AN INVESTIGATION OF THE BEHAVIOR OF THE MASS OF THE ATMOSPHERE OVER A CENTURY

by

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ABSTRACT

The behavior of the mass of the atmosphere from 1890 to 1990 is inferred from this investigation of the perturbation of the total mass of the atmosphere (m'). Global monthly mean station pressure measurements (raw and converted from sea level pressure measurements) from the National Center for Atmospheric Research (NCAR) are converted to perturbation in station pressure (p') then m'. An analysis of the behavior of the perturbation of the total mass of the atmosphere over a century shows that it is decreasing. It oscillates with an average period of 12.57 years. The behavior of p' is the same. The existence and frequency of the maxima and minima of m' point to a twelve year cycle in the total mass of the atmosphere.

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Introduction

For years, meteorologists have been interested in the total mass of the atmosphere and its behavior. A key indicator of how the total mass of the atmosphere behaves is the behavior of the perturbation of the total mass of the atmosphere. The purpose of this thesis is to investigate the behavior of the total mass of the atmosphere by looking at it perturbation (m') over a century.

During the 1980's there was a thorough estimate of these quantities and the discovery of an annual cycle due to variations in water vapor. The total mass, itself, may be derived from global atmospheric pressure analyses. Its fluctuations globally, hemispherically, or regionally signify redistribution of atmospheric mass on the same scales and are vital indicators of flow anomalies, atmospheric forcing, or large scale barotropic modes.

Mascart (1892) was the first to estimate the total mass of the atmosphere. Since then at least fifteen others have done the same using assumptions and approximations different from each other and from Mascart. Because of this, their results differed; leaving their validity in doubt. In 1981, Trenberth performed the most thorough estimate and analysis of the total mass of the atmosphere, with few assumptions or approximations. He also verified that there is an annual cycle, which led to further examinations of total mass fluctuation and what this meant for mass fluxes and redistribution all over the globe.

In Trenberth's and subsequent studies, changes in water vapor consistently appear as the primary factor accounting for the annual cycle of the atmospheric mass. That part of the atmosphere which is not water vapor, the dry atmosphere, stays relatively constant. Volcanic outgassing, the release of gases by humans, and losses to space prove to be negligible effects on the total mass of the atmosphere in comparison.

Either sea level pressure exclusively or in tandem with station pressure has been used to estimate atmospheric mass, and this has been done mostly on time scales of a few years (less than one decade). This study investigates the behavior of the perturbation of the total mass of the atmosphere over one hundred years using station pressure only (either raw or converted from sea level pressure). Variations in atmospheric mass on this time scale may denote longer term climate fluctuations that produce variations of water vapor.

In the next section of this thesis, the Literature Review, details of past investigations and conclusions about atmospheric mass and its redistribution will be discussed. Next, the Data section will describe the data used for this research and the calculations and procedures involved in examining station pressure. The Computation of the Perturbation of Total Mass (m') portion will explain the equation used for the conversion of station pressure to mass. The analysis and discussion of the final results will be addressed in the part entitled Results. This will be followed by Concluding Remarks, References and Acknowledgments.

Literature Review

In this section, previous work on the total mass of the atmosphere will be discussed. As stated in the introduction, Mascart (1892) is on record as making the first attempt to calculate the total mass of the atmosphere, and subsequent scientists tried to do the same thing. Trenberth (1981) provides what is perhaps the most comprehensive analysis of the behavior of the total atmospheric mass. He performed a thorough investigation and intercomparison of the estimations and calculations of total atmospheric mass by scientists that preceded him. He noted the different assumptions that were made, then presented a recalculation of the total mass of the atmosphere using a minimum number of assumptions and approximations. At the same time he analyzed the behavior of the total mass, sea level pressure (SLP), and surface pressure, and the pressure attributed to water vapor.

The data he used were twenty years (1957 to 1978) of seasonal mean SLP from the US Navy, six years (1972 to 1978) of monthly mean SLP from Australia's World Meteorological Center (WMC), Crutcher and Meserve's (1971) long term northern hemispheric (NH) mean SLP, geopotential heights, temperatures, and dew point temperatures, long term southern hemispheric (SH) data from Taljaardetal (1969), Oort and Rasmusson's (1971) mean specific humidities, and mean geometric heights of topography from the Scripps Institute of Oceanography.

Using this data, the total mass of the atmosphere was reestimated to be 5.137×10^{18} kilograms (kg); 2.564×10^{18} kg and

2.574×10^{18} kg in the NH and SH, respectively. Total mass had an annual cycle of amplitude 1.1×10^{15} kg. When the total atmosphere was separated into its dry component and water vapor, the total dry atmospheric mass was conserved to within 0.2×10^{15} kg, and the total mass of water vapor was 13×10^{15} kg and had an annual cycle with a range of 1.0×10^{15} kg. Therefore, water vapor constituted virtually all of the change in the mass of the entire atmosphere.

There was an annual cycle in global surface pressure with a range of 0.5 millibars (mb). Regionally, maxima in surface pressure occurred at 22°N and 20°S. Its annual cycle in the SH subtropics was greater than that in any other area.

A strong annual cycle of SLP was evident. SLP maxima occur between 40°S and 60°S during the fall and spring and over Antarctica in January and July. The cycle was antisymmetric about 5°N and had a peak in the subtropics (28°N and 24°S). An annual cycle also dominated the region north of 60°N, and semiannual cycles dominated the region south of 40°S.

The cycles in pressure were representative of a seasonal redistribution of mass. The interhemispheric flow of mass was estimated to be 4.0×10^{15} kg.

Trenberth and Christy (1985) and Christy and Trenberth (1985) researched mass redistribution. In the first paper they did an intercomparison of two different datasets then studied the different modes of fluctuation of atmospheric mass using empirical orthogonal functions (EOF's) calculated from both datasets.

One set of data came from the National Meteorological Center (NMC), and the other came from Australia and the US Navy

(AUSNAV). They overlapped from 1977 to 1982, and during this period they were compared. The NMC set had 2.5° gridded SLP from pole to pole, and the AUSNAV set had 5° gridded surface pressure values from 0°N to 90°N and 10°s to 90°S.

Problems arose in the NMC set when dry air was not conserved, despite the presence of a mean annual cycle in surface pressure that was attributed to water vapor only. Also there were sharp declines and increases due to the installation of new algorithms and models within the dataset.

In comparing the NMC and AUSNAV datasets, similarities were found occasionally in the annual cycles of SLP in the NH. In general, however, differences appeared in the annual cycles and in the zonal monthly means of SLP in both hemispheres. Greater differences appeared in the SH, and were attributed to underestimations in the NMC's analysis of SH cyclonic storms and the abnormally strong highs and lows during 1979.

A study of the AUSNAV set indicated that mass was being redistributed. A negative correlation existed between the seasonal mean SLP values of the NH and SH. Compensation of mass was within each hemisphere. In the NH, mass compensation occurred between 30°N and 50°N. In the SH, mass compensation was between the belts of 30°S to 50°S and 60°S to 80°S.

The detailed EOF analyses revealed and verified in detail the kind of mass redistribution that was happening. From the modes shown by the EOF's, interhemispheric and intrahemispheric exchanges of mass were identified. Specifically 1) there was an exchange of atmospheric mass within each hemisphere, 2) there was an exchange of mass between the extratropics of each hemisphere, and 3) there was a symmetric mode of mass exchange between the tropics and extratropics.

The first two EOF's, EOF1 and EOF2, explained a majority of this activity (41.3% and 24.4%, respectively). EOF1 displayed the intrahemispheric exchanges of mass. The EOF2 analyses revealed the global scale modes of mass redistribution. The EOF3 analysis of the NMC set and the EOF4 analysis of the AUSNAV set revealed a mode in which the extratropics of the NH and SH are in phase with the tropics and subtropics. The EOF3 and EOF4 analyses of the AUSNAV and NMC sets, respectively, revealed an intrahemispheric "seesaw" relation between the atmospheric mass at high latitudes and the middle latitudes.

Interannual variability was observed in SLP and surface pressure, and water vapor was identified again as the substantial constituent involved. El Niño Southern Oscillation (ENSO) was found to be a significant contributor to the variation of water vapor, thus contributing to the fluctuation of pressure. Outside the tropics, ENSO had little impact. However, in the tropics warm sea surface temperatures caused a surface pressure increase of 0.2 mb. The SO (Southern Oscillation) was associated with huge anomalies in diabatic heating that were seen by shifts in mass convergence zones. The SO was also responsible for major east west mass redistribution in the tropics and subtropics.

In Christy and Trenberth's (1985) second collaboration, the association of a significant global redistribution of atmospheric mass with the mean annual cycle of atmospheric mass was pointed out again. Fifty-six years of 5° gridded NH SLP measurements and 11.25 years of 5° gridded SH SLP values were analyzed hemispherically, zonally, and seasonally. These data covered an area spanning 17.5° to 90° in each hemisphere.

From an initial plot of SLP alone, high pressure belts were found in the subtropics and low pressure belts were observed near 60°N to 65°N and 60°S to 70°S. Also, the NH mean SLP was 1014.71 mb and the SH mean SLP was 1007.05 mb. SLP from each hemisphere had an annual cycle. The NH and SH annual cycle of SLP had ranges of 4.9 mb and 2.1 mb, respectively (1 mb = 1.82×10^{15} kg). The deepest minimum occurred in the early 1940's and the highest maxima happened in the late 1940's and early 1970's. Seasonally, the variability of the mean SLP was most pronounced in winter and least pronounced in spring in each hemisphere.

Reasons for the hemispheric variability of the SLP were deduced when the zonal mean SLP was converted to mass and the zonal variations of mass were examined. The minimum in the NH mean SLP in the early 1940's was the result of negative anomalies in the 30°N to 50°N belt and near 80°N. The NH mean SLP maximum in the early 1970's resulted from anomalies in the 35°N to 50°N latitudinal region.

Smoothed time series of anomalies in the seasonal mean zonal atmospheric mass showed evidence for compensation in mass fluctuations in the NH. As one latitudinal region acquired positive anomalies, another latitudinal region developed negative anomalies. Negative correlations like these were present in the NH and moved northward in the spring and southward in the fall.

EOF analyses of the zonal mean SLP values were performed to explain the variances of zonal mean SLP and confirm the deductions of why SLP varies and to observe the compensation of mass fluctuations. EOF1 explained the most and its general feature was the exchange of mass between the 30°N to 50°N latitudinal belt and zones north of 65°N. EOF1 shows interacting zones migrating to the north until August, then moving back to the south. EOF1 was called "the mode that indicates a compensation in the hemispheric mass profile." In the SH, this compensatory behavior was seen in the negative correlation between the 35°S to 50°S and 65°S to 80°S latitudinal regions.

EOF3 described any enhanced or reduced mean features in the hemispheric total mass balance since it resembled the overall zonal mean SLP profile. EOF analyses were grouped by season in order to observe the shifting of correlated latitudinal regions either poleward or equatorward.

Trenberth, Christy, and Olson (1987) performed an analysis of global atmospheric mass, surface pressure and water vapor variations. Total atmospheric mass had an annual cycle, and water vapor was entirely responsible for the changes in total mass.

The global data covered seven years (1978 to 1985) and were obtained from the World Meteorological Organization (WMO) and the Global Weather Experiment (GWE). The analyses of the data were from the European Center for Medium Range Weather Forecasts (ECMWF).

The highest values of the zonal mean surface pressure were in the 26°S to 52°S belt and the lowest ones occurred near 35°N in coincidence with the location of the Himalayas. Maximum annual mean values of zonal mean pressure related to water vapor were found at the equator. This value decreased towards higher latitudes, and at almost all latitudes the SH values were lower than the NH ones. The values of surface pressure were different from those used by Trenberth in 1981 so the total mass of the atmosphere was reestimated to be 5.1361 x 10^{18} kg. The mass of water vapor was estimated to be 1.46 x 10^{16} kg. The total mass had an annual cycle that was due to water vapor. Its amplitude was 1.0 x 10^{15} kg. The maximum and minimum in total atmospheric mass were 5.1371 x 10^{18} kg and 5.1355 x 10^{18} kg, respectively.

In a subsequent project by Christy, Trenberth, and Anderson (1989) another analysis of the redistribution of atmospheric mass was performed. This time, the data came from NMC and ECMWF and covered a different time period and used a different grid. But the same type of EOF analyses were used and similar observations of interhemispheric and intrahemispheric mass redistribution were discussed. A more complex EOF analysis (CEOF) was performed, which allowed for the observation of the propagation and development of mass field anomalies.

Most recently, Trenberth and Guillemot (1994) investigated the total mass and surface pressure of the atmosphere using analyzed data from ECMWF (1985-1993). The conclusions were similar to those from the early 1980's. The mean annual mass and pressure were 984.76 mb and 5.1441 x 10^{18} kg, respectively. The range of the total mass was 1.93 x 10^{15} kg and was due, again, to the changes in water vapor. Due to variations in instrumentation and the analysis system used to obtain the data, trends in the dry and moist air masses were spurious and caused problems. Separate computations found that the mean mass of water vapor was 1.25 x 10^{16} kg. El Niño was a possible factor in the cycle of the total mass again. The hemispheres, again, compensated for one another's changes in the atmospheric mass.

Data

The data for the present study are from several sources made available by the National Center for Atmospheric Research (NCAR). NCAR compiled "world monthly surface station climatological data" from the National Climatic Data Center (NCDC), the Harvard College Observatory, Florida State University, the US Weather Bureau, the Smithsonian Institution, the Environmental Data and Informational Services and itself. They are from stations all over the earth that have continuously measured station pressure or sea level pressure (SLP). There are 137 stations in total. 111 of them are in the northern hemisphere (NH). 26 are located in the southern hemisphere (SH).

The average starting year and average ending year period of record (POR) for the stations are 1887 and 1992, respectively. The average length of the their POR is 104 years. The average length of any gaps within each station's POR is nine and a half years. When a gap appeared within a station's POR, that station is ignored only during the length of the gap.

Three fourths of the data consist of raw, global monthly mean station pressure observations. The data in the remaining fourth are raw, global monthly mean SLP values. We used SLP data from those stations only with an elevation less than 300 meters (m). For these data, the SLP measurements are hydrostatically converted to station pressure measurements, such that:

$$p_{sta} = \exp\left[\ln(p_{slp}) + z * g(\phi)/(R * T)\right] \tag{1}$$

where p_{stn} is station pressure, p_{slp} is sea level pressure, z is station elevation, $g(\phi)$ is the gravitational acceleration, ϕ is latitude, R is the gas constant, and T is temperature. Once all the data are expressed as monthly mean station pressure, they are broken up into four year intervals and then averaged over four years to filter noise and high frequency fluctuations.

It is important that the elevation of a station remains constant so as not to bias the record. Eight percent of the stations were relocated during the period of record. For those stations the station pressure is adjusted to its equivalent value at the elevation present during the majority of the POR. Provided the change in elevation was less than 300 m, this calculation is also based on the hydrostatic equation, as follows

$$p_{new} = \exp\left[\ln(p_{old}) - (z_{maj} - z_{old}) * g(\phi)/(R * T)\right] \qquad (2)$$

where p_{new} is the station, p_{old} is the station pressure at the old elevation, zmaj is the station elevation that appears for the majority of the POR for a given stations, $g(\phi)$ is the gravitational acceleration, ϕ is latitude, R is the gas constant, and T is temperature.

Computation of the Perturbation of Total Mass (m')

To get a cursory indication of how the total mass of the atmosphere behaves over a century, linear regressions of the four year averages of the perturbation of station pressure (p'_{sta}) and the perturbation of mass (m'_{sta}) are performed for each station. The perturbations in each case are defined as differences from the time-mean values. This minimizes the effects of data gaps in some of the records. An analysis of the slopes of the linear regressions of these two quantities for each station suggests that there is a general decrease in m' over a hundred years. Histograms of the slopes (Figures 1 and 2) reveal that a majority of the stations' slopes are either zero or negative.

Using four year averaged station pressure measurements, the perturbation of the mass of the total atmosphere per area of earth is calculated. First the perturbation of station pressure (p') is calculated. The mean station pressure (p_{bar}) of each station, n, is computed using the formula

$$pbar_n = \sum_i psta_i/I \qquad (4)$$

where i is the number of measurement associated with p_{sta}, p_{sta} is an individual station pressure measurement, and I is the total number of measurements during each station's POR. Then the pbar for each station is subtracted from each monthly station pressure measurement (p_{sta_i}) to get the associated station pressure perturbation (p'_{sta})

$$p'_{sta_i} = p_{sta_i} - p_{bar_n} \tag{5}$$

Using the formulae from Trenberth (1981) the perturbation of mass (m'_{sta}) associated with every station pressure measurement is calculated as follows:

$$m'_{sta_i} = p_{sta_i}(\phi) * [1 - 2 * \alpha * \sin^2(\phi)]/g(\phi) \tag{6}$$

where m'_{sta} is the perturbation of mass and p'_{sta} is the perturbation in station pressure,

$$\alpha = (a^2 - b^2)/(2 * a^2) = 0.00336 \tag{7}$$

where a is the equatorial radius (6378388 m) and b is the polar radius (6356912 m), ϕ is latitude, and

$$g(\phi) = 9.80616 * [1 - 0.0026373 * \cos(2*\phi) + 5.9 \times 10^{-6} * \cos^2(2*\phi)] \tag{8}$$

This expression is used to correct for the effect gravity has on the column of mercury in a barometer (Trenberth, 1981).

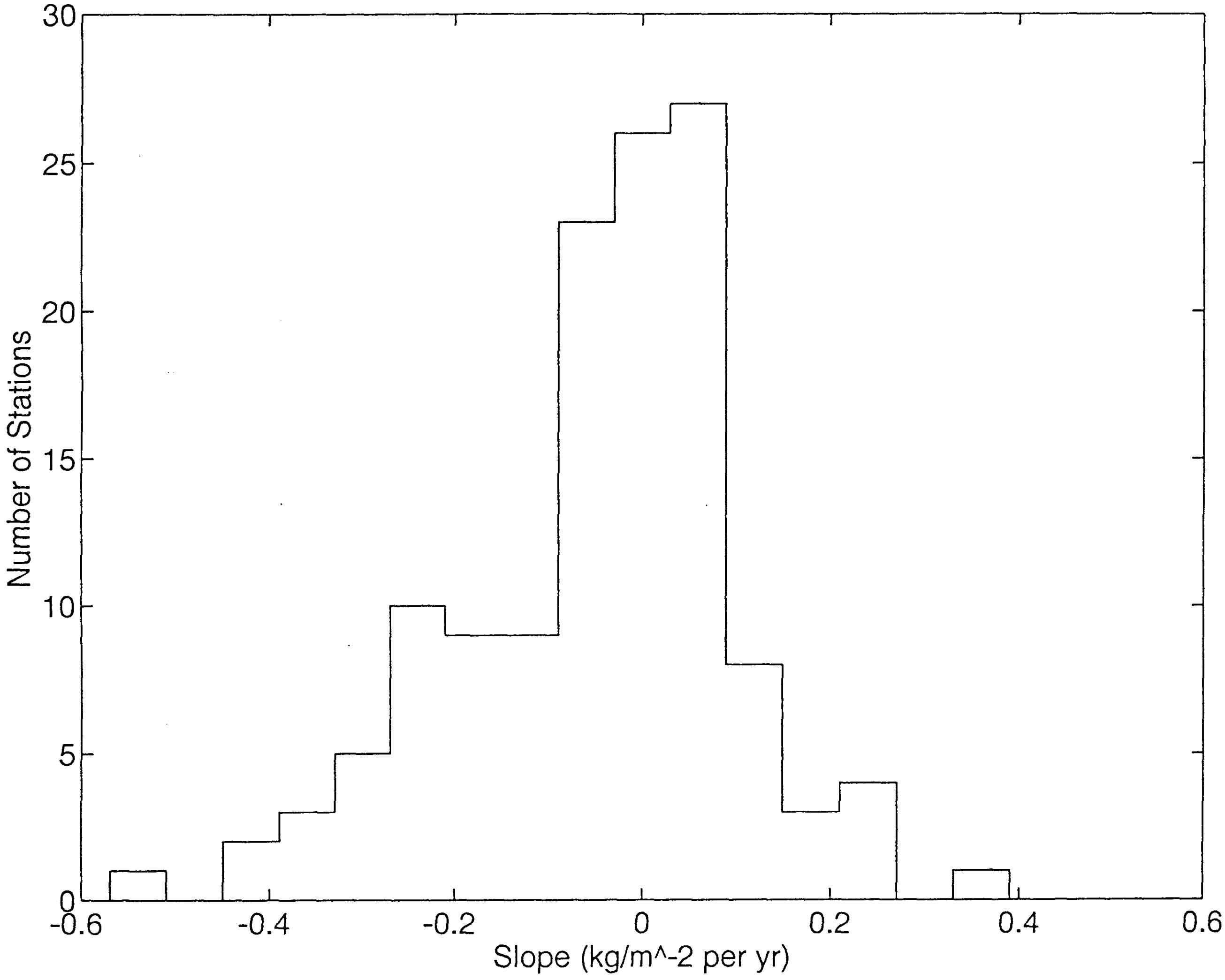
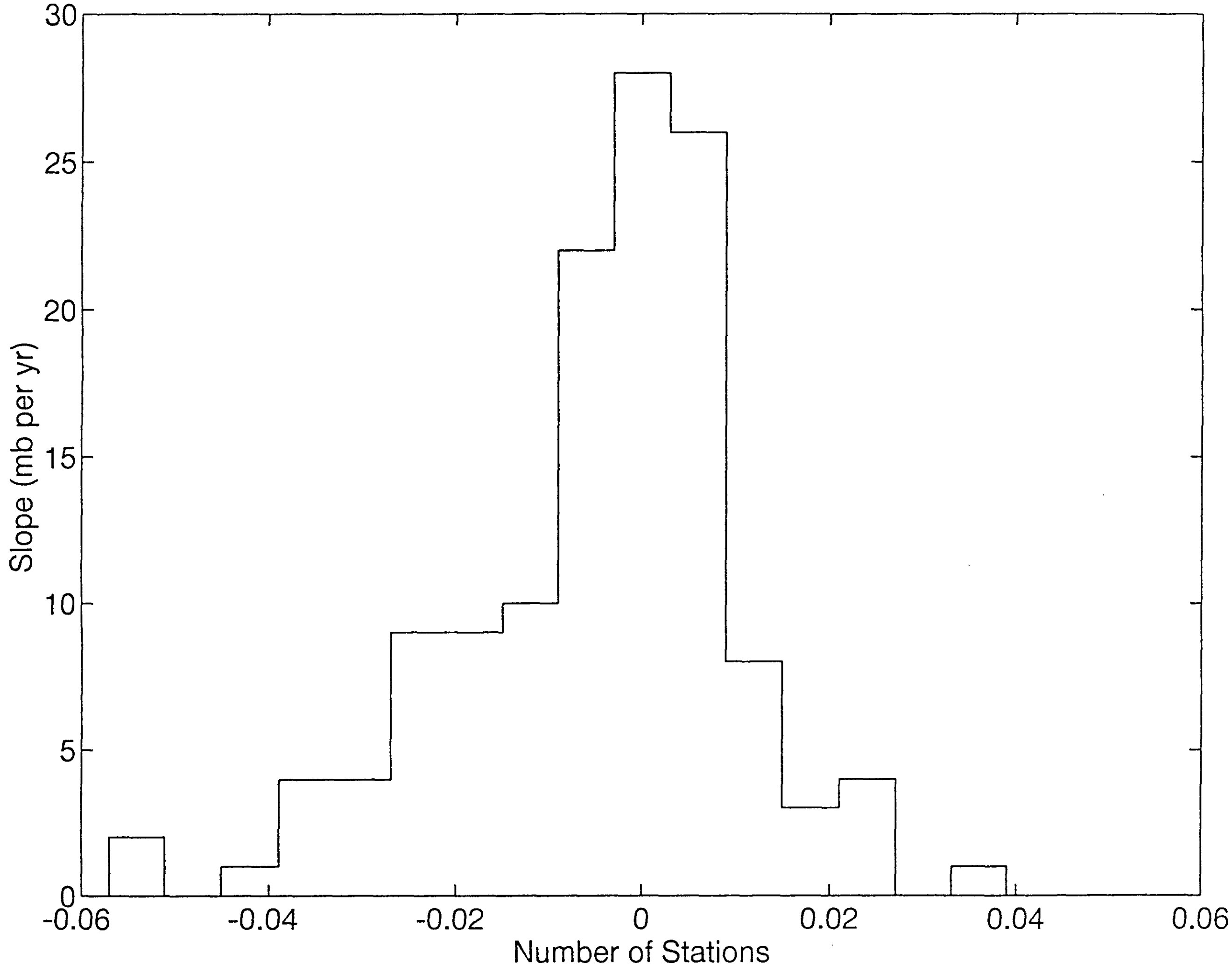


Figure 1. Stations and Slopes of Their m Linear Regressions

Figure 2. Stations and Slopes of Their p prime Linear Regressions



Results

The results of the computation of the perturbation of the total mass (m') of the atmosphere from four year averaged station pressure observations can be seen in Figure 3 and Table 1. Over the course of a century (1890 to 1990), the total mass of the atmosphere has, on average, a twelve and a half year cycle. The average range in the perturbation is 2.1469 kilograms (kg) of atmosphere per square meter of earth (m^{-2}). Its average peak is 1.0297 kg m-2 and its average low is -8.2539×10^{-1} kg m^{-2}. Extrema in the perturbation occur every 12.57 years. A linear regression of the data shows a general decrease in m'. This decline is in agreement with the histograms (Figs. 1 & 2), which show that a majority of the stations had negative slopes in their linear regression analyses of m'_{sta} and p'_{sta}. The mean slope of the regressions of m'_{sta} is -6.4276×10^{-2} kg m^{-2} per year. The mean perturbation of the total mass of the atmosphere over one hundred years is -4.4198×10^{-3} kg m^{-2}.

A look at the behavior of the station pressure (p') reveals the exact same cycle and trend (see Figure 4 and Table 2). It, too, has on average a twelve and a half year cycle, and its linear regression also shows a general decrease with time of -6.7925×10^{-3} millibars (mb) per year. This trend is also evident in the histogram of the stations with the slopes of their p'_{sta} linear regressions. The mean slope of these regressions is -6.1816×10^{-3} mb per year. The mean p' change over a hundred years is -9.2247×10^{-4} mb. The average range of p' is 2.1146×10^{-1} mb and its average maximum and minimum are 2.3713×10^{-1} mb and -8.1331×10^{-2} mb, respectively. The Maxima and minima of station pressure take place every 12.57 and eleven and a half years, on average.

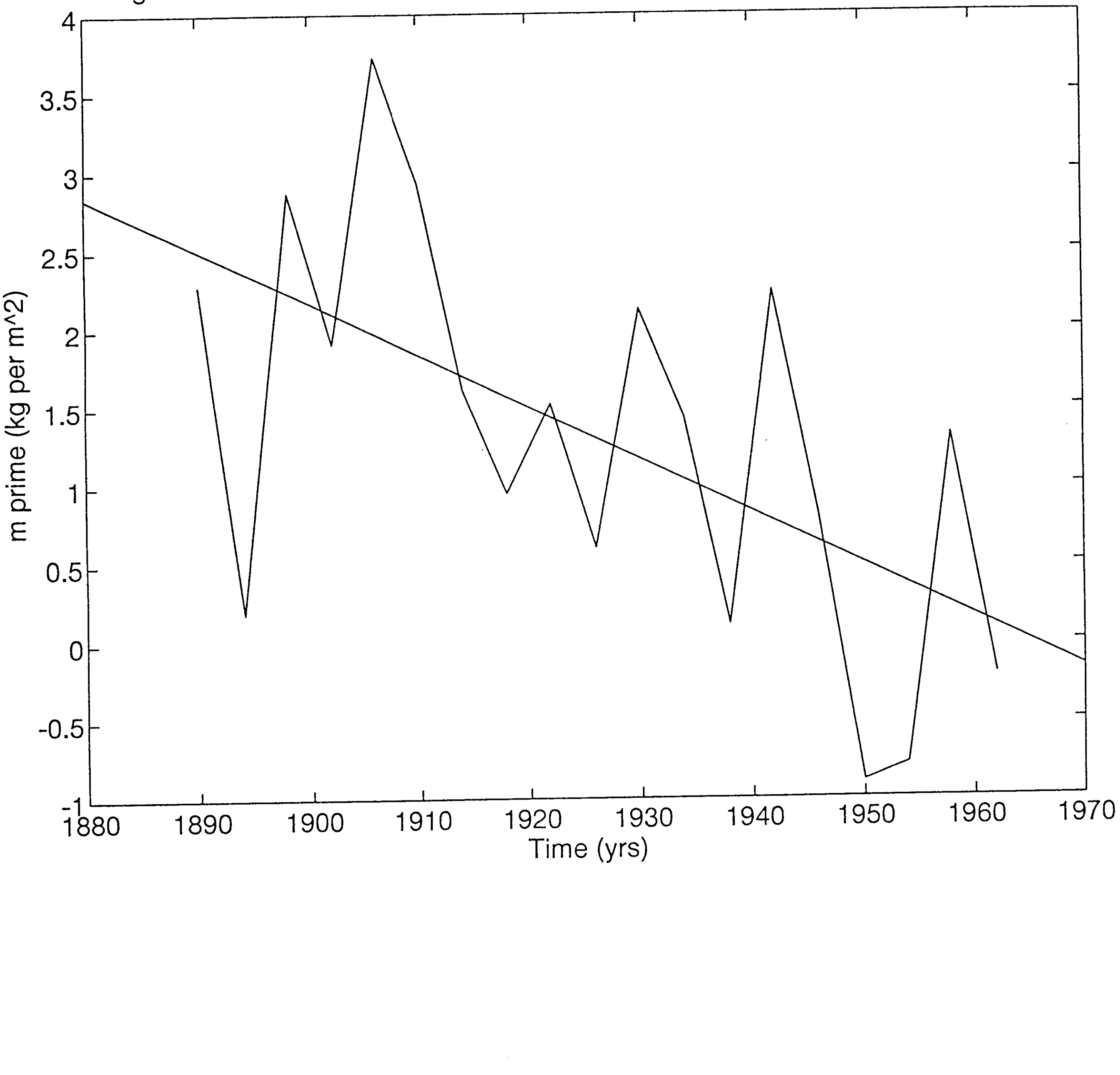


Figure 3. Behavior of the Perturbation of the Total Mass of the Atmosphere (m')

Table 1. Values of m' from 1890 to 1990

Year Averaged Around	**m' (kgm^{-2})**
1890	2.4194
1894	0.24801
1898	2.8308
1902	1.9331
1906	3.7208
1910	2.8998
1914	1.6644
1918	0.97254
1922	1.4992
1926	0.60887
1930	2.1106
1934	1.4300
1938	9.9157×10^{-2}
1942	2.2771
1946	0.82091
1950	-0.89695
1954	-0.76677
1958	1.3216
1962	-0.21242
1966	-2.0832
1970	-3.1276
1974	-5.8295
1978	-3.2484
1982	-3.7383
1986	-2.2742
1990	-4.7939

Figure 4. Behavior of the Perturbation of the Total Station Pressure of the Atmosphere (p')

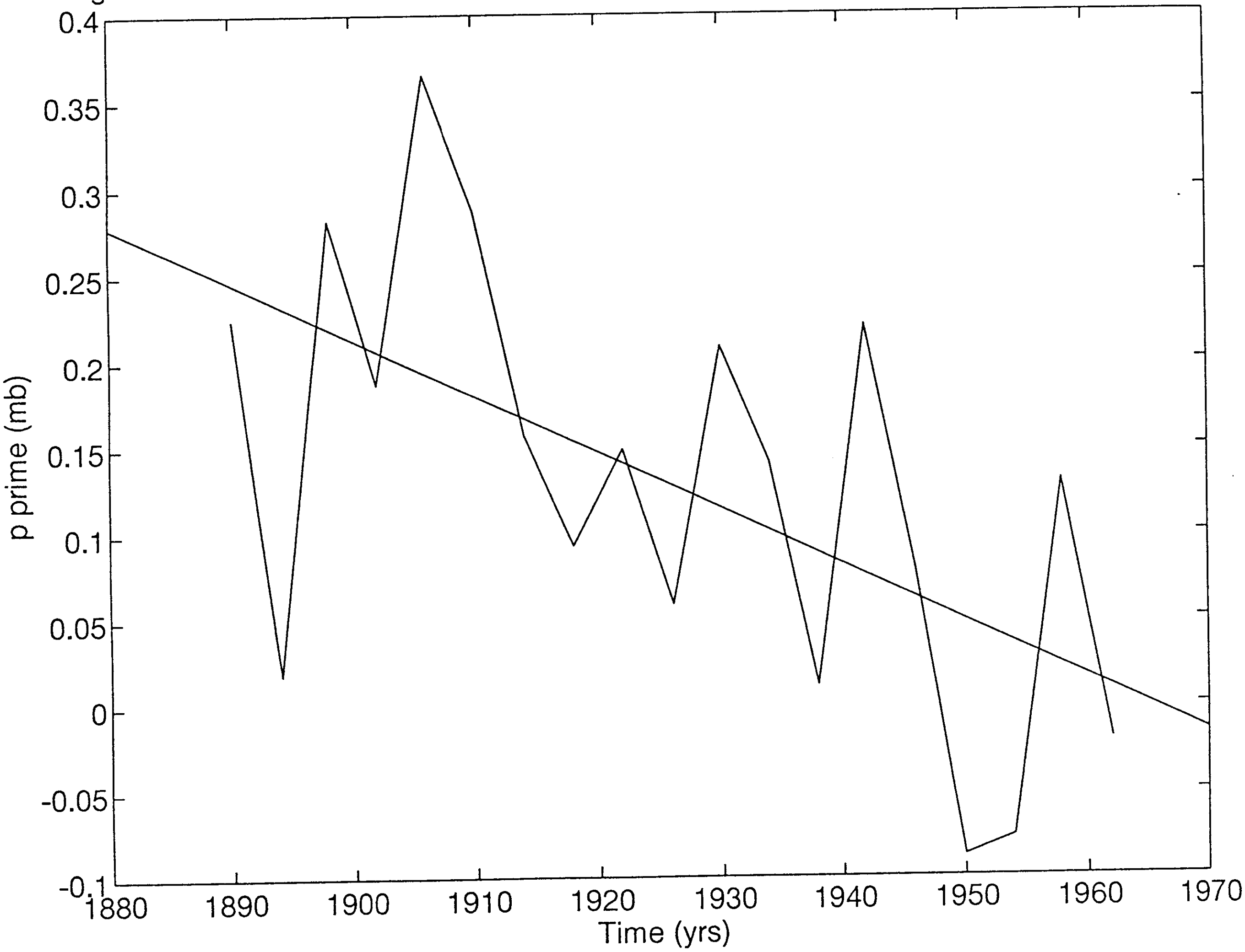


Table 2. Values of p' from 1890 to 1990

Year Averaged Around	p' (mb)
1890	2.2497×10^{-1}
1894	1.8718×10^{-2}
1898	2.8238×10^{-1}
1902	1.8730×10^{-1}
1906	3.6580×10^{-1}
1910	2.8758×10^{-1}
1914	1.5753×10^{-1}
1918	9.3356×10^{-2}
1922	1.4901×10^{-1}
1926	5.8880×10^{-2}
1930	2.0845×10^{-1}
1934	1.4132×10^{-1}
1938	1.1293×10^{-2}
1942	2.2026×10^{-1}
1946	8.0042×10^{-2}
1950	-8.7998×10^{-2}
1954	-7.6669×10^{-2}
1958	1.3002×10^{-1}
1962	-2.0425×10^{-2}
1966	-2.0460×10^{-1}
1970	-3.0649×10^{-1}
1974	-5.6728×10^{-1}
1978	-3.1876×10^{-1}
1982	-3.6492×10^{-1}
1986	-2.2236×10^{-1}
1990	-4.7140×10^{-1}

Concluding Remarks

An analysis of the behavior of the total mass of the atmosphere over a century has shown that it is decreasing. Its maxima and minima separately occur on average every 12.57 years. The behavior of p' is the same. Although the mass calculation has not yet taken into account an appropriate area weighting, the fact that the majority of stations show decreasing pressure over a century suggests that the water vapor content of the atmosphere is not increasing and may be decreasing. This is inconsistent with other measures of global change that indicate increasing global temperature.

Geographically, most of the stations are in the northern hemisphere and many were grouped in industrial countries. Only a few represent remote oceanic areas or developing countries. Future investigations, in which data will be weighted according to station location, may improve the final results of m'. Higher time resolution, where measurements are weekly, daily, 12, 6, 9, 3-hourly, or hourly may be used to further analyze the cycle of m' to see if it is more than or less than 12 years.

Greater time resolution would also allow a study of the impact of the El Niño Southern Oscillation (ENSO), the cycle of which is four to seven years. There are collections of data that contain hourly or three hourly records of pressure, from which the mass of the atmosphere can be derived. However, their POR's were too short or there were gaps present that were too large for a study of behavior over one hundred years. Their POR's may be long enough to examine whether the signature of ENSO exists.

Just as there have been subsequent investigations of the redistribution of mass on an annual and intraseasonal basis, it should be possible to investigate the decadal or longer period behavior of this and other phenomena, such as storm track creation, development, and variation.

For many of the stations contained in the dataset for this study, there were sharp rises and declines in station pressure over short time intervals. Many of these occurred in 1961 and were accompanied by unexplained changes in station elevation, latitude, and longitude, which would change in 1961 then revert to its pre-1961 value in 1971. From 1962 to 1974 there is a continuing decline of m'. Despite attempts to weed out these surprise changes, they may have found there way into the final results. To check this, a combination of data from another source(s) may be used and m' may be recalculated after 1962.

The Specialist for the dataset at NCAR could not pinpoint the exact reason(s) for the jumps and dips but said they may be due to differences in station library use or recalibrations of elevation during the compilation and merging of the World Weather Records from the Smithsonian Institution and the Environmental Data and Information Services and the Monthly Climatic Data for the World from NCDC. A thorough comparison of the two and examination of each may reveal the reason(s) for the unexplained occurrences and result in the publication of a more accurate and precise dataset.

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