual value of 38%! In fact the probability to obtain **n** times the face 1 goes under 5% only for **n** superior or equal to *nine*. It means that, under these conditions, a map having one hundred grid points is significant at 5% only when its number of significant grid points is superior or equal to *nine*.

The maps could be assessed this way, but in fact the grid point values in a meteorological field are not independent, so applying significant tests to every grid point are not independent. Thus a less important number of significant points can be expected for the same confidence level, but its precise value is unknown.

To assess what will be called the global significance of the maps, the bootstrap method has been used again (Matthews and Kiladis, 1999). The test statistic is the number of grid points significant at the α level. The corresponding null distribution(s) is (are) calculated from the random maps created previously. The number of significant grid points in the actual composite maps is then compared to that (those) distribution(s) with a one-tailed test.

On figure II.3 is shown an example of a composite map globally significant at 99%.

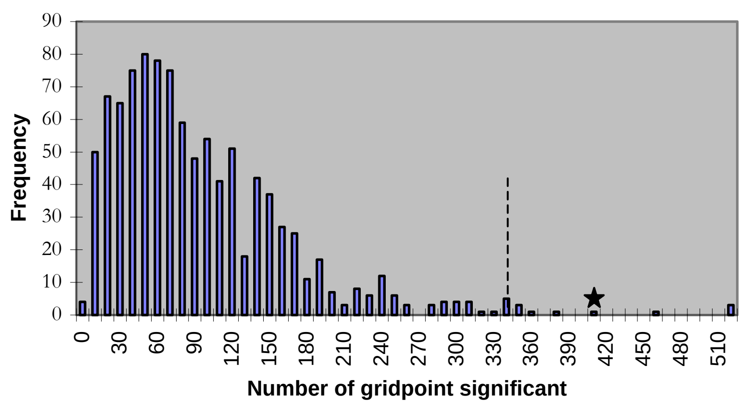

Fig II.3: example of null distribution for the global significance test.

This null distribution was generated while assessing the global significance of an 850 hPa mean geopotential height map for heat waves. This histogram gathers the global significance (number of gridpoints significant at the 5% level) of 1000 random maps. The occurrence value has been added and is shown by a star. 99% of the values stand to the left of the dashed line.

This significance test allows working with only the most significant maps, where the meteorological signal is bigger than the noise. **However even if a map is not significant it does not mean that its significant areas are not reliable, it just means that their global size is not more important than the one for a random composite map**.

More generally, this enhancement shows clearly that the bootstrap method is very powerful and convenient, because it allows using any test statistic with the same ease.

4. IMPROVEMENT OF THE STANDARD DEVIATION

It is easy to imagine how different the occurrences for a given event could be, even if this group is as homogeneous as possible: there is not necessarily a reason for the meteorological variables to describe exactly the same pattern from one occurrence to another, even in the regions we called similar. For instance, a trough on the Pacific could go further south for one occurrence, further west for another, etc. Therefore, it might be easier to find statistical significance among a region instead of on a single grid point.

A simple but efficient regional significance test has been implemented, and used mainly to improve the standard deviation. The test is to replace each input field by another one, calculated by making a nine points average around each grid point. This smoothing, used with the standard deviation, might improve the significance results when several offsets remain between all the occurrence fields.

II.D. Statistical treatment : summary

The actual algorithm, including all the enhancements described above, is shown on figure II.4.

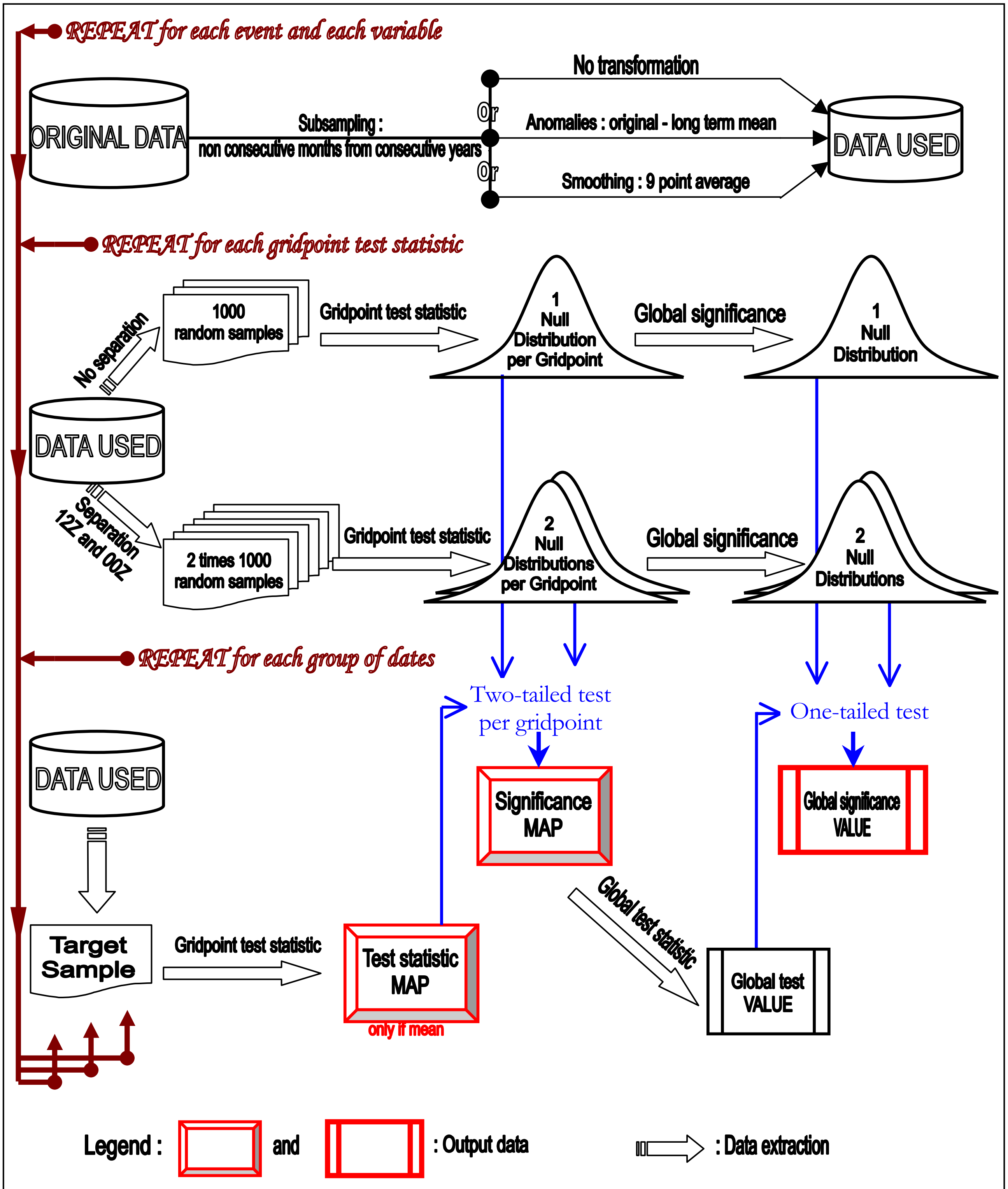

Figure II.4 : comprehensive algorithm

PART III : RESULTS

STATISTICAL ASSESSMENT CHOICES

The four types of events described above have been studied using Sacramento area data, for the sixteen variables presented in Table I.2. The different choices underlying the results are described in this section: first the parameters used to perform the statistical assessment are discussed, then the use and the benefits provided by the enhancements, described in II.C, are shown.

The analysis of these results, seen in III.C to III.F, is intentionally different from Staudenmaier's; while in the original study local phenomena were put into relief, here the stress is put on the larger synoptic situation. Two reasons explain this choice. First, the precision of the dataset used, 2.5 degrees in latitude/longitude, makes the results much more informative on a large scale than on a local one. Second, this analysis is done to provide guidance in the forecast of these events, thus it is interesting to put into relief the broad synoptic situations able to generate some severe events because such situations are better forecasted by a model than some local effects.

1. PARAMETERS USED

The common parameters used to obtain the following results are shown on Table III.1. The final choice of these parameters was made after several tests. The levels of significance are high, and give a much better description of the situation than a single level. The number of random samples was limited to one thousand by the computer performance, but it is already a sufficiently large number to give reliable results.

All the hours listed are relative to the beginning of the event. For all the events but heavy rain 0 hour corresponds to 3 a.m. (local time) on the first day of the event. For heavy rain 0 hour represents the beginning of the rain in Sacramento.

Table III.1: common parameters

Grid point test statistics	Mean
	Standard deviation smoothed (sds)
Levels of significance	Grid point significance: 99%, 98% and 95%.
	Global significance: 99%, 98% and 95%.
Number of random samples	1000
Null distribution	Double*
Type of Bootstrap	Without replacement
Length	Dataset: from January 1979 to December 1999*
	Period in advance of a severe event: 96 hours* with data each 12 hours.

*: Except where mentioned

The occurrence dates will be described more precisely for each event. For each event the statistical assessment has been performed several times with different occurrence dates, to check the consistency of the results and to find a good balance between enough dates and homogeneous ones. The dates used for these results are the best compromise.

2. ENHANCEMENTS

All the enhancements described in II.C have been used. Their use and above all their different benefits in this study are presented.

a) Anomalies

First, the statistical assessment has been performed on total and anomaly fields. To work with anomalies allowed us to take all the dates found without restriction to certain months. Thus, anomalies results are supposed to be the most accurate, having the more dates and being season insensitive.

However these results were found to be very similar to the total field ones: virtually the same significant maps and zones, nothing more and, important too, nothing less. It seems that the types of events studied here present a good seasonal stratification, thus the following analysis is mainly based on total fields.

This option should be more useful on other types of events, such as the wind events, that occur during a longer period of the year.

b) Double null distribution

The use of a single distribution gives for several variables results that are obviously biased; for instance on the surface temperature field during the summer, the continental temperatures are all very high during the day and all very low during the night. Some other variables are affected too, but the consequences on the results are lighter, hence barely visible. That is the case for instance, with the geopotential heights at low elevations over the continent during the summer.

Therefore a double null distribution has been used for each variable, except for heavy rain (cf. III.D.).

c) Global significance

The global significance test statistic has been defined as the number of grid points that are significant at a level superior or equal to 95%.

Only the significance maps whose global significance was above 95% have been plotted, hence analyzed. This has been a very useful way to keep only the most interesting maps, and makes the following analysis much more reliable. This approach might hide some weak but interesting signals, but above all it prevents one from analyzing signals not related to the severe event.

d) Standard deviation smoothed

A comparison between the usual standard deviation (grid point per grid point, **std**) and the smoothed one (9 point average, **sds**) has been done. The results are pretty similar, because the fields used are already very smooth, but the significant areas with the latter are sometimes bigger than the ones with the former. Consequently the smoothed standard deviation has been used to obtain these results.

III.B. Generalities on the plots

1. RESULTS FILES

All the result maps were stored in NetCDF files, whilst the global significance of each composite map was stored as an ASCII file (an example is shown on Appendix III.1).
The results concerning one event are stored in four different files. One file interrogates total fields stored on pressure levels. Another file has the corresponding anomalies for pressure level data. An analogous pair of files (total and anomalies) are constructed for the surface and tropopause level fields. For each variable, these files contain three fields: the composite map (i.e. the mean occurrence field), the significance map for the mean field, and the standard deviation significance map. These fields are available for each level and each hour.
The global architecture of these files and the names in use in this study are summarized by the figure III.1.

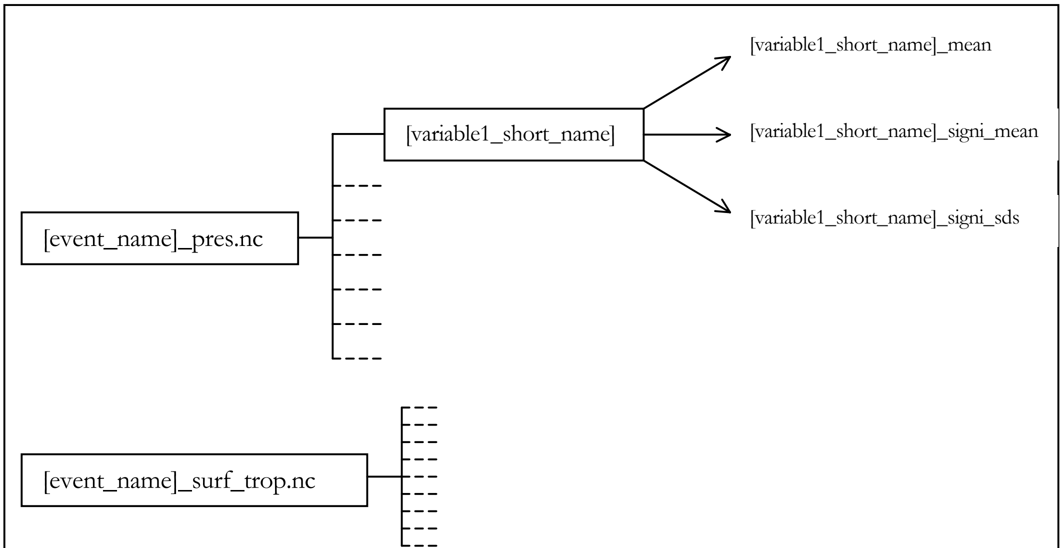

Figure III.1: Architecture of the NetCDF result files
The short names of the variables are listed in Table I.2; the same architecture applies for the anomaly files.

The NetCDF files must be created before running the statistical assessment program, whilst ASCII ones are automatically generated. A Fortran program has been developed to help in creating customizable NetCDF files (cf. Appendix III.2).

2. DESCRIPTION OF THE PLOTS

All the figures have been plotted using Ferret, software widely used in the oceanographic community for its customizable and quality graphics.

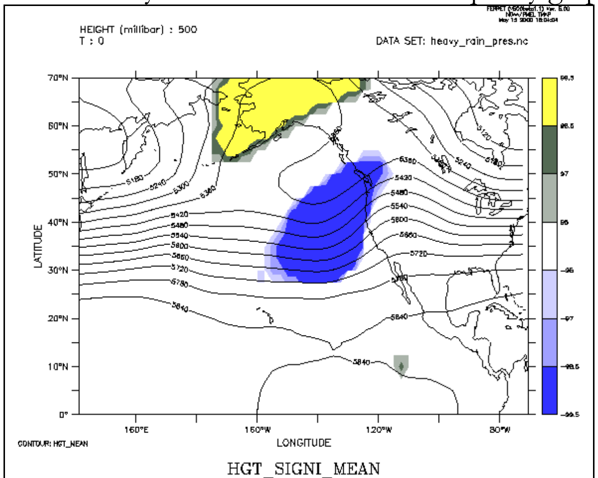

Figure III.2: example of plot

For the great majority of the maps plotted, the composite map is contoured, and significance map to a test statistic is superimposed (cf. Figure III.2).

The significant areas range from blue where the statistic test values are unusually low to yellow where these values are unusually high. The non-significant zones are white. The different levels of significance are –99, -98, -95, 0, 95, 98 and 99%.

The color panel has been chosen to be readable even in black and white. The bright areas with darker ones around (yellow with maroon around) indicate that these significant values are unusually high, while the progressively darker ones (light blue to dark blue) are the significant, unusually low values (cf. Appendix III.3.a for a comparison between color and black and white maps).

For better visibility, the humidity maps have been plotted with other conventions (cf. Appendix III.3.b). The contours correspond to the significant areas; the dark lines show areas with unusually high values while thinner lines show zones with unusually low values. The humidity field is plotted in a grayscale.

Another exception is the wind plot: the composite map is the mean field of wind calculated from the mean fields of zonal and meridional wind. The significant areas are only the ones relative to either the zonal or the meridional wind (cf. Appendix III.3.c). Therefore their interpolation is slightly harder than for the other fields.

It must be noticed that wind composite maps are interesting even if the vectors have been averaged. The wind patterns for every occurrence are quite similar, in most areas the wind has roughly the same direction. Thus it makes sense to average them.

Finally each plot is self-describing: on Figure III.2 we can identify the result file name (upper right), the level and the hour prior to the beginning of the event (upper left), the name of the colored field (lower middle) and the contoured field (lower left). The latter is very important for the humidity field, because the contoured field is either the mean or the standard deviation significance map. In Appendix III.3.b both of these two kinds of significance maps are plotted, and one must be aware of that while analyzing the plots.

3. Interpretation of the plots

The mean patterns give basic information on the event, but the significant areas allow deeper analysis and more confidence in these fields. Two different test statistics have been used, and for each of them a discussion of their interpretation follows.

a) Mean

These significant areas distinguish in the mean field where the values are unusually high or low. For instance, on a geopotential height field, colored areas are interpreted as unusual ridges or troughs. What is unusual could be the pattern or the mean value. When an area has unusually high values, **we do not know in fact if it is due to a rare pattern or if it is a common pattern but with higher values**. Therefore forecast experience and climatological values are necessary to interpret these maps.

For clearer explanations during the analysis, areas where the mean is unusually high (low) will be called areas with high (low) values.

b) Standard deviation

The standard deviation significant areas show where on the composite map the occurrence values have unusually small or large standard deviation. One might think that the only interesting areas are the ones with small standard deviation: the occurrences fields are pretty similar in these zones. Since they are similar, the pattern is more easily spotted by a forecaster.

But once again we must be aware of the climatology. Indeed some regions have pretty stable patterns during a season, i.e. a low climatological standard deviation. Thus the occurrences may have an unusually high standard deviation value there if the individual events differ from the climatological pattern in a wider range (but with anomalies of a single sign) than most events differ from each other. The large standard deviation might misleadingly suggest that the events are not that similar, but the pattern is still easily spotted.

Another view of how important areas with high standard deviation values could be is the following example. A propagating trough with slight phase differences from one occurrence to another can yield large standard deviation on the edges, if this trough is intense.

For clearer explanations during the analysis, areas where the standard deviation is unusually high (low) will be called areas with scattered (close) values.

III.C. Long Duration Dense Fog

1. Presentation

This event is, among all the severe events studied, the most common one because twenty-five occurrences have been found within twenty years. The criteria for this event may not seem very strict because the formation of dense fog during only one hour five days in a row is enough to call this period a dense fog event. Moreover it is known that fog is a real forecast challenge, thus to study this event with the precision of the NCEP Reanalysis model would appear to be very hard.

a) Occurrences

The occurrence dates found (cf. Appendix II.1.a) range from November to February, i.e. during the rainy season. This homogeneity allowed taking all of them into account for the analysis on the usual fields.
The total amount of significant maps for this event is the smallest of all the events studied, which underlines that the large scale meteorological signal is weak.

b) Staudenmaier's results

In a nutshell, Staudenmaier found two areas of high pressure over California, with a weak gradient between them that maintains light winds. Moreover he found strong subsidence over northern California, with 500 hPa geopotential heights surprisingly high having an average of 5770 meters.

2. Analysis

a) Field description[1]

The main pattern for geopotential heights 24 hours before the beginning of this event is a trough south of Alaska, north of Hawaii (cf. Appendix III.4.a). A huge ridge, without significant values, spread from southern California towards Alaska, with an axis following roughly the coastline. A second trough, shown by low values of heights, lies west of the major one. A low appears at 700 hPa just south of the Alaska coast.
During the 24 hours prior to the onset of the event, the major trough moves slowly eastwards, and the ridge strengthens up to have high values over California at 0 hour, which confirms *a posteriori* the assessment of Staudenmaier. The second trough to the west persists at 700 hPa and moves faster than the major one. Moreover low values appear on Hudson Bay at 0 hour.
The 850 hPa level (cf. Appendix III.4.c) gives an interesting view of the situation just before the beginning: the two troughs are well seen and their associated lows over the Bering Sea gather at 0 hour, whilst the heights over California quickly increase.

[1] Cf. Appendix I.1.b and I.1.c for geographical names

The ridge that affects California was an expected figure for this event, even if its duration and strength were underestimated, but the troughs appear to be totally unexpected features. The existence of the main one is undoubtedly true because its mean appears to be very significant - 99% level on a huge region. Moreover the values on the upper region of this trough are close at 300 hPa, between -84 and -12 hours (cf. Appendix III.4.b). It means that the upper location of the trough is very similar from one occurrence to another. This last field also shows another significant region for the standard deviation, a large zone around Hawaii from -36 hours to -12 hours. This area is much smaller but very consistent, thus probably linked to an actual signal.

Omega fields (cf. Appendix III.4.f), mainly at 700 hPa, show clearly the activity of the main trough, with instability around the cold front and global subsidence after. This activity is significant and is unusually far south, just north of Hawaii, even for the winter season. Two other areas appear but are less significant; rising appears over the Gulf of Alaska and slight high values over California show subsidence. The two last areas may be explained with a look on the temperature fields (cf. Appendix III.4.d): the ridge comes along with high temperatures, and it seems that the warm advection is more important at 850 hPa than aloft, explaining the rising north of the ridge. The temperature fields show again the presence of the major trough, 24 hours in advance at 850 hPa (cf. Appendix III.4.c).

This situation is also seen on the two other pressure level fields. First the troughs appear as a dry tongue of specific humidity, and the ridge brings high humidity into the Gulf of Alaska, mainly at 500 hPa (cf. Appendix III.4.e). These significant areas may appear small compared to the previous ones, but they are as significant. The number of grid points significant depends on the variable, and for instance humidity maps have usually small significant areas, even when they are globally significant at the 99% level.

The wind fields (cf. Appendix III.4.g-j) show clearly these three preponderant meteorological objects too. The extreme winds north of the ridge or south of the troughs are seen on zonal component significant areas, while unusual zonally-varying oscillations are shown by meridional component significant zones. In fact these maps are interesting because they are significant earlier than the geopotential heights. It may be easier to notice the building of the major trough 36 hours in advance thanks to the 500 hPa wind field, with strong zonal winds unusually far south (northwest of Hawaii).
The surface winds (cf. Appendix III.4.k-l) show roughly the same patterns concerning the significant areas. Because of the ridge, strong south winds occur offshore of California, making the winds in the Central Valley weak though not unusual, even at 0 hour.

The other surface field, the temperature (cf. Appendix III.4.m-n), shows mainly that the occurrences are very close for this parameter. A large area of close values is seen from -60 hours to 0 hour, from 160º West to the Californian coast. Another interesting area is on Hudson Bay, where the values are both close and low.

b) <u>Synopsis</u>

A pre-existing ridge along the west coast of North America strengthens with the approach of a deep trough, reinforced in turn by a second one. This huge ridge keeps the winds in the Sacramento Valley light and suppresses vertical mixing a low levels. The pattern moves very slowly leading to a lasting fog. Of course, high humidity must pre-exist, hence the pattern occurs during the rainy season.

It is very interesting to notice how the ridge strengthens, apparently by a kind of wave amplification: a trough over the Pacific Ocean deepens, a ridge downstream increases, and at 0 hour some consequences can even be seen over the Hudson Bay. It must be noticed that this pattern is, spatially speaking, almost stationary. Indeed if the ridge was not large enough, the trough would move towards California and would change fog conditions into rainy conditions. This signal appears clearly, hence it can be considered as reliable.

The synoptic signature of this event seems clear and some clues can be given to forecast this situation. The presence of fog and its long duration have been explained, but some questions remain around the humidity problem that could explain why this fog is a dense one. The humidity fields show nothing significant over California. In fact it comes as no surprise because episodes of long duration dense fog in Sacramento are only a Central Valley pattern, not the Sierra Nevada foothills, or San Francisco Bay area. Indeed, Sacramento persistent fog episodes are episodes of unusually fine weather in the surrounding areas. Also, humidity fields are not amongst the most reliable fields. Finally, the resolution of the NCEP model may hide some large local variations over California, but it gives a good overview of the synoptic situation.

III.D. Heavy Rain

1. Presentation

This event is the only one delimited with one-hour accuracy, because a heavy rain period does not occur at the same time of a day contrary to the other events. This accuracy could not be used totally because the reanalysis data used have a twelve hours interval.
The criteria for this event has been clarified and probably relaxed compared to the ones Staudenmaier used in the original study. Now the number of occurrences suits better the short twenty-year study, but these new criteria may gather non-homogeneous occurrences.

a) Occurrences:

Fourteen occurrences have been found in twenty years, ranging from November to April. According to the precise hour of beginning and the difference between the local and the model time, the model output that represents better the beginning of each occurrence has been established; all the occurrences but two, 01/24/1997 and 01/12/1993, start at 12Z (cf. Appendix II.1.b).
Among these fourteen episodes all but two occur during the period of November through February, thus the statistical significance of the total fields has been performed only on the twelve winter occurrences. More precisely the number of occurrences taken into account depends on whether the variable has a daily oscillation or not. If not, the twelve occurrences relative to the rainy season have been used with a single null distribution, and if yes, two null distributions were performed but were taken into account for only ten dates: the ones that start at 12Z and occurred between November and February.
For the statistical assessment using the anomaly fields, all the fourteen dates were taken for the variables without daily oscillation, and twelve for the other variables.
In spite of all these differences, a great seasonal homogeneity between all the fields was reached.

b) Staudenmaier's results

Staudenmaier found that the area was dominated by low pressure off the coast of Oregon, without high heights over south California. He found a confluence of a cold polar jet stream and a subtropical one that goes across the U.S. without circulating around the Gulf of Alaska. 500 hPa heights were found to be typically below 5640 meters.

2. Analysis

a) Field description[1]

The geopotential height fields (cf. Appendix III.5.a-c) show, of course, a trough west of the Californian coast with very low values. The other significant area is over Alaska with high values.

[1] Cf. Appendix I.1.b and I.1.c for geographical names

The pattern of the three upper levels is very similar, and shows that the trough barely moves between -72 and -24 hours. In fact it deepens and moves slightly eastwards, but not as fast as one could have expected. Then during the last day it moves towards California, but it is still very slow. During all this time the high values over Alaska remain very stable, with a slight up and down changes of these values. The pattern that forms is a well-known "dipole" block whose eastward progression is expected to be slow.
At 850 and 700 hPa levels, high heights are found off the west coast of Mexico; the south edge of this area is significant with high values between -72 and -48 hours, whilst its west edge is significant with high values during the last day prior to the event. The low in the Gulf of Alaska is closed only at -12h.
The behavior of the significant trough is the same at 850 hPa as aloft, but the high value area over Alaska appears less clearly, and only between -48 and -12 hours. The Appendix III.5.d shows the 850 hPa anomaly field, and it has exactly the same significant areas. On this field it may be even clearer that the trough deepens without moving: the significant area increases but the center of the low barely moves in 72 hours.

The almost static trough might indicate that the different occurrences are different enough to create in the mean field an artificially placed trough. This notion could be confirmed by the standard deviation at 300 hPa (cf. Appendix III.5.e), which shows scattered values upstream of the trough. However, further study of these fields can lead to a different conclusion: on the lower levels, 700 hPa and 850 hPa (cf. Appendix III.5.b-c), a weak trough is seen -48, -36, -24 and -12 hours just upstream the significant one. It appears to merge with the main low, possibly slowing it down. The raining period over Sacramento is thereby prolonged as this, and perhaps more than one, short wave migrates around the main low.

The study of the omega fields (cf. Appendix III.5.f) shows clearly the development of substantial rising over California at -12 and 0 hour whilst before that happens, the behavior does not seem very continuous. The only pattern that is stable is a small region with high values on the West coast of Canada. However this area is probably due to orography, because it is located where the surface winds are downslope over a mountainous zone. (Some nearby surface winds are significant.) Eventually, the temporal discontinuity of this field can be seen as either another clue that the occurrences are quite different or as a consequence of the "B" quality rating of this field.

An interesting "B" field for the event is the relative humidity (cf. Appendix III.5.g-h). Mean and standard deviation maps are significant but do not change the previous analysis. In fact a nearly saturated area appears and barely moves, accordingly to the trough behavior. Areas with low relative humidity are seen in the Gulf of Alaska, linked with the unusually high geopotential heights. This zone also has scattered values, which may show different patterns or intensities through the occurrences. Once again the lower data quality inherent to a "B" field should be noted.

The temperature fields, at 850 and 700 hPa (cf. Appendix III.5.i-j) show roughly that the high heights over Alaska are linked with warm advection near there. At the same time, cold temperatures develop over southwest Canada. An interesting pattern exists at 850 hPa at 0 hour: a tongue of high temperature values appears, as if it was the warm sector of a system. The 850 hPa mean anomaly field (cf. Appendix III.5.k) shows the same evolution and the same warm sector over the Southwestern U.S.. The size and the location of this system are very impressive: a large amount of warm advection occurs ahead of the main trough, in part because the low is unusually far southward.

Wind fields show some very large significant areas. Aloft, at 500 hPa (cf. Appendix III.5.l-m), the first significant areas to appear are between the main low and Alaska ridge. Consistent with a dipole block, the zonal wind is unusually weak. Of course, the strong winds are deflected around the block to the north and to the south. The former is seen in the meridional wind field (cf. Appendix III.5.m) over the Bering Sea. For the latter, unusually strong winds are found from Hawaii to the east of California by compiling the unusual areas for the two components. At lower elevations the strong wind flow out of the subtropics intensifies southwest of California and is seen as far as 72 hours in advance, along with the southeast wind on the Bering Sea.
At –36 and –24 hours on Appendix III.5.o a weak significant oscillation appears, upstream of the major one, and underlines the possibility of an approaching trough upstream.

At the surface level (cf. Appendix III.5.p-r) the anti-clockwise rotation of the wind over the Pacific Ocean appears as unusual areas in the zonal component of the wind very early too: strong west wind very far south (between Hawaii and Baja California), and east winds further north (seen as unusually low values of the mean zonal wind). What is more interesting at this level is that some standard deviation maps are significant, and show in fact only areas with scattered values. This can be due to minor differences between the occurrences in a zone where the wind is strong, but it can also be due to a major phase offset between several occurrences.
Whatever are the reasons, it means that to interpret the surface wind requires care: averaging vectors assumes that they are close, one occurrence to another one. Moreover this field is the only wind field in the B data-quality category.

b) Synopsis

After this brief overview of the fields it seems that the occurrences are not enough homogeneous, or at least that strong phase offsets remain.
At the beginning of the event, i.e. at the relative hour 0, the offset between two occurrences can be as large as 12 hours because the data are available only twice a day. That is already important, but the further back in time one goes, the greater may become the offset, due to differences in speed or pattern. That explanation has an important consequence for the composite maps: the mean trough may appear to deepen because the individual troughs for each event become progressively more in phase. However a weak signal has been seen indicating several short waves circulating around the main low.
The criteria for heavy rain should be reformulated, in the purpose to obtain, if possible, a more homogeneous group of situations. To keep a correct number of occurrences the length of the period studied should increase, and the frequency of the data values should be decreased (to 4x per day) to reduce the phase offset.

III.E. Hard Freeze

1. Presentation

a) Occurrences

This event is the one with the lowest number of cases: 11, occurring in only three different months: December, January and February (cf. Appendix II.1.c). Thus all of them have been used for the statistical assessment of both the total and the anomaly fields.

b) Staudenmaier study

He found that the cold advection is basically due to a northerly flow behind a polar front. He noticed two areas of high pressure, one offshore thought due to subsidence and another inland thought due to anticyclogenesis. The circulation of the arctic air mass is from Canada to the upper midwestern U.S. then westwards to California. The temperature at 850 hPa is below 5º Celsius.

2. Analysis

a) Field description[1]

The geopotential heights are very similar from 300 hPa to 700 hPa, and are informative as far as 72 hours in advance (cf. Appendix III.6.a-c). The broader pattern has a huge ridge centered at 140° West, spreading over the Gulf of Alaska, Alaska and Western Canada. This ridge already exists at -72 hours, it then strengthens until -48 hours, and finally its axis rotates from north-northwest to north-northeast during the last two days. The two other significant areas are first a deep sharp trough, with a southwest axis from Central Canada towards California, and second, a ridge over the Southeast U.S. and Sargasso Sea. The evolution of the trough is closely linked to that eastern pacific ridge; both deepen during three days. The ridge near the southeastern USA is pretty consistent at 300 hPa, whilst at 700 hPa it strengthens synchronously with the deepening of the trough.

The trough extending from central Canada towards California comes as no surprise, because the lower heights follow from the cold arctic air directly beneath. This cold air travels over land, without any warming as would occur from crossing over the Pacific Ocean. This landward path was noticed by Staudenmaier, but the scale of this event is huge and appears well in advance. Moreover the significant area near the Southeast U.S. seems very interesting, and may provide a clue to understand and forecast a hard freeze pattern on California.

This pattern near the Southeast does not have such a strong signal in the temperature fields (cf. Appendix III.6.d-f). In fact it is seen only at 500 hPa, as a zone of high temperatures. It appears before any other significant areas, and decreases progressively to disappear at -36 hours. It

[1] Cf. Appendix I.1.b and I.1.c for geographical names

reappears at the beginning of the event (0 hour) at 500 hPa and 850 hPa. The parallel evolution of the ridge and the trough is well shown on these two levels. One interesting thing at 850 hPa is that the values over the Bering Sea are both high and close, showing that the occurrences are very similar in this region.
The pattern over Alaska is thus pretty similar with the one for heavy rain cases, with unusually warm temperature and a large ridge in geopotential. Of course their pattern are quite different offshore of California.

Contrary to the heavy rain cases, the occurrences appear to be well grouped for this event because many maps are significant far in advance and their evolution is not weak but coherent. Thus the analysis of omega fields that are globally significant seems more relevant (cf. Appendix III.6.g-h). In spite of the noise inherent to this kind of map two main patterns appear clearly: the rising over the Bring Sea and western Alaska behind the ridge and a strong subsidence linked to the arctic air advection. It just puts into relief the strength of the trough at every level. There is no signal related to what was noticed over the Southeast U.S..

Other quality class B significant fields are the relative humidity fields (cf. Appendix III.6.i-j). The relative humidity at 300 hPa shows clearly a huge tongue of moisture from Hawaii to Alaska (-60 hours). Then the Alaska region remains unusually damp while a dry area extends from central Canada towards California. The pattern at 850 hPa reveals a dry area on the eastern Gulf of Alaska growing and moving southwest from -60 to 0 hour. Such a dry area is consistent with the sinking (cf. Appendix III.6.g-h) of cold air behind the trough in Southwest Canada. Temperature advections are greater at 850 hPa than at 300 hPa, thus a more interesting field at this level is the specific humidity, invariant with temperatures changes. A quick look at these maps (cf. Appendix III.6.k) shows a clearer meteorological signal, with a wet area over Alaska and a dry one to the southeast, over the western US. It is interesting to notice than a significant area also appears over the Southeast U.S., showing high values during the last 12 hours.

Hard freeze is the only event with numerous tropopause fields globally significant, more precisely the significance of the mean of the tropopause pressure between -96 hours to 0 hour (cf. Appendix III.6.l-m). Firstly the main significant pattern is a large area of high values, i.e. unusually low tropopause, south of Hawaii. Then quickly the Pacific ridge and western North America trough pattern appears, the former with low values, i.e. unusually high tropopause, from central Pacific to Alaska and the latter with high values from Canada southwestwards. The former significant area over the tropical Pacific might be seen as a precursor of the hard freeze event, however it has not been classified this way. The main reason is that this area, though large, is on a weak-gradient zone for that field, which is moreover a noisy field - category "B-". Even with 99% significance the effects of the zone remain uncertain and above all, the slight variation between significance and non-significance cannot be seen during real-time forecasting.

The last field studied is the wind, which underlines what was seen previously and brings a new and interesting view. First of all, the ridge/trough pattern is easily seen at every level, from -60 hours to 0. The meridional component shows unusual southerly winds west of the ridge and unusual northerly winds west of the Canadian trough (cf. Appendix III.6.o,q,s,t), the zonal component shows weak winds to the north and strong west winds south of the Canadian trough.

What occurs over the central USA should be considered with more attention. First, since –84 hours, unusual southwesterly winds are detected. As early as 60 hours in advance, weak winds are detected over the Gulf of Mexico at 500 hPa and above (zonal component). They are linked with a strong anticyclone in the Southeast U.S., curving the wind northeastwards and increasing its speed (zonal and meridional components). This anticyclone remains stable for several days with the same consequences, and starts to be visible at 850 hPa only at -12 hours, showing a great strength at 0 hour on its meridional component, and close values.
Some standard deviation maps are significant (cf. Appendix III.6.u), and show close values in the places we have already mentioned as significant. That result underlines their important role in this event.

b) Synopsis

The hard freeze episodes are more homogeneous than the other cases considered here, all three patterns seen at first in the geopotential height fields are all important for the genesis of a hard freeze event on California. In a nutshell, the development of a huge ridge over the Pacific Ocean creates a deep trough over Northwestern North America having a northeast-southwest axis, from central Canada towards California. This axis orientation and the strength of this trough seem related to the presence of a strong anticyclone over the Gulf of Mexico.
The strength of the Alaskan ridge is surely very important to create a hard freeze event in California, but the strong anticyclone on the southeast part of the USA may, unexpectedly, play a key role as well.

The warm advection over the Bering Sea contributes to the strong ridge over Alaska. This ridge is in the identical location as the feature seen for the heavy rain cases (comparison between Appendix III.5.b with Appendix III.6.b). The big difference is that the heavy rain event has a strong low between Hawaii and California; that low is absent for the hard freeze case. Consequently the 5580 meter contour at 500 hPa is zonally-oriented for the heavy rain event but loops over Alaska for the hard freeze event. So prior to the hard freeze, shorter waves can loop up into Alaska and drop down, "digging" the trough over Southwestern Canada. For the heavy rain case these systems die out or head south and loop around the low off California.

III.F. Heat Wave

1. Presentation

This event is the only one to take place during the summer, and the only one to be defined exactly the same way as Staudenmaier did.
It is also the only one that has been studied from two points of view, considering either its beginning or its end. The second point of view was in fact a way to study the delta breeze, the usual way a heat wave is stopped. The latter is challenging to study, because contrary to its start, the end of a heat wave appears to be something very local. Forecasters have seen only slight differences of geopotential fields between the start or not of the delta breeze.

a) Occurrences

Fifteen dates were found, ranging from June to September (cf. Appendix II.1.d). Of course all have been taken for the study in anomaly fields, but the September date had been avoided for the study with total fields, decreasing the number of occurrences to fourteen.
Here again, the anomaly study is neither more nor less informative, showing that the use of a full forecast field is satisfactory.

b) Staudenmaier's study

He found that the maximum heating occurred when 500 hPa height over Nevada was high and exceeded 5920 meters, the 5880 meter contour encompassing a large area. At 850 hPa a high center is offshore California, with a weak northerly gradient across the state. It is usually stopped when a short-wave trough comes.

2. Analysis: beginning of a heat wave[1]

Once again, the geopotential height fields give a great overview of the situation and its evolution. The first significant maps are at –36 hours. Aloft (cf. Appendix III.7.a-b), a ridge with high values is seen from the central Pacific towards the Bering Sea, and high values are also seen north of the Gulf of Mexico. During the next day and a half, the ridge remains essentially stationary; a zone of high values appears along the US west coast and is linked with one on the southeast coast. Then, at 0 hour, a huge area of high values forms over the west side of North America. Between these two huge and significant ridges a trough with low values deepens, becoming significantly deep at –12 hours, south of a low in the Gulf of Alaska.
The evolution at 850 hPa is also very interesting and slightly different (cf. Appendix III.7.c). A geopotential ridge is based over the central Pacific at -36 hours, with a significant north-axis ridge towards the Bering Sea, and a significant geopotential high is present over the Gulf of Mexico. The ridge over the western Pacific Ocean decreases while another one develops towards California and the Pacific Northwest. A significant trough develops in between, similar to upper levels. Thus an area of high values is created over a large part of North America, with a significant trough to the west.

[1] Cf. Appendix I.1.b and I.1.c for geographical names

As at 300 hPa, the 850 hPa ridge along the west coast seems related to other large-scale features: a ridge in the far western Pacific and high pressures southeast of the USA that move westwards. Moreover wave amplification appears to be the reason of the ridge strength on the west coast of the USA. This phenomenon is even clearer on anomaly fields (cf. Appendix III.7.d): the active centers do not move in sixty hours, but their strength increases, forming a ridge-trough-ridge pattern. The anomaly pattern has little signal in the southeast U.S..

Many temperature fields are significant, mainly near the surface. First, the two upper fields (cf. Appendix III.7.e) are significant only during the last day and show the warm advections associated with the two ridges. What is interesting to notice is that the mean fields do not change that much in 24 hours, but the significant areas do, mainly over the Pacific Coast. Thus the evolution is not as quick as the significant areas show, a non significant pre-conditioning does exist.
The length of the significant period increases to two and half days at 850, on both mean and standard deviation fields. Contrary to the geopotential fields, the thermal ridge from the central Pacific towards the Bering Sea keeps on strengthening, with high values reaching Alaska at –12 hours hPa (cf. Appendix III.7.f). During this time, on the east part of the map, a temperature high moves northwestwards and becomes significant at –12 hours. Due to a strong daily oscillation, these maps can be compared only every 24 hours. In between, cooling has occurred over the Gulf of Alaska.
The values of the thermal ridge over the Pacific are not only high, they are close, too, at 850 hPa (cf. Appendix III.7.g). More precisely, from –72 to –24 hours the values at the base of the ridge and the ones relative to the low over the Gulf of Alaska appear to be significant on the standard deviation map. This result shows that the occurrences are very homogeneous over these regions, because it is rare to obtain unusually high and close values. Therefore, the thermal ridge over the northwestern Pacific appears to be a very standard feature before a heat wave in California.

The surface temperature fields appear to be even more significant (cf. Appendix III.7.h-j), from –96 hours to 0 on the two test statistics, but its poor quality compared to the other fields makes it less reliable. The main pattern is a huge thermal ridge, once again having both close and high values, extending from West of Hawaii towards California. During the same time, warm advection with high values occurs also in the Bering Sea and high values are seen over California at –12 hours.
This pattern is coherent with the geopotential height ridge seen at 850 hPa from Hawaii to California: it is linked with warm advection, and appears to be a consistent pattern through all the occurrences.

The wind fields at 300 hPa just underline what has been seen (cf. Appendix III.7.k): significant areas are more prominent in the meridional wind component and bracket the trough south of Alaska. At 850 hPa (cf. Appendix III.7.l) another detail is very important over California at 0 hour. The wind is unusually weak, due to the weak gradient of the ridge; the grid points closest to Sacramento have weak northeasterly winds, these offshore winds are a well-known property of the heat wave and they block any cooling breeze from off the Ocean.

The last field described is the tropopause pressure (cf. Appendix III.7.m), with both mean and standard deviation showing significant areas. From –72 hours to 0 hour close values appear where we have already noted interesting patterns: southeast of the USA, the Central Pacific and finally California. The low and high value areas that appear at –12 hours and 0 hour show the pattern of ridge-trough-ridge and its strength across the troposphere.

3. ANALYSIS: END OF A HEAT WAVE[1]

For this event the significance assessment has been performed only from 0 hour to –60 hours, because the shortest heat waves studied last only three days.

The pattern in the geopotential height field at 300 hPa (cf. Appendix III.8.a) obviously follows the heat wave pattern studied above, with the two ridges and the middle trough, each of them having significant values. During these two and half days the pattern changes along with the two ridges. The Pacific one reaches a peak at –48 hours then decreases. The ridge inland at –60 hours starts to have an oscillation on its west edge at –36 hours, then moves offshore, along the coastline, and moves northwestwards up to the Bering Sea. This slight shift to the west appears to be a key factor in reaching the end of the heat wave. The apparent shift is partly due to a flattening of the ridge.
The situation at 850 hPa (cf. Appendix III.8.b) reveals the westwards shift of the west coast ridge more clearly. The geopotential ridge over the Bering Sea breaks down and is replaced with a prominent trough. The low in the Gulf of Alaska also seems to merge with the new Bering Sea low. The center of the high at the California coast moves towards the northeast. The flattening of the 300 hPa ridge over the Northwestern U.S. is accompanied by a reduction of the heights over the northern Great Basin and Rockies of the U.S.. The 1540 meter line is quite revealing in this regard. That line moves offshore and shows how heights fall over California and Nevada; the effect is subtle because the heights are still significantly higher than normal.

As expected, the end of a heat wave event is due to the change from a blocked situation to a more zonal one over the Pacific. What is interesting for forecast purposes is how, and how similar through the occurrences. The pattern described above reveals how subtle the changes are, and is reliable because the occurrences are very close on the West Coast of North America (cf. Appendix III.8.c). The very close values on geopotential field cannot be used as values predicting a heat wave, because only slight variations of this field occur above California between –60 and 0 hour. Thus numeric value data may not be able to indicate precisely the end of a heat wave, but changes in the pattern hold some promise.

The sea level pressure field is also very interesting (cf. Appendix III.8.d), and shows higher values around the eastern edge of the Gulf of Alaska. The subtropical high center located near the west coast at -60 hour splits into smaller areas, one forms inland but diminishes while the major one moves northward off Canada's West Coast. The split is partially masked by diurnal variation in this field. The area of lower pressure north of Hawaii at –48 hours expands to the northeast of Hawaii until 0 hour. The pattern over western Canada and USA appears to be very informative because the occurrences are very close over this area (cf. Appendix III.8.e), whereas the one around Hawaii has scattered values.

[1] Cf. Appendix I.1.b and I.1.c for geographical names

The temperature fields also have continuity with the start of a heat wave. However no signal that could indicate the end of a heat wave episode has been found on the mean significance maps (cf. Appendix III.8.f-g) because the temperatures remain high over the region. The standard deviation significance maps (cf. Appendix III.8.h-i) show close values on California during this two and half days period, but again the differences between –24 hours and 0 hour are far from obvious if considering the values.
The wind field (cf. Appendix III.8.j) underlines the ridge migration near the coast, but does not bring any new information. For example, the winds do not become strongly onshore at 850 hPa.

4. SYNOPSIS

The heat wave occurrences appear very homogeneous and allow confidence in the accuracy of the results.
A heat wave episode in Sacramento is in fact a very large-scale event that occurs usually over several southwestern states, and thus its synoptic signature appears clearly. A huge ridge from the central Pacific towards the Bering Sea and high geopotential height above the Gulf of Mexico seem to have a role in building a huge ridge over the west coast. The two of them provide energy, respectively by wave amplification and temperature advection.

As expected, the end of such an episode is very hard to see. A synoptic scale signature does appear to exist, showing a migration of low level high pressure ridge northward along the North American west coast, but the differences between the last day and the previous one are very subtle. Thus the criteria that can be given by the composite maps will probably not be able to forecast the end of a heat wave with enough accuracy.

III.G. Conclusion and prospects

The quality and reliability of the results are very different from one type of event to the other. Roughly speaking, three categories can be drawn.
The first contains only the heavy rain event, and is the category for which the results are noisy due to a non-homogeneous classification of the occurrences. A weak pattern was observed, but it applies only to a subsample of all the occurrences. The first step to improve the results for this event is to redefine its criteria. Even with increasing the period of the study, it is not certain that better homogeneity can be reached because a heavy rain event in Sacramento may have several ways of formation.
The second category includes two events: long fog and end of heat wave. In this case the results, although non-optimal, are more interesting than for the previous category. The occurrences appear to be homogeneous, and their associated mean large-scale pattern is easily seen. However the role played by non-synoptic patterns in these events is very important, and must be taken into account for a precise forecast of such occurrences. Thus the results obtained with the NCEP data give only an overview of these events, emphasizing synoptic features while hiding details that could be important for accurate forecasts.
The third and last category regroups the two last types of events: hard freeze and heat wave. Their common characteristic is to be a large-scale event, i.e. when this type of event occurs in Sacramento area it actually occurs within the majority of the southwest U.S.A. This, along with very homogeneous occurrences, makes obtaining reliable and useful results possible. The synoptic signature is perfectly shown and is enough for accurate forecast guidance.

In addition of the usual forecasting method, these typical patterns can give a very useful forecast guidance. The synoptic situations have been described, and they share some common patterns. First, several severe events in Sacramento seem to be due to a wave amplification that starts over the Pacific Ocean. Second, the pattern in the Gulf of Mexico also conditions the occurrence of heat wave and hard freeze events. An analysis of the energy transfers on the reliable composite maps could be useful to reach a better understanding of the role of these zones.

Finally the results obtained in this study make clear what can be expected from this method and how to improve it. The classification of occurrences is, as said previously, preponderant. Only events with similar occurrences can be studied with success. Moreover they have to be large-scale phenomenon. Under these conditions the results appear very reliable, with huge areas significant at a very high level.
Two ways may improve the quality of the results. The first one is to work with more accurate data, which could be done when the new ECMWF reanalysis will be completed (ERA-40). The second is to increase the period of the study, from twenty to forty years for instance. The number of occurrences will increase accordingly, even with stronger criteria. However the shifts in reanalysis data due to changes in observational systems must be taken into account, and their consequences in a study must be checked.

Conclusion

The initial aim of this study, to give a forecast guidance for significant weather events in the Sacramento area, has been reached. The synoptic method used underlines reliable active zones for the majority of the event types studied. Thus for each type of event a typical pattern, favorable to its development, has been established. These patterns illustrate that the situations over the Bering Sea and the Gulf of Mexico are very often related to a severe weather event happening in California.
In addition of the usual forecasting method, these typical patterns are very useful for forecasters in two ways. First they can be compared to the current model fields if the forecaster has some doubts about what is going to happen. Their second and main advantage is to make anticipation possible. Ideally, the beginnings of a typical pattern would alert the forecaster who would then adapt his interpretation.

The use of this method has given great feedback on its possibilities and limitations. First of all, heavy rain events showed how important it is to reach a good homogeneity between all the occurrences. Once this is done the global synoptic pattern, if it exists, is clearly shown; this pattern is useful for precise forecast guidance only if the local effects are not dominant for the studied event. Consequently, the most interesting results have been obtained for large-scale phenomena with homogeneous occurrences, such as hard freeze or heat wave events.

Finally, using a great number of variables over a large geographical area, working with anomaly and total fields made composite maps more informative than ones in Staudenmaier's original study. Moreover, the different statistical tests made an accurate and reliable analysis of these maps possible, with very significant patterns.

Several possibilities are available to develop further this method that has already great results. One is to use another dataset, more accurate and maybe with an increase of the study period length. The next reanalysis from the ECMWF, ERA-40, seems to be very promising for this purpose. Another potential evolution is to study further the dynamics underlying these severe events.

This study method of significant weather events is very general. It can be used in many different cases, due to a general and accurate statistical approach, as well as to several options, such as the use of anomaly fields. Thus it can be easily applied on other regions of the globe, and for other severe event types.

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Partie française

Cette partie présente un bon aperçu en français de ce document. Sont traduits intégralement la notice analytique, l'introduction et la conclusion. En outre un résumé des trois parties est présenté. Enfin, diverses remarques sur les figures obtenues lors de cette étude sont faites pour permettre une compréhension et une lecture rapides de celles ci.

Notice analytique

Une méthode d'étude de situations météorologiques exceptionnelles est présentée puis appliquée sur la Californie centrale.
Les situations exceptionnelles archivées sont rassemblées en groupes homogènes puis, pour chacun d'entre eux, des cartes de synthèse sont élaborées. Ces cartes sont créées pour diverses variables météorologiques ainsi que pour plusieurs échéances précédant le début des situations à étudier. Des tests de significativité, conduits de manière non-paramétrique en utilisant la méthode de ré-échantillonnage dite du Bootstrap, sont ensuite effectués sur ces cartes pour mettre en évidence de manière objective d'éventuelles zones, qualifiées d'inhabituelles, en rapport avec la situation type étudiée.
L'analyse de ces résultats permet de mieux comprendre comment ces situations exceptionnelles se forment, et par conséquent apporte une aide nouvelle pour leur prévision.
Cette méthode a été appliquée sur la région de Sacramento pour quatre types de situations exceptionnelles : brouillard dense de longue durée, épisode pluvieux intense, vagues de chaleur et de froid.

Introduction

Les situations météorologiques exceptionnelles fascinent autant qu'elles effrayent, et sont un casse-tête pour les prévisionistes. Ce sont à la fois des situations très délicates à prévoir et qui se doivent d'être prévues avec précision pour la sécurité du grand public. Les modèles de prévision météorologique ont fait des progrès considérables durant les vingt dernières années mais de telles conditions restent encore trop souvent mal prévues.
Une approche originale pour essayer d'améliorer la prévision de tels évènements a été effectuée au bureau du National Weather Service à Sacramento (Californie, Etats-Unis). Elle consistait à élaborer des cartes de synthèse pour chaque type de situation exceptionnelle, cartes montrant une situation que l'on pourrait qualifier de moyenne ou de typique. Ainsi un prévisioniste expérimenté pouvait en extraire les principales caractéristiques, notamment celles relatives à leur formation. Toutefois cette première étude ne repose que sur une analyse directe de champs moyens, ce qui peut amener facilement à des conclusions erronées.

Le principal apport de cette présente étude est qu'elle possède une approche statistique inédite et performante, adaptée au faible nombre de cas étudiés. Ceci permet de mettre en évidence de manière objective d'éventuelles zones, qualifiées d'inhabituelles, en rapport avec la situation type étudiée. La confiance que l'on peut apporter aux cartes de synthèse est également évaluée. En outre, le nombre de cartes de synthèse a été considérablement aggrandi, permettant une approche synoptique exhaustive.

Ce document présente dans une première partie l'étude du National Weather Service et les améliorations à lui apporter. Divers aspects statistiques et techniques sont également traités.
La deuxième partie consiste en une description détaillée de la démarche utilisée. En premier lieu le regroupement des occurrences en types homogènes de situations est présenté. C'est une condition nécessaire pour une analyse statistique informative. Ensuite la méthode d'analyse statistique des cartes moyennes est détaillée.
Enfin, la troisième partie expose les résultats obtenus avec cette méthode sur la région de Sacramento pour quatre types de situations météorologiques exceptionnelles : brouillard dense de longue durée, épisode pluvieux intense, vagues de chaleur et de froid.

Résumé

Les différentes situations météorologiques exceptionnelles qui se produisent dans la région de Sacramento (Californie, Etats-Unis) ont été étudiées d'une façon originale par le bureau local du National Weather Service. Différents types de situations ont été définis, et pour chacun d'entre eux des cartes dites de synthèse ont été élaborées. Ces cartes ont été obtenues en moyennant les champs relatifs à toutes les occurrences d'un certain type de situation, et ce pour différentes variables. Ensuite ces cartes ont été analysées par un prévisioniste, qui a expliqué le processus de formation de ces situations exceptionnelles.

La présente étude a repris cette idée de base et l'a largement complétée. Le but final de cette étude est de mieux comprendre le processus de formation de ces situations exceptionnelles afin d'en améliorer la prévision.
Tout d'abord une approche synoptique de ces phénomènes a été décidée, apparaissant comme la plus fiable. Le domaine d'étude a été étendu afin de couvrir toute l'Amérique du Nord et une large partie du Pacifique Nord. Le nombre de variables, initialement de deux, a été porté à seize, réparties sur différents niveaux, de la surface jusqu'à la tropopause. Enfin, afin de bien cerner l'évolution de ces situations, la durée d'étude va de l'apparition des conditions exceptionnelles à Sacramento et remonte plusieurs jours avant cette date. Les données utilisées sont issues du projet de réanalyse conjointe entre le NCEP (National Centers for Environmental Prediction, Etats-Unis) et le NCAR (National Center for Atmospheric Research, Etats-Unis). Ce choix a permis d'étudier une période de vingt ans avec une très bonne qualité de données.

Le plus grand apport de cette nouvelle étude réside dans l'implémentation d'un nouveau volet statistique. En effet l'étude directe de champs moyens est un exercice périlleux, pouvant facilement conduire à des conclusions erronées si l'on ne dispose pas d'informations supplémentaires. Des tests de significativité ont été appliqués aux valeurs en points de grille de chaque carte de synthèse. Une telle valeur, qui est la moyenne de celle de chaque occurrence, est dite significative si elle esr inhabituellement élevée (ou faible), ou si elle est issue de valeurs possédant un écart type inhabituellement faible (ou élevée). Ainsi des zones qualifiées d'inhabituelles sont délimitées sur les cartes de synthèse, permettant une analyse plus poussée et non biaisée. La méthode utilisée pour tester la significativité des valeurs moyennes est celle dite du Bootstrap, méthode non paramétrique de ré-échantillonage.

La démarche suivie pour analyser les situations exceptionnelles est la suivante. Tout d'abord seuls quatre types de situations ont été étudiés : brouillard dense de longue durée, épisode pluvieux intense, vagues de chaleur et de froid. Ces différentes catégories ont été redéfinies pour assurer un nombre suffisant d'occurrences en vingt ans et une bonne homogénéité entre ces dernières.
Ensuite pour chaque type d'évènement et chaque variable les mois correspondant à la saison durant laquelle se produisent les situations de ce type sont selectionnés, sur les vingt années de données. Sont construits à partir des ces données extraites mille échantillons aléatoires, chacun de taille le nombre d'occurrences de ce type d'évènement. A chacun de ces échantillons est

appliqué un test statistique, un calcul de moyenne ou d'écart-type. Ainsi une distribution nulle est obtenue pour chaque test et pour chaque point de grille du domaine étudié.
Le même test statistique est ensuite appliqué pour un "véritable" échantillon, correspondant aux occurrences étudiées et à une certaine échéance avant le début de la situation exceptionnelle. La valeur obtenue en chaque point de grille est alors comparée à la distribution nulle pour savoir si elle est significative ou pas.
Ainsi on peut savoir pour chaque carte de synthèse où sont les zones possédant une valeur moyenne anormalement élevée (ou basse), et dans quelles parties les occurrences ont des valeurs anormalement proches (ou éloignées).

A ce fonctionnement de base plusieurs améliorations ont été ajoutées pour s'assurer d'une qualité optimale. Tout d'abord cette démarche, développée en premier lieu pour les champs de sortie de modèle, a été étendue aux champs d'anomalies, afin d'être certain que la longueur de la "saison" étudiée n'entraine pas des erreurs dans les résultats.
En outre une distribution nulle plus performante a été nécessaire à cause des variables possédant une oscillation quotidienne. En fait deux distributions nulles peuvent être élaborées, une construite uniquement à partir de données correspondant au "jour" (12H) et l'autre uniquement à partir de données correspondant à la "nuit" (00H). La significativité des cartes de synthèse est ainsi testée en conséquence, sans erreur systématique.
La dernière amélioration majeure est un autre test de significativité, relatif cette fois aux cartes de synthèse. Pour chaque carte aléatoire obtenue le test de significativité par point de grille est effectué, puis le nombre de points de grille significatifs est comptabilisé. Ceci forme une distribution nulle relative au nombre total de points de grille significatifs. Cette comptabilisation est également effectuée pour les cartes de synthèse correspondantes, et les valeurs obtenues sont comparées à la distribution nulle pour savoir si elles sont significatives ou non. Il est ainsi possible de savoir quelles sont les cartes de synthèse possédant un signal d'intensité anormalement élevée.

Cette méthode a ensuite été mise en œuvre pour les quatre types de situations exceptionnelles évoquées précédemment.
Les résultats concernant le brouillard dense et de longue durée sont plus intéressants que ce la précision du modèle utilisé aurait pu laisser penser. La situation synoptique typique est une dorsale pré-existante sur la côte ouest de l'Amérique du Nord, qui se renforce beaucoup avec le creusement d'un thalweg stationnaire au large. Cependant il semble que des phénomènes intéressants ne sont pas vus, probablement à cause de la maille peu précise du modèle.

La situation d'épisode pluvieux intense pose certains problèmes. La situation synoptique est un blocage, avec des hautes pressions sur l'Alaska et un thalweg très creusé situé anormalement au sud. Cependant l'analyse plus précise de ces champs apparait hasardeuse. En effet beaucoup de raisons, comme l'évolution temporelle des champs, laissent penser que les différents cas étudiés ne sont pas assez homogènes. Ceci peut être attribué à des décalages entre les différents débuts d'épisodes pluvieux – inévitables avec des cartes disponibles seulement toutes les douze heures-, ou tout simplement au fait que ces épisodes pluvieux peuvent se former de multiples façons.

L'étude des cas de vagues de froid donne des résultats beaucoup plus intéressants, grâce à une excellente homogénéité des cas entre eux. La situation générale est le développement d'une dorsale très puissante à l'ouest des Etats-Unis, qui provoque en aval un thalweg très creusé advectant de l'air depuis le centre du Canada jusqu'au sud-ouest des Etats-Unis. Le plus intéressant et inattendu est la présence d'un fort anticyclone vers le Golfe du Mexique qui semble jouer un rôle important dans le développement de cette situation.

La dernière situation étudiée, celle des vagues de chaleur, s'est faite en deux temps, en s'interessant tout d'abord au début puis à la fin de ce phénomène. L'étude du début a été très informative, avec encore des cas très homogènes. Deux raisons semblent être à la base de l'apparition d'une forte dorsale sur l'ouest des Etats-Unis : une dorsale depuis le Pacifique central jusqu'à la mer de Béring, et des hauts géopotentiels sur le golfe du Mexique. Quant à la fin des vagues de chaleur, un cadre synoptique cohérent et fiable apparait. Cependant il ne renseigne pas précisement sur ce phénomène, où les causes sous synoptiques semblent très importantes.

Conclusion

L'objectif initial de cette étude, apporter une aide à la prévision de situations météorologiques exceptionnelles dans la région de Sacramento, a été atteint. L'approche synoptique menée a permis de mettre en évidence avec fiabilité les centres d'action pour la plupart des évènements exceptionnels. Ainsi, il a pu être défini pour chacun de ces évènements un schéma type, propice à son développement. Il est apparu que ces schémas partageaient des points communs, mettant en évidence que ce qui se passe sur la Mer de Béring ou sur le Golfe du Mexique a souvent un impact sur la Californie.
L'intérêt de ces schémas types pour la prévision est double, et vient en complément de l'approche traditionnelle. Les prévisionistes peuvent les utiliser en cas d'hésitation, en les comparant avec les champs du modèle. Leur principal intérêt reste cependant l'anticipation. Les prémices d'un schéma typique conduisant à une situation exceptionnelle doivent alerter le prévisioniste, ce qui le conduira à une analyse plus orientée.
L'application de cette méthode a également permis de mieux cerner ses possibilités et ses limites. Tout d'abord l'étude des épisodes pluvieux intenses a montré le besoin d'homogénéité entre les différentes occurrences. A partir de là le cadre synoptique commun, si existant, apparait clairement, mais ne permet pas toujours d'apporter une aide précise à la prévision si des effets locaux sont prépondérants pour le phénomène étudié. Par conséquent les résultats les plus utiles ont été obtenus pour les phénomènes de grande échelle et possédant des occurrences très homogènes, comme les vagues de froid ou de chaleur.

Finalement, l'utilisation d'un grand nombre de variables sur un domaine étendu, de champs d'anomalies et de champs classiques de prévision a permis d'obtenir des cartes de synthèse plus informatives que lors de l'étude initiale par Staudenmaier. En outre l'ensemble des tests statistiques a conduit à une analyse précise et digne de confiance de ces cartes, où de vastes zones sont très significatives.
Ces résultats déjà très satisfaisants pourront être complétés par les nombreuses possibilités de développement de cette méthode. La première d'entre elles est l'utilisation d'un autre jeu de données, plus précis et peut-être sur une plus longue période. La future réanalyse du ECMWF semble de ce point de vue prometteuse. Une autre possibilité est une étude plus poussée concernant la dynamique de ces situations exceptionnelles.
Cette méthode d'étude de situations météorologiques exceptionnelles est générale, et peut être appliquée à une multitude de cas différents grâce à une partie statistique poussée et générale, et à différentes options possibles comme l'utilisation de champs d'anomalies. Par conséquent elle peut être facilement mise en oeuvre sur d'autres régions du globe, et pour d'autres situations exceptionnelles.

Remarques sur les figures obtenues

Les cartes de synthèse et les cartes de significativité les plus intéressantes obtenues lors de cette étude sont présentées de l'annexe III.4 jusqu'à l'annexe III.8..
Un exemple de figure typique est présenté sur la figure III.2 : sur la carte de synthèse ont été superposées les zones significatives relatives à un test. En haut à gauche sont indiqués le niveau (500 hPa) et l'heure relative au début de l'évènement (0 heure). En haut à droite est présenté le type de situation exceptionnelle (heavy rain, pluie intense). En bas au milieu figure le nom des zones colorés (hgt_signi_mean, zones de géopotentiel significatives par rapport à leur moyenne), et à gauche le nom du champ en contours (géopotentiel).
Deux exceptions sont à noter : les champs d'humidité sont inversés, c'est à dire que les zones colorées correspondent au champ moyen et les zones significatives sont en contours ; les champs de vent ont comme champ moyen le vent total et comme zones significatives celles relatives à une seule de leur composante (méridionale ou zonale).

Les zones jaunes indiquent des valeurs significativement élevées, et les zones bleues des valeurs significativement faibles, que ce soit pour la moyenne ou l'écart type. Par exemple, sur la figure III.2, on note des hauteurs de géopotentiel anormalement hautes sur l'Alaska et anormalement basses sur le Pacifique.
Quelques autres exemples typiques sont présentés en annexe III.3, avec en outre une comparaison entre les cartes en couleur avec celles en noir et blanc.

La liste exhaustive des noms courts de variable utilisés (comme hgt pour hauteur de géopotentiel) sont dans le tableau I.2. Le test utilisé en plus de la moyenne (mean) est un écart type lissé (sds). Il est à noter que dans les deux cas le champ de référence est toujours le champ moyen.

<u>Remarque complémentaire :</u>

Un CD-Rom est joint à ce document. Il permet de consulter la version originale du tome des annexes, tout en couleur, et celle de ce document. De plus il contient l'ensemble de toutes les figures significatives, et les fichiers NetCDF de résultats. Les codes source des programmes et les exécutables sont également disponibles.

APPENDICES