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Trends in the surface meridional temperature gradient

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Abstract. Given the presence of a meridional temperature gradient (MTG) across midlatitudes, large-scale eddies transport heat poleward, thereby shaping Earth's climate. Defining an MTG index here as the difference in surface temperature between the 30°–35°N belt and the 50°–55°N belt, we use a temperature record compiled from observations over a 110-year period to determine a trend in the MTG in the last century. We find a significant decreasing trend in the MTG over this period of 0.4 ± 0.1°C per 100 years, along with indications of substantial multidecadal variability.

Introduction

The distribution of zonal-mean temperature from equator to poles is a fundamental indicator of any planet's climate and weather. The gradient of this distribution — i.e. the MTG — measures the difference in temperature between warmer, tropical latitudes and colder, high latitudes. We provide an operational definition of an MTG index and report an analysis of long-term trends in this quantity over the period of instrumental temperature records. While we do not attempt to provide a particular causal explanation of changes in the MTG, we do provide context to show why we think its empirical study is worthwhile.

Differential solar heating between equator and poles sets up a temperature imbalance, giving rise to atmospheric motions which, in turn, modify the temperature gradient by transporting heat polewards [*Stone*, 1984]. Thus the MTG is maintained as a balance between the equator-pole heating gradient and the fluxes of heat transported by atmospheric eddies and the mean meridional circulation (and ocean currents). There has been considerable attention to recent changes in the earth's global average temperature [*Jones et al.*, 1986a,b; *Hansen and Lebedeff*, 1987], but little attention to the MTG, even though it may be a more fundamental measure for climate dynamics [*Lindzen*, 1994].

At present, there is no single agreed upon or precise definition of the MTG, though it is understood to gauge the difference in temperature between the equator and the poles. *Rossby et al.* [1939] chose the latitude region 35° to 55° to compute the "zonal index" measuring the strength of the westerly winds in this zonal belt. These latitudes effectively define a midlatitude-oriented MTG, which will be most germane to midlatitude dynamics and storm systems. Following *Rossby et al.*, and because of the nature of the data available to us, we define an MTG index to be the difference in temperature between the 30°–35° belt and the 50°–55° belt.

There is evidence that the MTG has changed considerably in past climate periods. Proxy temperature records and climate model simulations provide indications that higher pole-to-equator temperature differentials accompanied ice ages, while lower values of the gradient prevailed in periods of greater warmth. Generally, tropical temperatures vary by only a few degrees from glacial to interglacial periods, while mid-latitude and polar temperatures vary quite a bit more. In addition, one set of climate model simulations suggests a global average surface temperature difference of about 10°C between the last ice age (18 thousand years ago) and the Mesozoic era (65 million years ago). At low latitudes in these simulations, however, this difference is less than 10°C while at high latitudes it varies from 20°C to 40°C depending on the season [*Rind*, 1986].

The roughly 0.5°C global warming found over the last century in the *Jones et al.* and *Hansen and Lebedeff* studies may have been accompanied by a change in MTG. Greenhouse change simulations with atmosphere–mixed layer ocean climate models point to a greater warming in the lower troposphere in polar regions than in the tropics [*Schlesinger and Mitchell*, 1987]. This would imply a *decrease* in MTG in response to greenhouse forcing. This simple picture is complicated by ocean dynamics, however, and some coupled ocean-atmosphere climate models point to a potential *increase* in the MTG in the Southern Hemisphere due to the strong coupling between surface temperatures and the deep ocean in high southern latitudes [*Held*, 1993]. In light of these simulations of potential future responses, we seek to assess how, if at all, the MTG has changed over the past century or so.[1]

Data

For this analysis we use a land/ocean dataset of average monthly surface temperature anomalies (deviations from reference values computed over 1950 – 1979; note that absolute temperatures cannot be recovered from this dataset) on a 5° by 5° grid for the years 1854 – 1991. More detail on these data is given in *Jones et al.* [1986a,b], *Jones and Briffa* [1992], and *Jones* [1994].

The zonal bands used in analyzing the MTG are in the 30° to 55° north regions, which do not include the most northern and southern zones in the Northern Hemisphere where missing data are problematic (combined, these extreme regions account for roughly 75 per-

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[1]For additional references and detail, see *Gitelman et al.*, 1997.

cent of the missing data in the hemisphere in the 'Jones' dataset). After 1880, there is a sharp drop off in the percentage of missing data in the zones used in the MTG calculation. For this reason our analysis is made on the time series of observations starting in 1881. There are slightly more missing data in the 50° to 55° N zone than in the 30° to 35° N zone, but, as our statistical analysis in the next section shows (see footnote 2), there does not appear to be any systematic pattern to the missing data that might affect the results of our analysis.

Missing data pose a more cumbersome problem in the Southern Hemisphere. It is not until 1950 that there are enough data in the MTG zones (30° to 35°S and 50° to 55°S) to begin calculating a reliable figure for the Southern Hemispheric MTG. We therefore focus here only on the Northern Hemisphere.

Statistical methods

To construct the MTG time series, monthly zonal averages of temperature anomalies in the relevant latitude belts (30°N to 35°N and 50°N to 55°N) are computed. Subtracting the 50°N to 55°N zone from the 30°N to 35°N zone yields the time series of zonal difference values. These zonal differences are assigned weights in proportion to the amount of available data contributing to each difference. The weighted difference is the MTG time series analyzed herein[2]. We examine both the monthly MTG time series and the annual series obtained by averaging over months, as well as four seasonally averaged series.

The model considered for these data is

$$Y_t = \alpha + \beta t + X_t \qquad (1)$$

where t is the time index in months or years, Y_t is the monthly (annual or seasonal) MTG value, and X_t is a mean zero random variable which accounts for additional variation in the MTG. For X_t, we consider the class of autoregressive moving average (ARMA) models and pure autoregressive (AR) models, popularized by *Box and Jenkins*, 1976. Estimates of the regression parameters in (1) are asymptotically independent of the parameter estimates in X_t, and so we should not expect the regression parameter estimates to change very much with different models for X_t. On the other hand, standard errors may change substantially [see *Gitelman et al.*, 1997, for references]. Because the X_t are assumed to be correlated in (1), the identification of a trend is not straightforward. In particular, calculations for the standard error of a trend estimate must somehow account for the correlations in the X_t process.

To determine the trend parameter, β, the problem is treated as a regression with time series errors: a linear estimate of the trend is obtained, and time series methods are used to model the residuals. We consider a doubly weighted least squares estimate for β, which takes its weights from both the proportion of available data used to compute each MTG value and from the autocovariance structure of the X_t process[3]. This doubly weighted least squares estimate is the best linear unbiased estimate for β.

A weighted least squares line (i.e., with weights proportional to the amount of available data contributing to each MTG observation) is fit and then subtracted from the MTG series. Based on standard ARMA model selection criteria, an appropriate model is chosen for the residuals. The autocovariance matrix of the residuals is estimated from the data by using the maximum likelihood estimates of the model parameters. The model parameter estimates are obtained using *S-Plus* [1991], which gives results using the likelihood conditioned on the first $p + q$ observations. These estimates and their standard errors are calculated using standard weighted least squares techniques [see *Gitelman et al.*, 1997].

In model (1), the trend is assumed to be a linear function of time. Although we do not expect the trend to be strictly linear, this model allows us to address the question of whether or not there is an overall tendency for the MTG to change with time. Similarly, linear trend models have been used to investigate long term behavior in global mean temperature time series [e.g., *Bloomfield*, 1992]. To highlight the non-linearity in the trend, we also use a popular scatterplot smoother, *lowess* [*Cleveland*, 1979; *S-Plus*, 1991], which fits a local, robust linear regression.

Results

Figure 1 shows the annual series of Northern Hemisphere MTG values constructed from the Jones dataset for the period 1880 to 1991. There is a downward trend in the data, highlighted by both the weighted least squares line (solid line) and the lowess fitted line with window parameter, $f = 0.3$ (dashed line). From the lowess line we observe that there appears to be substantial low frequency variability in the time series spanning decades. The rather sharp dip in the MTG series in the late 1970's may be related to the sharp increase in av-

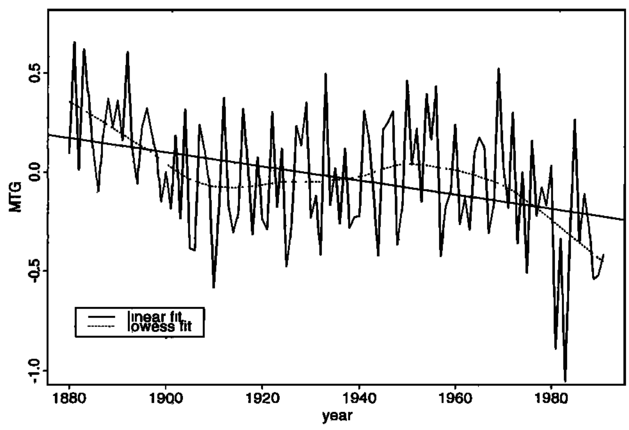

Figure 1. MTG for the Northern Hemisphere in °C, i.e. difference in zonal mean temperature anomalies between belts 30° - 35°N and 50° - 55°N.

[2] While weighting is appropriate, the results for the unweighted time series are similar. Note also that we calculate the MTG as an anomaly temperature difference in °C. The actual temperature difference between belts is the anomaly difference plus the difference between reference means for each belt. The difference can be converted to a true gradient by dividing by the distance between the centers of the two belts (2200 km).

[3] We also fit the usual weighted least squares estimate of β, using methods proposed by *Bloomfield* [1992]. The results using these two estimates are quite similar.

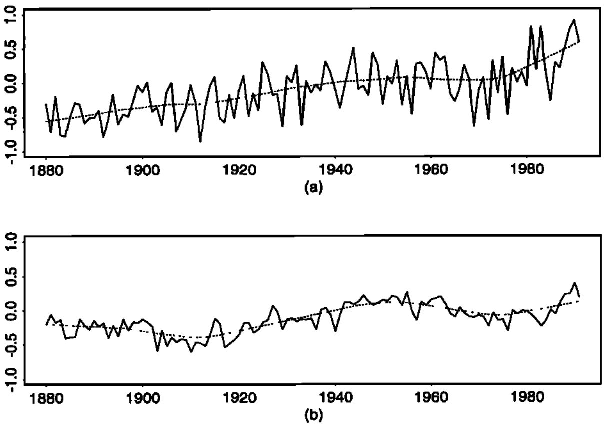

Figure 2. Average zonal temperature anomalies for (a) 50° to 55° and (b) 30° to 35° in °C.

erage global surface temperature around the same time [*Hansen and Lebedeff,* 1987] which occurs mostly in the high latitude zone. Figure 2 shows the two zones which make up the MTG (with dashed lowess lines, $f = 0.3$). While there appears to be greater variability in the 50° to 55° zone than in the 30° to 35° zone, there is a larger temperature increase in the northern zone.

After removing the weighted least squares estimates for α and β from the MTG values, the pure AR processes provide the best fit to the residuals. The selected models are all close in terms of their BIC values (Bayesian Information Criterion) [*Kass and Raftery,* 1995], though the AR(4) process seems best at reducing the residuals to white noise. There does appear to be a statistically significant trend in the MTG: a decrease of $0.38° \pm 0.08°$C per 100 years under the AR(4) model for the residuals. As expected, the trend estimates vary only about 4% across the models for X_t. The standard errors are also similar across different models, with only a 3% change across the 3 best fitting models.

We also considered the distribution of the MTG over the seasons of the year. Downward trends in the winter and spring series (not shown) are significantly different from zero (-0.70 ± 0.20 and -0.70 ± 0.17 per 100 years, respectively). No such trends are evident in the summer and autumn data. It appears therefore that the trend in the annual MTG series (Figure 1) results mainly from behavior in winter and spring. The model for the X_t process in each case is AR(5).

Discussion and conclusions

The results in the previous section provide evidence that the Northern Hemisphere meridional temperature gradient has decreased roughly $0.4° \pm 0.1°$C per 100 years, with the trend being significantly less than zero ($p < 0.001$). A consideration worth noting is the existence of climate variability on time scales longer than the observed record. In concluding that the detected trend appears to be significantly different from zero, there is an underlying assumption that the models we have selected for explaining the variability in the MTG apply even for very low frequency variation. It is uncertain whether decreases of around $0.4° \pm 0.1°$C in the overall MTG and $0.7° \pm 0.2°$C in the winter and spring series are too large to be accounted for as natural variation, because the MTG and its fluctuations have not been widely diagnosed. To be sure, such excursions are not unprecedented in the paleoclimate record.

Other studies of the temperature record have modeled the variation using fractionally-integrated white noise processes [*Hosking,* 1981], which can help to account for long-range dependence in the data [e.g. *Bloomfield,* 1992]. Such models will produce different, and sometimes larger, estimates of the standard error. A cursory analysis of the MTG data, using the spectrum and the autocorrelation function out to over 400 lags, does not indicate the presence of long-range dependence in the data. With these caveats taken into consideration, it appears that there has been a significant decrease in the meridional temperature gradient in the Northern Hemisphere over the last century or so.

The precise relationship between the MTG and the global mean surface air temperature, T, depends on how any changes in temperature are distributed with latitude. Clearly, if changes in temperature are uniform with latitude, then the MTG will be unchanged; otherwise not. Over the entire length of the time series considered here, there has been an increase in observed T [*Jones et al.,* 1986a,b], while herein we have observed a decrease in MTG. This relationship is more complicated, however, at higher (multi-decadal scale) frequencies. The lowess fit to the MTG series in Figure 1 suggests variability indicative of a decline in MTG from the beginning of the series until around 1910, followed by a leveling off until about 1950, and then a further period of decrease through to the end of the series. In turn, this suggests that there are periods where T does not increase (pre-1910; see Figure 5 in *Jones and Briffa,* 1992), but where the MTG decreases; periods where T increases (1910–1940), but the MTG is relatively constant[4]; and periods where T increases and the MTG decreases (1950-1990). Thus, the distribution of temperature change with latitude seems to be characterized by substantial multidecadal scale variability, and it is apparently not a simple function of changes in T on these time scales. The expectation from equilibrium climate model simulations that greenhouse-induced increases in T would be reflected mostly in high latitudes (thereby leading to reductions in MTG) applies at best to our entire record and is not well reflected in the transient MTG behavior in Figure 1. Alternatively, one might view the correspondence since 1950 as indicative of the equilibrium results.

Potential changes in the MTG have been linked with potential changes in storminess in midlatitudes. Decreases in the MTG (ceteris paribus) should lead to weaker midlatitude eddies[5]. This assumes that the decrease in lower tropospheric MTG is more important than the projected increase in upper tropospheric MTG [*Held,* 1993], and that diminished heat transport be-

[4] Note that this constancy in MTG is associated with apparent increases in temperature in both MTG zones (see Figure 2).

[5] Note that the MTG and heat flux are positively correlated for externally forced changes in the MTG (such as due to increases in greenhouse gases), but for internal or free variations in the heat flux, the heat flux and MTG are negatively correlated [*Stone and Miller,* 1980].

tween 35° and 55° is more likely to be associated with reduced eddy activity than with reduced mean meridional circulation or ocean circulation (which transport less heat than eddies in this region). However, all else is not constant, and other factors will influence eddy activity. Increases in atmospheric moisture content (implying increases in eddy meridional latent heat fluxes) and a reduction of the land-sea thermal contrast in east coast regions contribute, along with a decrease in MTG, to a reduction in eddy activity in the modeling study of *Zhang and Wang* [1996][6].

Observations of cyclone frequency over North America show a general reduction of cyclone counts since 1950 [*Changnon*, 1995]. Over the common period of record since 1950, our lowess analysis of the MTG index also indicates a general reduction, although year-to-year correlations with Changnon's North America cyclone counts are not significant. These indications are quite tentative, however, due to the short period of record considered and the limited hemispheric coverage in the Changnon data. A further complication is that cyclones may respond to a decrease in MTG (or increases in atmospheric moisture and decreases in land-sea thermal contrasts) through changes in intensity not frequency.

The decrease in mean MTG found here is also broadly consistent with the results of *Karl et al.* [1996] showing a reduction in day-to-day temperature variability over the U.S. this century. The expectation from dynamical considerations, that decreasing MTG implies decreasing temperature variability, might be confounded by possible changes in variance of the MTG over the period of record, which could also affect temperature variability. We also analyzed the variance of the MTG series for the presence of a trend but did not detect a significant trend over the period of available record.

In conclusion, by examining the observed surface temperature record, we detect a decreasing trend in the surface MTG for the Northern Hemisphere over a 110-year period. This trend overlies what appears to be substantial multidecadal variability. The direction of the detected long term trend in Northern Hemisphere MTG is consistent with changes in the equator-pole temperature gradient inferred from warm and cold period paleoclimate records and modeling studies. We believe this is the first explicit estimation of an MTG trend, and it is consistent with earlier studies that discuss qualitative latitudinal temperature differences in warming [e.g., *Hansen and Lebedeff*, 1987; *Parker et al.*, 1994].

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References

Bloomfield, P., Trends in global temperature, *Clim. Change, 21*, 1-16, 1992.

Box, G., and G. Jenkins, *Time Series Analysis: Forecasting and Control*, 575 pp., Holden-Day, San Francisco, 1976.

Changnon, D., J.J. Noel, and L.H. Maze, Determining cyclone frequencies using equal-area circles, *Mon. Wea. Rev., 123*, 2285-2294, 1995.

Cleveland, W., Robust locally weighted regression and smoothing scatterplots, *J. Am. Stat. Assn., 74*, 829-836, 1979.

Gitelman, A., J. Risbey, R.E. Kass, and R. Rosen, Trends in the surface meridional temperature gradient, Tech. Rep. 655, Department of Statistics, Carnegie Mellon University, (www.stat.cmu.edu/www/cmu-stats/tr/), 1997.

Hansen, J.E., and S. Lebedeff, Global trends of measured surface air temperature, *J. Geophys. Res., 92*, 13,345-13,372, 1987.

Held, I.M., Large-scale dynamics and global warming, *Bull. Amer. Meteor. Soc., 74*, 228-241, 1993.

Hosking, J.R.M., Fractional differencing, *Biometrika, 68*, 165-176, 1981.

Jones, P.D., Hemispheric surface air temperature variations: a reanalysis and an update to 1993, *J. Clim., 7*, 1794-1802, 1994.

Jones, P.D., and K. Briffa, Global surface air temperature variations over the twentieth century. Part1: Spatial, temporal and seasonal details, *Holocene, 2*, 174-188, 1992.

Jones, P.D., S.C.B. Raper, R.S. Bradley, H.F. Diaz, P.M. Kelly, and T.M.L. Wigley, Northern Hemisphere surface air temperature variations: 1851-1984, *J. Clim. Appl. Meteor., 25*, 161-179, 1986a.

Jones, P.D., S.C.B. Raper, and T.M.L Wigley, Southern Hemisphere surface air temperature variations: 1851-1984, *J. Clim. Appl. Meteor., 25*, 1213-1230, 1986b.

Karl, T.R., R.W. Knight, D.R. Easterling, and R.G. Quayle, Indices of climate change for the United States, *Bull. Amer. Meteor. Soc., 77*, 279-292, 1996.

Kass, R.E., and A.E. Raftery, Bayes factors and model uncertainty, *J. Amer. Stat. Assn., 90*, 773-795, 1995.

Lindzen, R.S., Climate dynamics and global change, *Ann. Rev. Fluid Mech., 26*, 353-378, 1994.

Parker, D., P.D. Jones, C. Folland, and A. Bevan, Interdecadal changes of surface temperature since the late nineteenth century, *J. Geophys. Res., 99*, 14,373-14,399, 1994.

Rind, D., The dynamics of warm and cold climates, *J. Atmos. Sci., 43*, 3-24, 1986.

Rossby, C.-G. and collaborators, Relation between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semi-permanent centers of action, *J. Marine Res., 2*, 38-54, 1939.

Schlesinger M., and J. Mitchell, Climate model simulations of the equilibrium climatic response to increased carbon dioxide, *Rev. Geophys., 25*, 760-798, 1987.

S-Plus, *S-PLUS User's Manual, Version 3.0*, Statistical Sciences, Inc., 1991.

Stone, P., Feedbacks between dynamical heat fluxes and temperature structure in the atmosphere, *Geophys. Monograph, 29*, 6-17, 1984.

Stone, P., and D. Miller, Empirical relations between seasonal changes in meridional temperature gradients and meridional fluxes of heat, *J. Atmos. Sci., 37*, 1708-1721, 1980.

Zhang, Y, and W.-C. Wang, Model simulated northern winter cyclone and anticyclone activity under a greenhouse warming scenario, PCMDI report no. 33, Lawrence Livermore National Laboratory, Livermore, California, 1996.

[6]Note that increases in atmospheric moisture per se also *strengthen* eddies due to greater latent heat release in the eddy.

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