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Detecting environmental changes and trends

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Abstract

Detecting changes in climate variables is a difficult process that depends on several parameters. These parameters include not only the size of the trend and the accuracy of the measurements, but also the magnitude of variability and the autocorrelation of the observations. The ability to detect a trend can vary from location to location and can vary with height at a single location. These differences are illustrated using observations from the Forecast Systems Laboratory Radiosonde Database to determine the natural variability and autocorrelation of temperature data as a function of altitude. As an example, the results for Topeka, Kansas, a mid-continent, stable monitoring site, indicate that trends of a fixed magnitude are easier to detect in the free troposphere than in either the boundary layer or the lower stratosphere. The free troposphere may be an important region for climate monitoring, especially given general circulation model projections of a nearly vertically-constant warming throughout the tropospheric altitudes. These types of investigations, which use past data to determine the natural variability and memory inherent in environmental parameters, can help identify geographic and altitude regions that may be critical for climate monitoring. © 2002 Published by Elsevier Science Ltd.

Keywords: Trend detection; Climate change; Radiosonde temperatures; Troposphere; Variability; Autocorrelation

1. Introduction

Trends in environmental data are an important issue for both the scientific community and the general public. Our current understanding of human impacts on the environment, particularly those associated with increased greenhouse warming, suggests that a number of parameters are likely to be changing. Identifying these changes can be difficult, however, and many of the environmental datasets currently available do not show any statistically significant trends. Our ability to detect changes can depend very much on the parameter being studied. Some measurements, such as the time series of carbon dioxide at Mauna Loa, exhibit changes that well exceed the natural variability. In many environmental parameters, however, finding small changes amidst relatively large natural variability presents a constant challenge to researchers exploring trends. By improving our understanding of the variability inherent in environmental parameters, particularly as a function of location or altitude, we can develop reasonable expectations for when and where a trend may be detected earliest.

A number of investigators (e.g., Angell, 1988, 1999; Oort and Liu, 1993; Labitzke and van Loon, 1995; Pielke et al., 1998; Gaffen et al., 2000a; Hurrell et al., 2000; NRC, 2000 and therein) have previously analyzed upper-air temperature observations for signs of climate change. Detecting these changes above the levels of natural climate variability is difficult, requiring clear identification of changes or trends that seem to agree with anthropogenically-forced climate models. Most of these general circulation models (GCMs) indicate future warming not only at the surface, but throughout the entire troposphere. Signs of this warming may be more detectable in altitude regions that are less strongly affected by mixing and other processes.

To illustrate how trend detectability can vary with altitude, we use radiosonde profiles from one of the 172 North American sonde stations having more than ten years of data. These profiles provide a means to assess the variability and autocorrelation of the temperature time series at different atmospheric altitudes. The estimates of variability and autocorrelation derived from

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these data can be extended to the future and combined with expected temperature trends to determine when and at which altitudes the changes may be detected earliest.

2. Techniques and discussion

The methods outlined here follow techniques commonly used to assess trends in environmental data. These techniques have been developed within the statistical community over the past forty years and account not only for the variability in the data but also, as is common for environmental parameters, the autocorrelation of the data. Procedures have been developed (Tiao et al., 1990; Weatherhead et al., 1998, 2000) to make reasonable estimates of how long it will take to detect expected trends, given the current understanding of variability in datasets. Applying these techniques can highlight certain regions of the world as being particularly important for detecting trends, for example the southern mid-latitudes for detecting ozone recovery (Weatherhead et al., 2000). In the case of vertical temperature data, these techniques can determine whether certain altitude regions may be more optimal than others for detecting trends.

In many statistical trend analyses of monthly time series data Y_t of a geophysical variable (for instance, total ozone, surface temperature, or upper-air temperature), a model of the following form has frequently been found to be adequate:

$$Y_t = \mu + S_t + \omega X_t + N_t \tag{1}$$

where μ is the monthly mean and S_t is a seasonal component that can often be represented as

$$S_t = \sum_{j=1}^{4}[\beta_{1,j}\sin(2\pi jt/12) + \beta_{2,j}\cos(2\pi jt/12)] \tag{2}$$

The seasonal cycle magnitude, as well as the trend, variability, and autocorrelation, all vary with height. The model is fitted separately at each height to represent the changes in each of these parameters. In Eq. (1), ωX_t represents the derived trend and N_t is the unexplained noise term most often assumed to be autoregressive with time lag of 1 when monthly data are considered. The fact that temperature measurements can be adequately analyzed in terms of such a model allows us to estimate the time needed to detect future trends. Further description of the model is available from Weatherhead et al. (1998).

Detecting a statistically significant trend depends fundamentally on finding a signal (ω) which is both large relative to the background noise (N_t) and independent of the seasonal signal (S_t) and other explanatory variables used. More specifically, trend detectability depends mainly on three factors:

- the size of the trend to be detected,
- unexplained variability in the data, and
- autocorrelation of the noise in the data.

The size of the trend to be detected can vary with location around the world, as reported for temperature data by the Intergovernmental Panel for Climate Change Third Assessment Report (IPCC, 2001). Similarly, both the magnitude of variability and the autocorrelation of an environmental parameter can vary with location and height in the atmosphere (Weatherhead et al., 1998). Locations at which one can expect to detect climate change earliest have been discussed and are often thought to be associated with the locations where the expected trends are largest. However, the ability to detect a given trend is also strongly influenced by the noise and autocorrelation. Because all three parameters affecting one's ability to detect a trend vary with location, identifying the areas best for detecting trends becomes less intuitive. Careful analyses of available information can provide estimates of how long it will take to detect specific trends. These analyses often indicate that a given trend can be detected in some parameters or at some locations in considerably less time than at other locations and that these parameters and locations are not always inherently obvious.

Under reasonable expectations, the number of years to detect a trend can be roughly approximated by:

$$n^* \cong \left[\frac{3.3\sigma}{\omega_0(1-\varphi)}\right]^{2/3} = \left[\frac{3.3\sigma_N}{\omega_0}\sqrt{\frac{1+\varphi}{1-\varphi}}\right]^{2/3} \tag{3}$$

where σ is the month-to-month variability in the data, ϕ is the autocorrelation in the month-to-month data and ω_0 is the expected trend (see Weatherhead et al. (1998) for the more exact formula). Using the variability and autocorrelation computed from existing data records, we can estimate the time needed to detect any future trend.

3. The Forecast Systems Laboratory radiosonde database

We explore trend detectability in temperature profile measurements archived by the National Oceanic and Atmospheric Administration's Forecast Systems Laboratory. The archived upper-air observations for North America were collected from the National Climatic Data Center (NCDC) and Global Telecommunications Services (GTS) and merged into a common database format for the period 1946–1996. Although these data were collected for weather forecasting purposes rather than for detection of climate change (Schwartz and Wade, 1993), the 40-year record provides an interesting time series for investigation. Analyzing past trends is not a part of our current efforts, and it should be noted that any derived trends can only be meaningful if the data are of sufficient precision and accuracy to be used for climatological purposes (Schwartz and Wade, 1993; Wade, 1995; Gaffen et al., 2000b).

Before being merged into the data archive, each profile was subjected to a variety of quality control (QC) checks, including a hydrostatic consistency scheme. Considerable effort was also placed on insuring the accuracy of the metadata for each station, which is an important starting point for the QC routines. In addition, a station equipment history was compiled to indicate any changes in equipment over the station record. Schwartz and Govett (1992) provide a more detailed report on the database and on the hydrostatic checking and correcting schemes. The QC checks include evaluating the temperature and dewpoint data for out-of-range values as well as performing duplicate level checks. The hydrostatic check is one of the most sophisticated checks performed. This check is similar to the ones originally performed by Inman (1967) but was expanded to include checks and corrections to significant level data.

No radiation correction schemes have been applied to the temperature data, although this correction could be performed easily if it were determined which scheme should be used and that applying such a correction is important for climate considerations (Gaffen, 1994). The current system of checks corrected many simple problems, such as incorrect sign on temperature or missing digits on heights or temperature, found in the archived data prior to the start of automated processing in about 1972. The combined out-of-range checks and hydrostatic consistency checks produced a database that is mostly free of the temperature and geopotential height errors commonly found in radiosonde data prior to automation. Slonaker et al. (1996) and other researchers have used versions of this database since its initial release in 1991 and have not reported any serious problems with the data quality.

For this study, a mid-continent station having a long record of radiosonde profiles was sought for investigating changes in statistical parameters and characterizing the variability and autocorrelation as a function of altitude. Deriving trends was not an objective of this study, and, as previously stated, many investigations (Schwartz and Wade, 1993; Wade, 1995; Gaffen et al., 2000b) have pointed out that the data may be problematic for such studies. The question addressed here is twofold: if we have good measurements in the future, are we likely to detect trends in the atmosphere in a reasonable length of time? Are there better places to monitor given what we know about the character of the atmosphere and the magnitude of trends being predicted? To answer this question, the stability of the data record, and specifically, whether there were any changes in the location of the station, are important to consider. With these factors in mind, we selected the Topeka, Kansas, station, which offers a long period (1956–1996) of stable observations. The sondes are launched from a location at 39.07°N latitude, 95.62°W longitude and report measurements from the surface to approximately 100 mb.

4. Case study

Fig. 1 shows the 0 Z time series of sonde temperature measurements from Topeka, Kansas. The observations are continuous from 1956 to 1996 and cover the altitude range from the surface to 100 mb. The month-to-month

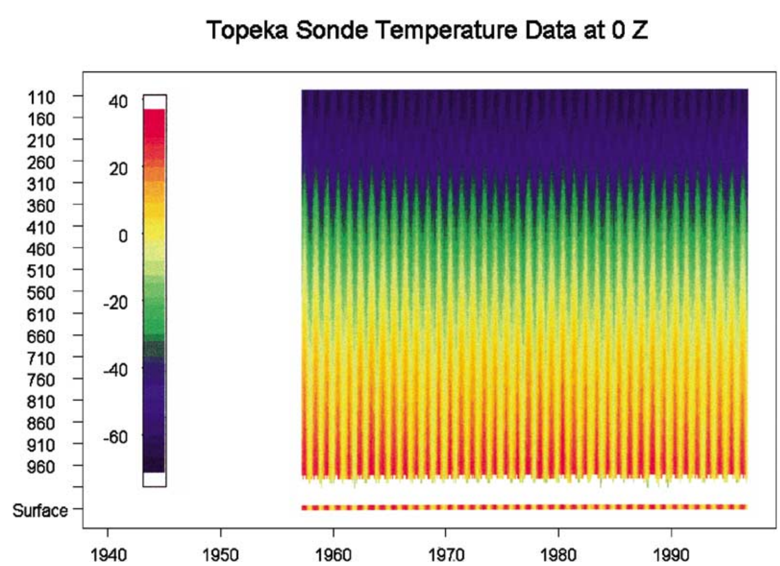

Fig. 1. Time series of sonde temperature measurements from Topeka, Kansas, at 0 Z.

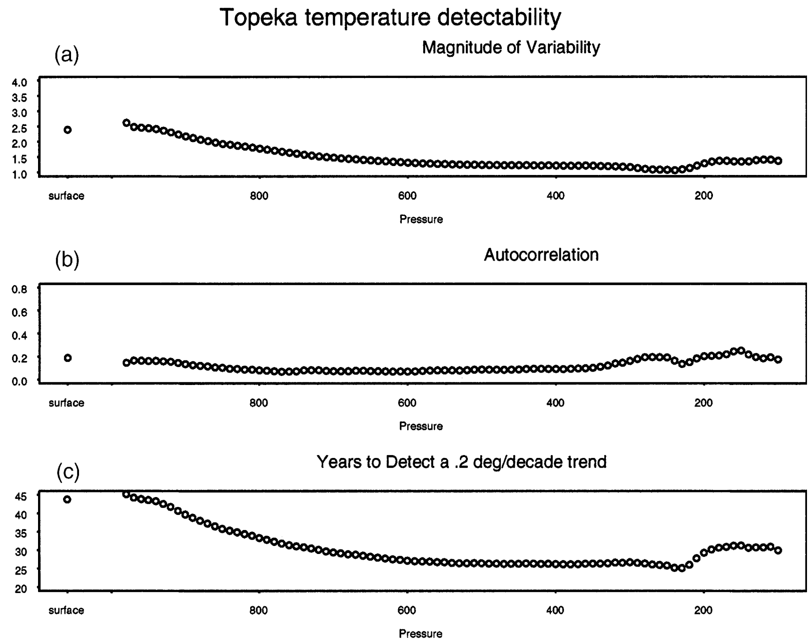

Fig. 2. (a) Month-to-month variability of Topeka, Kansas, 0 Z sonde measurements as a function of altitude. (b) Autocorrelation of the monthly-averaged 0 Z sonde measurements at Topeka, Kansas. (c) Years to detect a 0.2 °C per decade trend in temperature measurements as a function of altitude.

variability of these observations as a function of altitude is shown in Fig. 2a. The variability is largest in the boundary layer, decreases throughout the free troposphere, and increases again near the tropopause. Similarly, the autocorrelation of the monthly-averaged measurements is also larger near the surface (Fig. 2b). The autocorrelation values are lower in the free troposphere and are highest in the upper troposphere and into the lower stratosphere. In doing these calculations, we use the past data only to understand the magnitude of variability and autocorrelation in the data. Problems that may render the data insufficient for deriving trends generally have only a very small impact on the estimates of variability and autocorrelation.

We stated earlier that the variability and autocorrelation act together to confound trend detection. Using the techniques above, we use these calculations of variability and autocorrelation to estimate the time required to detect a 0.2° per decade future trend. The results are shown in Fig. 2c and indicate that the free troposphere may be a much better place than either the boundary layer or the lower stratosphere for detecting trends. Near the surface, the time required to detect the 0.2° per decade trend approaches 40 years. In the free troposphere, the number of years required to detect the same trend is decreased to approximately 25 years. These differences are partly attributable to how the different regions of the atmosphere behave: the boundary layer and lower stratosphere exhibit the greatest variability primarily because of the strong dynamic and radiative influences in those regions.

Observation quality can also affect the times required for trend detection. Observations in the free troposphere have unique problems, but despite any potential measurement difficulties, the observations are often more stable and can exhibit better quality than those collected at the surface. Unlike the surface, the free troposphere is not strongly affected by changes in land use and other local influences. The stability of the data record, combined with lower variability in that part of the atmosphere, make the free troposphere an important place for investigating climate change.

5. Conclusions

The ability to detect trends is confounded by both the natural variability and autocorrelation of the data. These values can vary from parameter to parameter, so that some types of observations may be more conducive than others for trend detection. Because variability and autocorrelation also vary with location and with height, some regions or altitude ranges can be better than others for more quickly detecting trends, even when evaluating the same atmospheric parameter. In the case of atmospheric temperatures, the free troposphere seems likely to be such an area, having less variability and inherent memory than temperatures near the surface. Temperature measurements in the free troposphere also tend to be free of some of the quality problems that plague observations at the surface, including site changes, urban influences, and other factors.

Whether the parameter in question is temperature, total ozone, or another environmental variable, the information derived from existing data records can be useful both to establish areas of high priority for study and to determine reasonable expectations for the time necessary to monitor. Knowledge of how an environmental parameter's variability and autocorrelation differ with location and altitude can help explain why detecting trends sometimes takes much longer than we might expect and why some locations may be inherently more efficient than others for detecting trends.

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References

Angell, J.K., 1988. Variations and trends in tropospheric and stratospheric global temperatures. 1958–87, J. Clim. 1, 1296–1313.

Angell, J.K., 1999. Comparison of surface and tropospheric trends estimated from a 63-station radiosonde network. 1958–1998, Geophys. Res. Lett. 26, 2761–2764.

Gaffen, D.J., 1994. Temporal inhomogeneities in radiosonde temperature records. J. Geophys. Res. 99 (D2), 3667–3676.

Gaffen, D.J., Santer, B.D., Boyle, J.S., Christy, J.R., Graham, N.E., Ross, R.J., 2000a. Multidecadal changes in the vertical structure of the tropical troposphere. Science 287, 1242–1245.

Gaffen, D.J., Sargent, M.A., Habermann, R.E., Lanzante, J.R., 2000b. Sensitivity of tropospheric and stratospheric temperature trends to radiosonde data quality. J. Clim. 13 (10), 1776–1796.

Hurrell, J.W., Brown, S.J., Trenberth, K.E., Christy, J.R., 2000. Comparison of tropospheric temperatures from radiosondes and satellites. 1979–1998, Bull. Amer. Meteorol. Soc. 81, 2165–2177.

Inman, R.L., 1967. Objective Detection and Correction of Errors in Radiosonde Data. ESSA Research lab Tech. Memo., NSSL 40, p. 50 (Available from National Severe Storms Laboratory, Norman, OK 73069).

International Panel on Climate Change, 2001. Third Assessment Report, Climate Change 2001 The Scientific Basis, Working Group 1.

Labitzke, K., van Loon, H., 1995. A note on the distribution of trends below 10 hPa: the extratropical Northern Hemisphere. J. Meteor. Soc. Jpn. 73, 883–889.

National Research Council, 2000. Reconciling observations of global temperature change, Panel on Reconciling Temperature Observations, National Academy of Sciences, p. 85.

Oort, A.H., Liu, H., 1993. Upper-air temperature trends over the globe. 1956–1989, J. Clim. 6, 292–307.

Pielke Sr., R.A., Eastman, J., Chase, T.N., Knaff, J., Kittel, T.G.F., 1998. 1973–1996 trends in depth-averaged tropospheric temperature. J. Geophys. Res. 103, 16,927–16,933.

Schwartz, B.E., Govett, M., 1992. A Hydrostatically consistent North American Radiosonde Data Base at the Forecast Systems Laboratory. 1946-Present. NOAA Technical Memorandum ERL FSL-4, p. 81.

Schwartz, B.E., Wade, C., 1993. Considerations for the Climatologist using North American radiosonde Data. 8th Symposium on Meteorological Observations and Instrumentation, 73rd AMS Annual Meeting, 17–22 January.

Slonaker, R.L., Schwartz, B.E., Emery, W.J., 1996. Occurrence of nonsurface superadiabatic lapse rates within raob data. Weather and Forecasting 11, 350–359.

Tiao, G.C., Reinsel, G.C., Xu, D., Pedrick, J.H., Zhu, X., Miller, A.J., DeLuisi, J.J., Mateer, C.L., Wuebbles, D.J., 1990. Effects of autocorrelation and temporal sampling schemes on estimates of trend and spatial correlation. J. Geophys. Res. 95, 20,507–20, 517.

Wade, C, 1995. Calibration and Data Reduction Problems Affecting National Weather Service Radiosonde Measurements. 9th Symposium on Meteorological Observations and Instrumentation, pp. 37–42.

Weatherhead, E.C., Reinsel, G.C., Tiao, G.C., Meng, X-L., Choi, D., Cheang, W-K., Keller, T., DeLuisi, J., Wuebbles, D.J., Kerr, J.B., Miller, A.J., Oltmans, S.J., Frederick, J.E., 1998. Factors affecting the detection of trends: Statistical considerations and applications to environmental data. J. Geophys. Res. 103 (D14), 17,149–17, 161.

Weatherhead, E.C., Reinsel, G.C., Tiao, G.C., Jackman, C.H., Bishop, L., Frith, S.M., DeLuisi, J., Keller, T., Oltmans, S.J., Fleming, E.L., Wuebbles, D.J., Kerr, J.B., Miller, A.J., Herman, J., McPeters, R., Nagatani, R.M., Frederick, J.E., 2000. Detecting the recovery of total column ozone. J. Geophys. Res. 105 (D17), 22,210.