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GLOBAL CHANGE INTEGRATING FACTORS: TROPICAL TROPOPAUSE TRENDS

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This research proposes new criteria, shifts in the height and temperature of the tropical tropopause, as measures of global climate change. The search for signs of global warming in the temperature signal near the earth's surface is extremely difficult, largely because numerous factors contribute to surface temperature forcing with only a small signal-to-noise ratio relative to long-term effects. In the long term, no part of the atmosphere can be considered individually because the evolution will be a function of all states of all portions. A large surface greenhouse signal might ultimately be expected, but the analysis of surface temperature may not be particularly useful for early detection.

What is suggested here is not an analysis of trends in the surface temperature field or any of its spatial averages, but rather an integrating factor or integrator, a single measure of global change that could be considered a test of significant change for the entire global system. Preferably, this global change integrator would vary slowly and would take into account many of the causes of climate change, with a relatively large signal-to-noise ratio. Such an integrator could be monitored, and abrupt or accelerated changes could serve as an early warning signal for policy makers and the public.

Earlier work has suggested that temperature has much less short-term and small-scale noise in the lower stratosphere, and thus the global warming signal at that level might be more easily deconvoluted[1], because the cooling rate near the 200-mb level is almost constant with latitude[2]. A study of the temperature signal at this pressure level might show a clearer trend due to increased levels of greenhouse gases, but it would yield information about the troposphere only by inference.

A factor that would integrate both tropospheric and stratospheric changes is the height of the tropopause[3], a measure of the vertical energy balance[4]. When large-scale

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seasonal averages are obtained in the tropics and subtropics, tropopause height is found to exhibit quite regular behavior. Of course, the tropopause is but one of a number of possible integrating factors; for example, one could examine the latitudinal extent of polar ice or the temperature of the tundra. However, to justify the usefulness of the tropical tropopause height as an indicator of climate change, it is necessary to understand what causes its formation, its stability, and possible changes[5].

A number of authors have reported studies of the tropical tropopause, although not as a basis for detection of global change. Reid and Gage[6] and others[7-10] have studied tropopause height from the perspectives of changes due to variations in solar flux, sea surface temperature, and the seasonal cycle. These papers suggest that to identify the forcing function for changes at the tropopause, one must consider all factors that contribute to the balance.

The temperature of the stratosphere[11], like that of the troposphere, is determined by the detailed balance of atmospheric dynamics, cloud formation and dissipation, and radiative processes including contributions from greenhouse gases. The atmosphere acts as a thin, compressible fluid layer on a spinning sphere, driven to motion by the resultant forces and the internal heat sources of (a) evaporation of water at the surface, (b) condensation of water during so-called cumulus-scale convection, and (c) radiative processes by the greenhouse gases. At the top, the global atmosphere loses 106 W m^{-2} annually, the loss being made up by 90 W m^{-2} of latent heat release and 16 W m^{-2} from eddy conduction from the surface[12]. The stratosphere is nearly in radiative equilibrium, but this is accomplished only by vertical transport of energy through the tropopause to the stratosphere. As long as the net vertical flux of energy is maintained from the troposphere, the stratospheric temperature profile is more or less independent of the physical conditions in the troposphere.

In the tropical troposphere, the vertical energy transport must be somewhat greater than that resulting from a radiative equilibrium profile[13-18], while meridional gradients in temperature are very small. On this basis, horizontal transport of heat can be neglected so that vertical convective processes can be considered to balance the cooling of radiative processes within the vertical column[2,19]. From this qualitative perspective, the moist convective processes continue to the top of the highest clouds, where the troposphere meets the necessary criteria to balance the stratospheric energy balance conditions. At that altitude the convective zone ends, defining the region bounding the lower atmosphere. The result is a discontinuity in the temperature profile, which is termed the tropopause.

In the atmosphere, dynamics determine the distribution of greenhouse gases, and changes in either their abundance or distribution can contribute to changes in convection and ultimately in the height of the tropopause. Since the radiative contributions of the gases vary greatly with altitude, this vertical radiative feedback mechanism may serve a very important role. It also complicates our understanding of the relative contributions of clouds versus greenhouse gases. Greater evaporative rates due to increased greenhouse effects[20,21] could enhance the probability of cumulus convection[22,23]. It is generally accepted that precipitation is a function of convection, and in the tropics[24] cloud clusters can lead to highly concentrated precipitation events. Hence, an understanding of the scale interactions from individual clusters is necessary to predict the height of the tropopause. This is a complicated line of reasoning, but it does point out the difficulty in the prediction of tropopause pressure of the real atmosphere. In addition, sporadic variations in the global ocean temperature arising from a variety of possible sources (e.g., variable cloudiness, volcanic activity, or solar variations) may need consideration in a full interpretation of the causes of an observed tropopause trend.

Ozone can, of course, be redistributed through moist convection; this may also be a determining factor in the height of the tropopause. Ivanova and others[25,26] suggested that the ozone profile might be expected to have a discontinuity with height, much like the tropopause, but later work[27] contended that this correlation is not universally strong. This later work questions the validity of the generalization in the tropics.

The data set analyzed here was developed by Oort[28]. It includes additional unpublished data for the years 1973-1988. The Oort data consist of monthly averaged values of measured temperature at fixed pressures (50, 100, 200, 300, 400, 500, 700, 850, 900, 950, and 1000 mb) for each 2.5 degrees latitude from 90 degrees north to 90 degrees south. Along each latitude line are 73 longitudinal grid values at each pressure level.

To obtain the monthly tropopause temperature and pressure values for a latitudinal band centered at 15 degrees north, values of temperature at 12.5, 15 and 17.5 degrees were averaged to obtain average vertically-aligned monthly temperature profiles as a function of pressure. These values were then fitted to a cubic analytic function to determine a continuous temperature profile. The tropopause was assumed to be the location where the lapse rate changed sign. The resultant tropopause values were then averaged for each season. (Note: the adequacy of this procedure for determining the location of the tropopause will be discussed in more detail in a subsequent article).

The results are shown in Figs. 1 and 2. The corresponding trends in seasonal and annual averages are shown in Table 1. Annual trends are -0.07 mb yr^{-1} and 0.03 K yr^{-1}. The standard deviations were 0.015 mb yr^{-1} for pressure and 0.017 K yr^{-1} for temperature. A test run with regard to the trends gave a value for pressure of much less than 0.001 mb yr^{-1}, representing the probability that the results could have been generated by chance [29].

These findings signal a slow but steady change in the climate system. As stated earlier, the source or sources of the trends may be complicated, and no claims about the causes are made in the present research. If these results are extrapolated to the earth's surface, if a linear response is assumed during a CO_2 doubling time of 120 yrs, and if all of the temperature change is due to greenhouse effects, the global C. global response would be 2.17°C. This value lies well within the lower end of estimates obtained by current climate models (1.5-4.5°C).

If extension of the present analysis to the entire tropical atmosphere leads to the same type of integrating trend, this result would signal a change in the climate processes that determine the overall volume of the troposphere, which could have implications for air quality. For example, does a tropopause temperature trend signal a change in the conditions for gaseous exchange between the troposphere and the stratosphere, with possible effects on chemistry in the vicinity of the tropopause because of different mixtures of reactants and different temperatures and pressures? The temperature shift would be expected to accelerate somewhat the rates of many of the individual reaction steps, and the pressure change could slightly affect certain steps in the mechanism (i.e., unimolecular reactions). Uncertainties in the ozone depletion chemistry and the radiative flux divergence near the tropopause have recently come to light[30], and the present result is an additional consideration that may link ozone depletion and climate change.

In view of the importance of detecting global change, the present findings make a strong case for future research to extend this procedure over the entire globe.

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TABLE 1 Tropopause temperature and pressure changes at 15 degrees N latitude over the years 1958-87 as determined from a recursion line fit.

	ΔP (mb)	σ_P	ΔT (K)	σ_T
Spring	-2.2	0.54	0.4	0.46
Summer	-2.5	0.47	1.6	0.50
Fall	-2.0	0.57	0.7	0.48
Winter	-2.0	0.42	1.1	0.61
Annual	-2.2	0.42	1.1	0.61
	or		or	
	-0.07 mb yr^{-1}		0.03 K yr^{-1}	

FIG. 1 Seasonal values of the tropopause temperature (K) within a five-degree latitudinal band centered around 15 degrees N latitude, for the years 1958-1987.

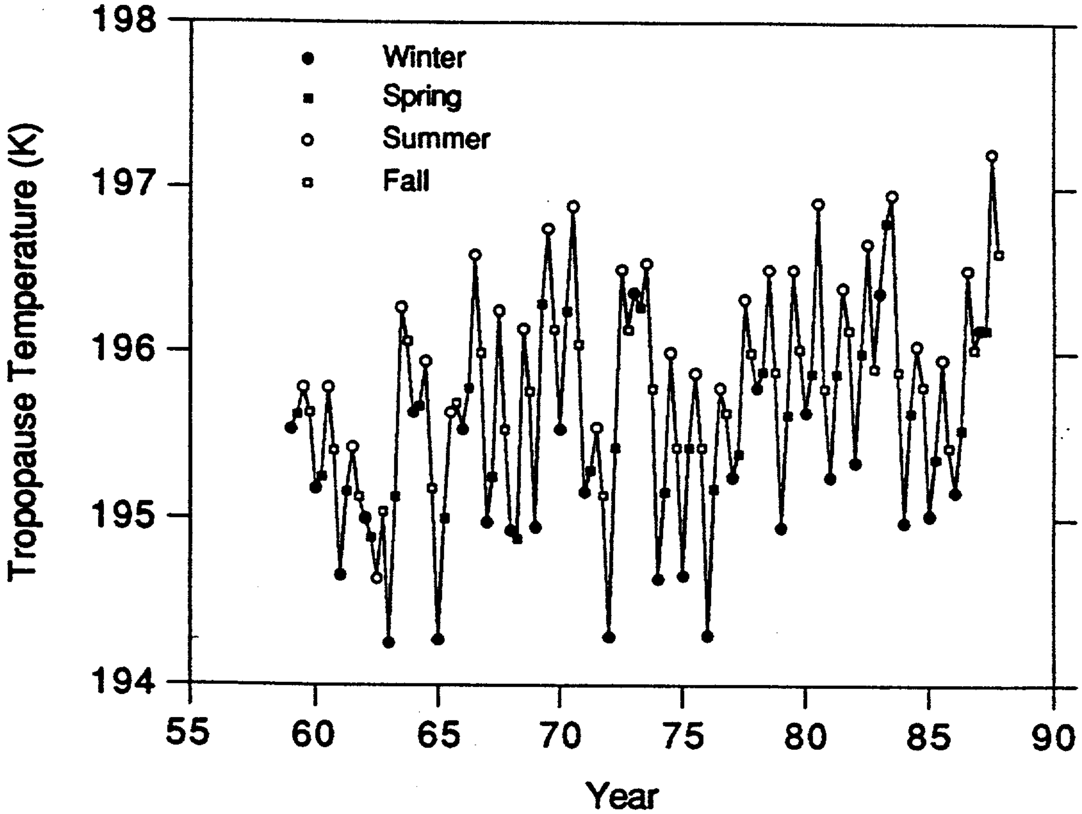

FIG. 2 Seasonal values of the tropopause pressure (mb) within a five-degree latitudinal band centered around 15 degrees N latitude, for the years 1958-1987.