Advanced Review

Stratospheric temperature trends: our evolving understanding

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We review the scientific literature since the 1960s to examine the evolution of modeling tools and observations that have advanced understanding of global stratospheric temperature changes. Observations show overall cooling of the stratosphere during the period for which they are available (since the late 1950s and late 1970s from radiosondes and satellites, respectively), interrupted by episodes of warming associated with volcanic eruptions, and superimposed on variations associated with the solar cycle. There has been little global mean temperature change since about 1995. The temporal and vertical structure of these variations are reasonably well explained by models that include changes in greenhouse gases, ozone, volcanic aerosols, and solar output, although there are significant uncertainties in the temperature observations and regarding the nature and influence of past changes in stratospheric water vapor. As a companion to a recent *WIREs* review of tropospheric temperature trends, this article identifies areas of commonality and contrast between the tropospheric and stratospheric trend literature. For example, the increased attention over time to radiosonde and satellite data quality has contributed to better characterization of uncertainty in observed trends both in the troposphere and in the lower stratosphere, and has highlighted the relative deficiency of attention to observations in the middle and upper stratosphere. In contrast to the relatively unchanging expectations of surface and tropospheric warming primarily induced by greenhouse gas increases, stratospheric temperature change expectations have arisen from experiments with a wider variety of model types, showing more complex trend patterns associated with a greater diversity of forcing agents. © 2011 John Wiley & Sons, Ltd. *WIREs Clim Change* 2011 2 592–616 DOI: 10.1002/wcc.125

INTRODUCTION

Over the past several decades, the vertical profile of atmospheric temperature trends has become recognized as an important indicator of climate change, because different climate forcing mechanisms exhibit distinct vertical warming and cooling patterns. In a companion review, Thorne et al.[1] surveyed the history of our understanding of temperature trends within the troposphere, the lowest ~10–20 km of the atmosphere in which weather occurs. That review provided a chronological overview of theoretical and observational investigations of tropospheric temperature trends, in light of the ongoing controversy over whether modeled and observed trends over the past half century agree. That debate arose with the 1990 publication of results from satellite observations.[2]

Thorne et al.[1] concluded that models and observations currently agree within their known uncertainties. Uncertainty estimates have increased over time for two main reasons. First, there are shortcomings in global temperature observing technologies used to monitor climate, and the scope of observational

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uncertainty was not fully appreciated until different research teams endeavored to create alternative estimates of temperature change using the same basic sets of observations. Second, the intrinsic uncertainty due to climate variability, or noise, was more fully appreciated as advances in computer power spurred the development of more climate models and allowed production of multiple realizations of climate simulations, known as ensemble experiments. Advances in understanding tropospheric temperature trends have been stimulated both by the scientific controversy and by national and international scientific assessments of climate change, two of which focused solely on this issue.[3,4]

This review extends the historical overview to the stratosphere, the atmospheric layer above the troposphere in the ~15–50-km altitude range. Several distinctions between tropospheric and stratospheric temperature trend research motivate separate treatment. First, although some temperature observations cover both layers, others are uniquely stratospheric. Second, until recently, different models have been used for the troposphere (where coupling to the ocean is important) and the stratosphere (because tropospheric models rarely extended deep into the stratosphere nor did they include all the physical and chemical processes necessary for simulating stratospheric climate). Third, in part because of these two differences, the scientific communities, and the resulting literatures, have been somewhat distinct. Fourth, although similar scientific uncertainties apply to both tropospheric and stratospheric temperature trends, those pertaining to the stratosphere, in contrast to the troposphere, have not entered into public policy debates, perhaps because tropospheric warming is perceived as more directly related to greenhouse-gas-induced surface climate change and associated impacts on human society and the environment.

This review follows the structure of, and makes liberal reference to, Thorne et al.[1] The section *Observing and Monitoring* provides an overview of stratospheric temperature observations, and the section *Modeling Stratospheric Temperature* describes modeling approaches. The section *Evolving Understanding of Temperature Trends*, the heart of the review, chronologically treats model and observational research developments and international scientific assessments. The discussion is largely restricted to global average changes in the stratospheric vertical temperature profile and their relation to changes in radiative forcing factors; zonal mean trends, their seasonal variations, and their possible connection with stratospheric circulation changes are discussed briefly. We close with a *Synthesis and Current Challenges* section.

OBSERVING AND MONITORING STRATOSPHERIC TEMPERATURE

Only a few observing systems offer data with long enough (i.e., multidecadal) records and the global coverage needed to evaluate stratospheric temperature trends. Balloon-borne radiosondes (with regular, quasi-global observations beginning in 1958) provide data over an irregular network of stations, and observations become less frequent with increased altitude, as seen in Figure 1. Microwave Sounding Units (MSUs), and Stratospheric Sounding Units (SSUs), which flew on U.S. National Oceanic and Atmospheric Administration (NOAA) polar-orbiting environmental satellites between 1979 and 2005, and Advanced Microwave Sounding Units (AMSUs), which continue to operate today, provide nearly globally complete data.

This section briefly reviews these observations and provides information on other systems that were useful in the past (rocketsondes), may be useful in the future (Global Navigation Satellite System or GNSS), or play an ancillary role in stratospheric temperature trend studies (stratospheric analyses, reanalyses, and lidar observations). As Thorne et al.[1] discuss the radiosonde and MSU observing systems in detail, we provide only superficial coverage here. Nor do we treat the topic of building global temperature datasets,[1] which involves data quality control and adjustments to remove time-varying biases that affect trend estimates, both of which involve many decisions and contribute to structural uncertainty in resulting time series.[5]

Radiosondes and Microwave Sounding Units

Figures 1 and 2 show the vertical coverage of radiosondes and satellite instruments, with radiosondes sampling only the lower stratosphere (LS) (up to about 30 km) with detailed vertical resolution, and the MSU sampling a single deep LS layer spanning about 15–22 km. (In addition to the LS, other MSU channels observe the troposphere and the tropopause region, which are not discussed here.) Long-term radiosonde, MSU, and, starting in 1998, AMSU records all have different time-varying biases (or inhomogeneities) with important ramifications for accurate estimation of temperature trends.[1,4]

Fundamentally, the focus of radiosonde and MSU observations has been in the troposphere where they are used in weather analysis and forecasting. They were not intended nor designed for monitoring

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FIGURE 1 | Percentage of expected radiosonde temperature reports received during October 2010 by the European Centre for Medium-Range Weather Forecasts (ECMWF) for the (bottom to top) 50-, 10-, and 5-hPa levels. A comparable map showing 700-hPa reporting performance is shown by Thorne et al.[1] [Figure courtesy of Antonio Garcia-Mendez (ECMWF)]

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FIGURE 2 | Vertical sampling of satellite and radiosonde observations of stratospheric temperature. *Left*: vertical weighting functions for satellite Microwave Sounding Unit (MSU) and Stratospheric Sounding Unit (SSU) stratospheric temperature observations as a function of pressure (left axis) and height (right axis). The dashed line at about 27 km (30 hPa) indicates the typical maximum height of historical global radiosondes data coverage (Figure 1). *Right*: schematic of atmospheric vertical structure and its latitudinal variation. (Modified from Climate Change Science Program Synthesis and Assessment Product 1.1[4])

climate change. Radiosonde observations typically have larger inhomogeneities in the stratosphere than the troposphere.[1,6,7] One specific stratospheric problem is that early balloons were fragile and tended to burst prematurely, particularly at low temperatures, thus undersampling higher altitudes and cold conditions.[8] Contemporary radiosondes often fail to reach 50 hPa and rarely reach 5 hPa (Figure 1). While inhomogeneities in MSU records also have a variety of causes,[1] unlike radiosondes, there is no *a priori* reason to expect MSU data to pose a greater challenge for determining stratospheric climate trends than tropospheric. Indeed, it has recently been shown that the MSU LS data suffer less bias for changes in satellite equatorial crossing time than the MSU tropospheric data.[9] Although the radiosonde record is ~20 years longer than the MSU record, stratospheric sampling by radiosondes was more sporadic in the early years, and the geographic coverage of the radiosonde network is much less complete (Figure 1).

As an overview, Figure 3 shows the general evolution of globally averaged LS temperatures as measured by radiosondes since 1958 and MSU since 1979 and estimated from the most recently produced datasets.[10–17] The data show two prominent and robust features: a long-term cooling exceeding 1 K and three instances of warming (of about 1 K in magnitude) associated with aerosols from major volcanic eruptions and lasting about 2 years. These features are larger than the uncertainty, as given by the differences between the plotted mean time series and the five different radiosonde datasets and three different MSU datasets. A third notable feature is the lack of any significant trend in globally averaged LS temperature from the mid-1990s to present.

Stratospheric Sounding Units

SSUs provide the only long-term near-global temperature data above the LS and were used in stratospheric temperature trend assessments even before MSU.[20] SSUs sense infrared radiation emitted by atmospheric carbon dioxide (CO_2) in three channels[21] extending from the upper troposphere to the lower mesosphere (Figure 2): channels 25 (with a peak sensitivity at ~30 km), 26 (~40 km), and 27 (~45 km), sometimes referred to as channels 1, 2, and 3, respectively. Synthetic channels with peak sensitivities at intermediate altitudes are constructed by combining off-nadir observations.[22]

Like MSU, the SSU was designed for weather forecasting rather than climate monitoring, and the analysis of SSU data shares many of the problems associated with MSU. Data are from a series of different satellites, with differing and drifting equatorial crossing times, frequently with little overlap between satellites. The period from 1978 to 2006 can be roughly characterized as seven segments when data from either a single or two different satellites carrying SSUs were available (see Ref 1, figure 5).

The SSU data require correction for three additional problems. First, the satellite carries a cell of CO_2, a vital part of the pressure modulator technique used to observe stratospheric emission, but the cells leak (causing an apparent but spurious increase in observed temperature), and their CO_2

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FIGURE 3 | Smoothed global mean lower stratospheric temperature anomalies for 1958–2010 based on five radiosonde [Hadley Centre Atmospheric Temperatures (HadAT),[10] Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC),[11] Iterative Universal Kriging (IUK),[12] RAdiosonde OBservation COrrection using REanalyses (RAOBCORE),[13] and Radiosonde Innovation Composite Homogenization (RICH)[14]] and three MSU [Remote Sensing Systems (RSS),[15] University of Alabama in Huntsville (UAH),[16] and NOAA Center for Satellite Applications and Research (STAR)[17,18]] datasets. Radiosonde data at different pressure levels have been averaged to correspond with the Microwave Sounding Unit (MSU) weighting function (Figure 2). The bottom trace is the mean of four of the five radiosonde datasets (excluding IUK, which does not extend beyond 2005). Anomalies are differences from 1979 to 1998 monthly mean values. Symbols indicate major volcanic eruptions with aerosols penetrating into the stratosphere in 1963 (Agung), 1982 (El Chichón), and 1991 (Pinatubo). Differences between individual datasets and the radiosonde mean are shown separately for the MSU (top) and radiosonde (middle) datasets. (Updated and modified from State of the Climate in 2008[19] and courtesy of Carl Mears, Remote Sensing Systems, and Katharine Willett, UK Met Office Hadley Centre)

content varies among SSU instruments.[23] Second, at the higher altitudes sensed by the SSU, the large diurnal and semidiurnal tides (due to absorption of solar radiation) require corrections that vary as equatorial crossing times change.[20,24] Finally, long-term temperature trends derived from SSU need adjustment for increasing atmospheric CO_2.[25] Because these corrections are particularly difficult for the synthetic channels, we do not treat those data here.

As with MSU, SSU has been replaced by AMSU, with five channels covering the domain previously observed by the three SSU channels.[23] Despite recent use of AMSU data to infer stratospheric temperature trends[26] and ongoing efforts to produce a coherent combined SSU/AMSU temperature record, such work is not yet mature enough to assess here.

Until recently, the only analysis of SSU data available in the literature was the work of Nash et al.[20,27,28] recently updated by Randel et al.[21] Liu and Weng[29] have now produced an alternative analysis for channels 25 and 26, which allows at least limited evaluation of structural uncertainty in derived trends associated with methodological choices. Figure 4 shows global temperature anomaly time series presented in these two papers and their differences for the two channels in common. In contrast to the MSU LS data (Figure 3), there are fewer independent analyses of SSU data and no radiosonde observations for comparison (except for SSU channel 25, which senses a layer similar to MSU LS; Figure 2). We discuss the long-term behavior of SSU time series in the section on *Reinvigorated Analyses of Stratospheric Temperature Observations*.

Other Observing Systems and Analyses

Early studies of stratospheric temperature trends incorporated rocketsonde observations [see World Meteorological Organization (WMO)[30] and references therein], mostly from Japan, the USA, and the former USSR, but the network is now essentially defunct. During its mid-1960s heyday, the US program launched rocketsondes at 30 sites several times per week,[30] and for a time rocketsondes were the only source of observations in the 30–70-km region.[31,32] But rocketsondes never provided global stratospheric observations; only 12 sites had coherent records spanning roughly the mid-1960s to mid-1990s.[33] Moreover, differing sensor types and changes in the corrections applied, and the lack of

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FIGURE 4 | Global temperature anomaly time series from Stratospheric Sounding Unit (SSU) data from the three SSU channels, as analyzed by Randel et al.[21] and, for channels 25 and 26, as analyzed by Liu and Weng,[29] and differences between them for channels 25 and 26. Symbols indicate major volcanic eruptions in 1982 (El Chichón) and 1991 (Pinatubo).

independent observations for comparison, pose considerable challenges to their use in trend studies.

Ground-based lidar measurements have largely superseded rocketsondes in the 30–75-km region.[34] Lidars emit laser pulses and measure their backscatter to derive atmospheric density profiles. Currently, only three stations have at least two decades of data, which are not sufficient to provide a global view of temperature trends.[21,35] Even local trends are difficult to interpret, because of the irregular observing schedules (only in clear conditions at night) and because trends at two nearby sites in Europe differ significantly, perhaps due to temporal sampling differences.[21] Nevertheless, lidars can provide some corroborative evidence for the trends estimated from satellite observations.

GNSS (or Global Positioning System, GPS) radio occultation (RO) measurements are an emerging climate monitoring technology, particularly applicable to stratospheric temperature studies. Navigational signals from GNSS satellites are received by low-Earth-orbiting RO satellites after being refracted by the intervening atmosphere. Associated delays can be converted to profiles of geophysical parameters (refractivity, temperature, and humidity).[36]

GNSS RO data are available globally and cover the entire atmospheric column with high vertical resolution (<1 km). However, broad (~200 km) horizontal weighting functions, and horizontal variability along the path, can introduce retrieval errors. Occultation measurements are not made on a regular schedule but occur when GNSS and RO satellite orbital geometries are suitable. Moreover, because obtaining temperature profiles requires additional processing, temperature data are not directly traceable to a standard and methodological choices introduce structural uncertainty.[37–40] Because RO records from a series of different measurement campaigns are short [CHAllenging Mini-satellite Payload (CHAMP): 2001–2008, Constellation Observing System for Meteorology, Ionosphere & Climate (COSMIC): 2006–present, GNSS Receiver for Atmospheric Sounding (GRAS): 2008–present, Global Positioning System/Meteorology (GPS/MET): only during 1995–1997 and sporadic], their value for trend monitoring is currently limited, although short-term trends have been estimated.[41]

Atmospheric analyses and reanalyses are potential sources of stratospheric temperature trend information. Analyses are maps of temperature data, prepared either manually or through assimilation into a model, that incorporate a variety of observation types. In stratospheric climate research (more so than for the troposphere), analyses have played an important role, with research teams at the NOAA National Weather Service[42] and at the Free University of Berlin[43,44] monitoring stratospheric conditions on a routine basis for several decades. Although important for identifying short-term stratospheric variations, such as sudden stratospheric warmings and the quasi-biennial oscillation (QBO), analyses are problematic for trend studies because they do not address potential data inhomogeneities.

Reanalyses are globally complete datasets resulting from assimilation of many types of observations into a single model to create a physically consistent rendering of the atmosphere. Owing to changes over time in the observing system, reanalyses have generally contained time-varying biases, making them ill-suited for temperature trend analyses in many regions,[4,45–51]

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particularly in the stratosphere,[21,52,53] although the newest[23] and future reanalyses may prove more applicable in this area.[45,54]

MODELING STRATOSPHERIC TEMPERATURE

Numerical models that simulate climate processes are necessary to identify causes of temperature trends and project future changes. In contrast with modeling studies of tropospheric temperature trends, where general circulation models (GCMs) quickly superseded one-dimensional (1-D) radiative convective models (RCMs) and have dominated the literature for decades,[1] a wide diversity of model types, summarized in Table 1, has been used to calculate stratospheric temperature change.

1-D (vertical) RCMs were widely used in early work,[55–57] where changes in constituents such as CO_2 and ozone were imposed on the model. In the 1970s, 1-D models, with specified surface and tropospheric temperatures, were developed that included representations of stratospheric chemistry, thereby allowing representation of feedbacks between temperature change (e.g., due to CO_2 changes) and ozone concentrations.[58–60] Because of the strong latitudinal variations in predicted changes in ozone, two-dimensional (2-D, latitude–height) models, which included the interaction between simplified dynamics, radiation, and chemistry,[61,62] played an important role in the development of understanding of stratospheric temperature change and are still in occasional use today.

Fixed dynamical heating (FDH) models were introduced in the late 1970s.[63,64] These normally 2-D (latitude–height) models assume that following a change in constituent concentrations (such as ozone or CO_2), radiative processes drive temperature change, while heating due to convergence of dynamical heat fluxes remains unchanged. The FDH assumption gives reasonable temperature change estimates, at least in low to mid latitudes, compared to GCM calculations,[64–66] at much reduced computational cost. They continue to be used today, partly because of the importance of stratospheric temperature change for the computation of radiative forcing for some climate change mechanisms (most notably changes in stratospheric ozone), and partly to diagnose causes of temperature changes in GCM experiments.

GCMs, the main modern tool for simulating stratospheric temperature change, are three-dimensional (3-D) representations of the atmosphere, sometimes coupled to a 3-D ocean model, and possibly other climate system components such as sea ice and land surfaces. GCM simulations of tropospheric climate change[67] typically do not contain sophisticated representations of atmospheric chemistry, and changes in stratospheric ozone have generally been imposed rather than fully modeled. Another historical shortcoming for stratospheric temperature studies is limited vertical extent and poor vertical resolution in the stratosphere, although many contemporary models are less restricted.

Coupled chemistry-climate models (CCMs) are atmospheric GCMs that represent stratospheric chemistry, particularly the processes most important for stratospheric ozone,[68–70] including transport of ozone-depleting substances (ODSs) into the stratosphere and gas phase and heterogeneous chemical processes involving ODSs, ozone, and other constituents. CCMs represent the troposphere, although with highly simplified tropospheric chemistry. They do not usually include ocean processes; sea surface temperatures are generally specified from observations or other models. They generally have relatively high

TABLE 1 | Comparison of Climate Model Types Used in Studies of Stratospheric Temperature Trends from the 1970s to Present, in Approximate Chronological Order of Introduction, with Earlier Types at the Top

Model Type	Geometry	Processes
One-dimensional models	1-D	Radiative transfer
		Vertical mixing (sometimes including tropospheric convection)
		Chemical processes (sometimes)
General circulation models	3-D	Radiative transfer
		Vertical mixing (convection)
		Atmospheric dynamics
2-D models	2-D	Radiative transfer
		Vertical mixing (sometimes including tropospheric convection)
		Atmospheric dynamics
		Chemical processes
Fixed dynamical heating models	Normally 2-D	Radiative transfer
Chemistry-climate models	3-D	Radiative transfer
		Vertical mixing (convection)
		Atmospheric dynamics
		Chemical processes

Geometry indicates the number of spatial dimensions represented. Physical processes include those represented explicitly or in parameterized form in most models of the type in question.

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vertical resolution in the stratosphere and simulate the main dynamical, radiative, and chemical processes that drive stratospheric temperature change. However, large differences in projected ozone changes[69,71] introduce additional uncertainty into simulated stratospheric temperature changes compared with model simulations that impose observed ozone changes.

EVOLVING UNDERSTANDING OF TEMPERATURE TRENDS

This section chronologically reviews the evolution of understanding of stratospheric temperature trends since the late 1960s. We also discuss short-term temperature variations [due to the El Niño-Southern Oscillation (ENSO), the QBO, major volcanic eruptions, and solar variations]. Temperature trends at the tropopause, the interface between the troposphere and stratosphere,[72–74] are outside the scope of this review.

A detailed review of the evolution of factors that force stratospheric temperature change (Figure 5) is also outside our scope, but a brief description is necessary to provide the context for understanding modeled and observed temperature trends.

- Carbon dioxide and other long-lived greenhouse gases (LLGHGs)—generally well-observed increase since preindustrial times.[75] CO_2-induced cooling also influences stratospheric ozone; the associated impact on temperature is now sometimes included when temperature trends are attributed to changes in CO_2.
- ODSs—well-observed increase from mid-20th century until the implementation of the Montreal Protocol on Substances that Deplete the Ozone Layer in the late 1980s, with changes in the mix of substances over time and a slow decrease

FIGURE 5 | Modeled and observed global stratospheric temperature trend profiles. *Left:* simulated global mean temperature trends for approximately 1980–2000, based on an average of several models, due to changes in long-lived greenhouse gases (LLGHGs) (including CO_2, CH_4, and N_2O) and various ozone-depleting substances (ODSs), changes in stratospheric ozone, and two different estimates (from balloon and satellite observations) of changes in stratospheric water vapor (Modified from Shine et al.[85]). *Middle:* simulated and observed 1979–2005 global mean temperature trends. Simulations are multimodel means, from seven chemistry-climate models (CCMs), of trends due to changes in LLGHGs (including CO_2, CH_4, N_2O, and associated changes in ozone and water vapor), ODSs [including chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and Halons and associated simulated changes in ozone, etc.], and natural forcings (volcanic aerosols and solar changes). Observations are from Stratospheric Sounding Unit (SSU) and Advanced Microwave Sounding Unit (AMSU)/Microwave Sounding Unit (MSU). Symbols are plotted at representative pressures for each satellite channel, and model trends, vertically weighted to correspond with these channels, are plotted at the same pressures (Modified from Gillett et al.[86]). *Right:* simulated and observed 1980–1999 near-global (70°N–70°S) temperature trends. Simulations are by 18 CCMs; individual and multimodel mean results are shown. Observations are from MSU and SSU. Error bars on observed trends are 95% confidence intervals. (Modified from CCMVal Report[69] and Forster et al.[87])

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in many of them in recent years.[52] Some ODSs [notably chlorofluorocarbons (CFCs)] could also be classified as LLGHGs but are often classified separately, as their dominant global mean effect on stratospheric temperature is associated with ozone depletion.

- Ozone—well-observed and marked springtime decrease in the Antarctic stratosphere that had become established by the early 1980s and continues to present; more modest global stratospheric decreases whose latitude and height dependence are known with less confidence. Increases in tropospheric ozone in most locations.[52,76]
- Stratospheric water vapor—evidence of increasing concentrations during the latter decades of the 20th century based on balloon-borne and satellite observations, but these are either of limited spatial extent or limited duration; better documented, abrupt decrease in about 2001[52,77–79] and increase later in the decade.[80,81]
- Solar radiation—direct observations of incoming solar radiation from satellites began in late 1970s showing an 11-year cycle and other variability.[75] Significant uncertainty in the wavelength dependence of that variability,[82–84] with potential impact on temperature.
- Volcanic aerosols—episodic injections (Figure 3) into the stratosphere resulting in sulfate particles which have an e-folding lifetime of 1–2 years. No major eruptions since Mt. Pinatubo in 1991.[75]
- Sea surface temperature—used to force CCMs; main variations are associated with ENSO and a multidecadal warming trend.

Because some of these show (coincidental or physically related) correlations (such as solar variations and volcanic aerosols, or LLGHGs and sea surface temperatures), isolating their effects is challenging.

To provide context, Figure 5 shows model-based representations of the effects of different forcings on the vertical temperature profile for a 20-year period (~1980–2000), from three 21st century studies,[85–87] two of which resulted from the Chemistry-Climate Model Validation Activity (CCMVal) involving 18 contemporary models.[69] The CCMVal simulations (Figure 5, right) show stratospheric cooling from about 100 to 1 hPa, and warming of the upper troposphere.

The net effect of LLGHG increases is cooling that increases with height. Likewise, ODSs (through their effect on ozone) cool the stratosphere, with cooling increasing with height to the stratopause (the top of the stratosphere, at ~50 km, 1 hPa). Models forced by observed ozone trends show stratospheric cooling with a more complex vertical profile than in the LLGHG and ODS cases, and they indicate that a potentially large cooling effect would result from increases in stratospheric water vapor, but with large uncertainty associated with the uncertainty in those changes[85] (Figure 5, left).

Early Model and Observational Studies (1960s and 1970s)

The earliest modeling studies discussing stratospheric temperature trends focused on anthropogenic increases in atmospheric CO_2 modifying temperature throughout the atmosphere. The seminal RCM study by Manabe and Wetherald[56] delineated the original, and remarkably enduring, framework for expectations of the vertical structure of human-induced temperature change. They were the first to point out stratospheric cooling accompanying the surface and tropospheric warming in response to a CO_2 increase. Doubling CO_2 (from 300 to 600 ppm) led to ~2.4 K surface warming and ~10 K upper stratospheric cooling,[56] emphasizing the greater sensitivity of stratospheric climate. In 1970, the influential early climate assessment *Study of Critical Environmental Problems*[88] projected that an 18% increase (by 2000) and a doubling of CO_2 would cause cooling of 0.5–1 and 2–4 K, respectively, at 20–25 km, albeit with considerable uncertainty. Associated surface warmings were 0.5 and 2 K.

Although the global warming impact of LLGHGs has dominated climate research for decades, the attention of the stratospheric climate research community soon shifted from CO_2 to ozone. In 1967, Manabe and Wetherald[56] had already shown that stratospheric temperature was sensitive to the specification of the vertical profile of ozone. During the 1970s, concerns about emissions of CFCs from various surface sources, and of oxides of nitrogen from planned fleets of supersonic aircraft, focused on potential stratospheric ozone depletion. By 1975, a US government review[89] indicated stratospheric cooling of up to 10 K, and an unknown tropospheric response, among the possible climate impacts of halving ozone concentrations; the report stressed the considerable uncertainty in this projection.

In the late 1970s, model investigations of the stratospheric temperature effects of ozone loss used either idealized ozone changes[63,64] or ozone changes computed using chemistry schemes within 1-D or 2-D

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models.[57–61] One key finding was the importance of the impact of CO_2-induced temperature change on stratospheric ozone in estimating temperature trends. The decreased stratospheric temperatures due to a CO_2 increase slowed stratospheric ozone destruction; the higher ozone concentrations caused heating that slightly offsets CO_2-induced cooling.

Meanwhile, many GCMs extended at most into the LS, and even there had poor vertical resolution. Manabe and Wetherald[56] were the first to show stratospheric cooling, and its latitude–height pattern, due to doubling CO_2 in a GCM extending to 32 km. Fels et al.[64] were the first to report the CO_2 cooling effect in a GCM extending throughout the stratosphere, with peak cooling of about 11 K at the stratopause (approximately three to six times the surface warming) for CO_2 doubling. The cooling, and its latitude–height pattern, agreed well with the first 2-D model calculations of the effect of a CO_2 doubling presented by Haigh and Pyle[61] a year earlier.

Other modeling experiments during this period led to an improved understanding of the influence of a variety of natural and anthropogenic forcings on the vertical temperature profile. Volcanic aerosols in the stratosphere were shown to cool the surface and troposphere and warm the stratosphere[90,91] (Figures 3 and 4).

LLGHGs other than CO_2 were found to have similar impacts on tropospheric temperatures to CO_2, but potentially distinct LS signatures, due to their lower infrared opacity. An increase in stratospheric concentrations of an LLGHG leads to both increased absorption of upwelling infrared radiation from the troposphere (warming the stratosphere) and increased emission of infrared radiation (cooling it); the net effect at a given altitude depends on the spectral properties of the gas and the upwelling infrared radiation, at the wavelength of interest. Optically thin gases such as CFCs absorb in the atmospheric window region, so led to warming near the tropical tropopause. Nitrous oxide (N_2O) and CFCs led to a warming of the LS, and methane (CH_4) caused cooling throughout the stratosphere.[92,93]

Observational analyses of stratospheric temperature trends during this early period were scarce, particularly above the LS. Satellite observations were not yet available, and the radiosonde network had only begun 'global' observations in 1958 [but with a strong bias toward populated Northern Hemisphere land areas in developed countries that remains today (Figure 1)]. Pioneering analysis of temperature observations by Angell,[94] using a 63-station radiosonde network[95–98] and rocketsonde data in the Western Hemisphere,[99] showed a remarkable array of signals in a relatively short record: temperature variations associated with the equatorial stratospheric QBO, stratospheric warming following the 1963 eruption of Mt. Agung in Bali, Indonesia, recent cooling of the LS, and variations in the middle and upper stratosphere that were attributed to solar cycle changes. Thus, understanding of stratospheric temperature trends during this early period was primarily based on modeling studies, mainly projecting future trends, and retrospective analysis of the relatively short radiosonde record of LS temperatures.

Assessments Focus on Forcing Mechanisms (1980s and Early 1990s)

The 1980s and early 1990s saw increased focus on the issues of stratospheric ozone depletion and LLGHG-induced climate change, and the establishment of international mechanisms for assessing and reporting scientific understanding of these issues. The 1985 discovery of large springtime depletion of ozone over Antarctica (the 'ozone hole')[100] motivated rapid growth in stratospheric research, including analyses of temperature change. The 1982 explosive eruption of the El Chichón volcano in Mexico provided an opportunity to determine the effect of the resulting sulfate aerosol on stratospheric temperatures.[101,102] The 1988 report of the International Ozone Trends Panel[30] (and a relatively minor update 1 year later[103]) and the first assessment report of the Intergovernmental Panel on Climate Change (IPCC)[104] assessed temperature trends and provide useful summaries of advances in the decade of the 1980s.

The ozone assessment[30] (prepared in accordance with the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer) devoted an entire chapter (and a large part of another chapter, on Antarctic ozone) to stratospheric temperature trends. Its summary of model simulations of 1970–1990 global mean temperature trends suggested 1.2–1.7 K decade^{-1} cooling of the upper stratosphere (at pressures less than 10 hPa), with smaller changes at LS altitudes. These simulations were not from GCMs but from models focused specifically on radiative and chemical processes, often for a particular latitude band.

However, a significant new development was the incorporation of observed historical stratospheric ozone changes in temperature trend calculations. Modeling studies that included Antarctic ozone loss suggested a substantial associated springtime cooling over Antarctica,[65,105] a conclusion subsequently supported by observations (see *Latitudinal and Seasonal*

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Structure of Trends section). WMO[30] provided an assessment of this mechanism, as well as estimates of global temperature change as a result of global changes in ozone that satellite measurements were beginning to reveal.

In assessing observed trends,[27,43,106–111] the WMO report[30] comprehensively reviewed the advantages and disadvantages of each available set of observations (radiosondes, rocketsonde, SSU, and analyses); it presented detailed comparisons of temperature time series, trends, and short-term changes (e.g., in response to El Chichón), for global and zonal means and for single locations for several levels; and it examined mechanisms controlling stratospheric temperature change, including changes in ozone, other trace gases, aerosols, solar radiation, and dynamics. The overall conclusions were that radiosonde and satellite datasets were in generally good agreement, although periods of disagreement were identified; trends based on rocketsonde data were highly uncertain; significant stratospheric cooling was limited to the Tropics and over Antarctica; and the LS warmed in response to El Chichón.

The first assessment report of the IPCC[104] (created to provide scientific underpinnings to the UN Framework Convention on Climate Change) also addressed observed stratospheric temperature trends. It concentrated on 1958–1989 trends from a 63-station subset of the global network,[95,96,107] which showed cooling of the 100–50-hPa LS layer over Antarctica, associated with the ozone hole. It also discussed the use of vertical temperature trend profiles (in the troposphere and stratosphere) as 'fingerprints' for detecting and identifying causes of climate change. The gross features of observed tropospheric warming and LS (pressures higher than 50 hPa) cooling appeared consistent with model simulations of the equilibrium response to greenhouse gas increases. However, problematic details included the inconsistency among models regarding the sign of the trend in the LS and near the tropopause, and the uncertain nature of the observations at pressures lower than 50 hPa. The ambiguity of possible causes of the stratospheric cooling (including ozone depletion, dissipation of volcanic aerosols, and increases in LLGHGs) was further complicated by recognition that the combined stratospheric cooling/tropospheric warming signal is also associated with natural climate variations (e.g., El Niño, which warms the troposphere and cools the tropical LS).[112] Nevertheless, the report found 'broad agreement between the observations and equilibrium model simulations', with the main differences being related to the altitude at which warming reverses to cooling.

A second pair of major assessments by WMO and IPCC in 1995[113,114] took a more nuanced view of stratospheric temperature trends. The IPCC Second Assessment Report[115] emphasized radiosonde data problems that led to spurious stratospheric cooling in the long-term record that begins in the late 1950s. By this time, the MSU data were featured as a complement to radiosonde data in the LS,[116] which was described as cooling at a rate of 0.34°C decade^{-1} since 1979 according to MSU, and at approximately the same rate since 1964 according to radiosonde data. But while radiosonde data homogeneity problems were starting to be recognized,[6,8] similar issues with MSU had yet to be identified.

Improved observations of ozone trends and investigations of its effects on LS temperatures[117,118] led WMO[113] to conclude that 'ozone depletion is likely to have been the dominant contributor to temperature trends in the LS since 1980 and is much more important than the well-mixed greenhouse gases'. The report also noted that other potential causes of LS temperature changes (such as changes in stratospheric water vapor) were hard to quantify.

The 1991 eruption of Mount Pinatubo provided a better opportunity to test the modeled response of stratospheric temperature to volcanic aerosol than did El Chichón, because the Pinatubo eruption injected more material into the stratosphere and was better observed. Good agreement between the observed and modeled warming of the LS[117] suggested the main mechanisms were reasonably well understood. Stratospheric temperature responses to the three major eruptions that had occurred since 1958 were found to be broadly similar,[119] but with some differences that were subsequently ascribed largely to the phase of the QBO at the time of eruption.[120]

Other developments in this period included a clear demonstration that increases in tropospheric ozone could lead to a significant cooling of the LS[121] and improved understanding of how increases in non-CO_2 greenhouse gases caused a distinct stratospheric temperature change compared to CO_2.[122]

Ozone and Water Vapor Effects Refined (Late 1990s, Early 2000s)

The years around the turn of the century saw considerable focus on stratospheric temperature trends. In 1995, SPARC [Stratospheric Processes And their Role in Climate, a core project of the World Climate Research Programme (WCRP)] established a Stratospheric Temperature Trend Assessment panel, chaired by V. Ramaswamy, 'to assess stratospheric temperature trends . . . using and intercomparing all available

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sources of data . . . including a study of the consistency of temperature trends with observed ozone trends and comparison with model predictions'.[123] As the first long-running coordinated activity in this area, the panel's contributions include the temperature-trend chapter of the WMO's *Scientific Assessment of Ozone Depletion*[124] and a review article.[33] These informed a brief discussion on stratospheric temperature in the IPCC's third assessment report,[125] which focused more on tropospheric and surface trends. The panel still exists, under the leadership of W. Randel and D. Thompson, as part of SPARC's theme of detection, attribution, and prediction of stratospheric change.

More refined observations of the vertical profile of ozone change were used in both GCM[126] and FDH[127] studies, which reinforced earlier conclusions that ozone depletion played a major role in the vertical, latitudinal, and seasonal variation of LS temperatures. However, differences among alternative LS ozone trend estimates led to differences in modeled temperature trends, particularly in the tropical LS.

Although they did not systematically compare observations and models, the SPARC panel concluded that the observed cooling in the middle and upper stratosphere exceeded expectations, given known trends in carbon dioxide and ozone.[33] This conclusion was based on an underestimate of ozone-induced cooling in the upper stratosphere, as the then-available model calculations had not extended to this height. Around the same time, several studies reported calculations that did so, using both observed and modeled ozone changes,[66,128–131] and showed greatly increased ozone-induced cooling and generally better agreement with observations.

Although work in the 1960s[56] showed the potential of changes in stratospheric water vapor to drive stratospheric temperature change, this topic was largely ignored until the late 1990s. Intriguing LS water vapor trends from balloon observations at Boulder, Colorado,[132] and short satellite records[133] were used in modeling studies[33,134] that showed LS water vapor changes could cause a cooling with a magnitude 20–30% of that due to ozone, and exceeding that of ozone in the upper stratosphere. However, uncertainty regarding both the geographical extent (in the LS) of the observed changes and their duration (in the upper stratosphere) inhibited firm conclusions.

The SPARC panel's update of trends from SSU data through 1995[33] (although Scaife et al.[28] had by then reported trends through 1997) showed a continuation of the almost linear decline in near-global temperature in the upper stratosphere/lower mesosphere. The cooling of 2.5 K decade^{-1} was larger in magnitude than trends observed anywhere else in the troposphere and stratosphere.

Shine et al.[85] produced the first multimodel comparison with observations, exploiting available FDH and GCM results using observed ozone trends, and, for the first time, results from CCMs that calculated ozone trends. Although this use of CCMs was an important methodological advance, an added complication in assessing their temperature trends was the need also to assess the quality of the simulated ozone change, which contributed to a large spread in the CCM temperature trends. In the upper stratosphere, changes in ozone and LLGHGs (of which CO_2 was the dominant contributor) appeared to explain the observed cooling, contributing approximately equally (Figure 5, left), resolving the apparent discrepancy noted earlier.[33] In the mid-stratosphere a new puzzle emerged, as the modeled cooling appeared to exceed that observed. In the LS, the situation was unchanged: ozone change was the dominant contributor, but it did not clearly explain all the observed cooling, and the possibility remained that water vapor trends might make a significant contribution (Figure 5, left).

Using radiosonde data and focusing on the tropical LS, Thompson and Solomon[135] reported much greater cooling than model expectations, and they argued for a missing mechanism. The integrity of the radiosonde data they used was subsequently challenged.[136–138]

More attention began to be focused on stratospheric temperature variations, as well as the multidecadal trend. In a GCM study, Ramaswamy et al.[139] found that 1979–2003 LS temperatures could be well simulated as a mixture of anthropogenic influences and the warming influence of the two major volcanic eruptions (El Chichón and Mt. Pinatubo) driving a step-like downward trend.[140]

Recent Advances and New Challenges (Late 2000s)

In the last 5 years, stratospheric temperature research has had four foci: reinvigorated analysis of radiosonde, MSU, and SSU data; coordinated modeling studies with sophisticated CCMs; documentation of stratospheric temperature variations associated with stratospheric water vapor changes and with two natural sources of climate variability, the solar cycle and ENSO; and investigation of seasonal and latitudinal patterns of temperature trends and their possible connection to changes in stratospheric circulation. The 2007 IPCC assessment[75] covered radiosonde and MSU advances, but stressing the troposphere and drawing on a US national assessment.[4] Growing

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recognition of linkages between ozone depletion and climate change was evidenced by dedicated chapters of both the 2006 and 2010 ozone assessments,[52,76] as well as a special report coordinated by the IPCC.[141]

Reinvigorated Analyses of Stratospheric Temperature Observations

Stratospheric climate research benefited substantially from the controversy surrounding tropospheric temperature trends;[1] increased scrutiny of radiosonde and MSU data and development of independent methods of adjusting inhomogeneous data resulted in several new LS temperature data products,[4,7,10–17,18,142] depicted in Figures 3 and 6. As a result, there are now more estimates of LS trends than during the 20th century, and, because of their convergence over time (mainly due to the smaller cooling trends in the bias-adjusted radiosonde data compared with earlier datasets), reduced uncertainty regarding the magnitude of the global mean LS cooling (about 0.3–0.5 K decade^{-1}, Figure 6).

Motivated in part by those advances, concern grew over the quality of middle and upper stratospheric SSU data, largely because only one team had analyzed the data and most of their results were reported in assessments, without the benefit of detailed methodological description in journal articles. Stimulated by the 1988 ozone trends panel report[30] and discussions of the SPARC Stratospheric Temperature Trends Assessment Panel (then cochaired by K. Shine and W. Randel), Shine et al.[25] showed that increases in atmospheric CO_2 significantly impacted the SSU weighting functions and derived temperature trends. Throughout most of the LS, adjustment made the derived trend significantly more negative (by typically several tenths of a degree per decade). Importantly, the adjustment at 5 hPa brought models and observations into much better agreement. The synthetic (or 'X') channels were not amenable to simple adjustment for the CO_2 change.[25]

FIGURE 6 | Evolution of estimates of observed cooling trends in global mean lower stratospheric (LS) temperatures during the satellite era (since 1979), based on satellite Microwave Sounding Unit (MSU) (blue) and radiosonde (red) observations. Symbols show trends for 1979 to the year plotted, as reported in the literature, except for 1979–2009 trends which were calculated for this study. Radiosonde data are vertically weighted to correspond with the MSU LS layer (Figure 2). Blue line shows trends from the current (September 2009) version of University of Alabama in Huntsville (UAH) MSU data for each year. Differences between this line and the UAH published estimates (blue circles) illustrate the degree of change in the different versions of this dataset. See Figure 3 legend for dataset names and associated references.

The SPARC panel[21] applied these SSU adjustments in an update of observed stratospheric trends. The panel expressed concern over documentation of the methodology for deriving trends from SSU data, noting that 'the details of the SSU data need to be clarified in the peer-reviewed literature' and suggesting the need for 'alternative independent SSU climate data products'. Liu and Weng[29] were the first to produce an alternative analysis for channels 25 and 26; Figure 4 compares the two analyses.

Like MSU and radiosondes, the SSU data show warming associated with the volcanic eruptions of El Chichón and Pinatubo, most marked in the two lower altitude channels, 25 and 26 (Figures 4 and 7). The upper stratospheric channel (27) indicates a cooling of about 3 K between 1978 and 2006, all of which occurred prior to 1996. The two channel 26 analyses show quite different characteristics; Randel et al.[21] indicate an overall cooling of around 0.5 K, while Liu and Weng[29] indicate a small warming. For channel 25, the overall cooling is quite similar (about 1 K) and the two time series are in particularly good agreement from 1989 onwards, but differ in the period following the El Chichón eruption, 1985–1989 (Figure 4).

Neither of the two SSU methodologies[20,29] is sufficiently well documented to confidently identify the reasons for these differences, but some tentative conclusions can be drawn. First, the disagreement between the channel 25 analyses between 1985 and 1989 (note in particular the abrupt decrease in 1989 in the Liu and Weng data[29]) appears to be associated with a reported radiometric error (of order 0.5 K) on the SSU instrument on the NOAA-9 satellite, considered in other analyses.[20,143] Other shifts in the differences between the analyses seem to coincide with changes in instruments (e.g., the 1995 transition between NOAA-11 and NOAA-14), suggesting that different data merging methods may explain the differences.

The channel 26 series are more problematic, with a 1 K relative drift between the two analyses over the 30-year record, larger than the trend in either of them (Figure 4). One analysis[29] shows no

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FIGURE 7 | Global mean temperature anomalies for 1979–2005 in the four vertical layers sampled by Microwave Sounding Unit lower stratosphere (MSU LS),[15] Stratospheric Sounding Unit (SSU) 25, SSU 26, and SSU 27.[21] The bottom trace is a combination (the average of channels 25 and 27 minus channel 26) of time series for the SSU layers from the models and as observed. See Figure 2 for the vertical layers. Observations are shown in black and simulations from eight models participating in Chemistry-Climate Model Validation Activity (CCMVal)[69] are shown in red.[86] All anomalies are relative to the full 1979–2005 period.

net mid-stratospheric cooling, while the other[21] has a significant trend. Again, some of the differences seem to be associated with satellite changes (NOAA-9 to NOAA-11 in 1989 and NOAA-11 to NOAA-14 in 1995). Another large change corresponds to a period when this channel's cell was leaking rapidly (for NOAA-7 between 1981 and 1983[20]). Liu and Weng[29] do not account for changes in observing time, due to either the change in satellite or drift in the original satellite orbit. This decision was based on earlier work relevant to the tropospheric MSU channel 2 and analysis of a period of small drift of the NOAA-15 satellite. In contrast, Nash and Forrester[20] do account for this effect.[24]

It is unclear if this diurnal effect explains the differences in Figure 4 or if both analyses of channel 26 have problems. All the CCMVal models show a remarkable vertical consistency of temperature variations in the SSU sampling region, with simulated channel 26 anomalies differing from the average of simulated channels 25 and 27 by less than 0.1 K (Figure 7). The observed difference in the Randel et al.[21] analysis is an order of magnitude larger and has a marked downward trend (Figure 7, bottom). While it is possible that the models are omitting other causes of temperature trends, these would have to be rather specific to the mid-stratosphere to explain the difference, which we judge unlikely.

Efforts underway to incorporate SSU data into reanalyses,[23,50] in which such issues as tidal corrections will be more explicitly taken into account, may allow improved exploitation of SSU data for trend analyses in future. However, severe difficulties using SSU data in reanalyses have been identified,[50,51] so reanalyses are not currently a reliable source of temperature trends in the middle to upper stratosphere.

Chemistry-Climate Model Advances

The most noteworthy modeling accomplishment of the past decade has been the development and intercomparison of many CCMs.[69,144,145] Although simulating stratospheric ozone changes has been the prime purpose of these activities,[52,76] high vertical resolution and relatively complete treatment of stratospheric processes make the models also applicable to stratospheric temperature studies. Moreover, because the zonal mean stratospheric temperature response to 3-D ozone changes differs from the zonal mean temperature response to zonal mean ozone changes,[146–148] CCMs are likely to simulate more realistic stratospheric temperature changes than GCMs with prescribed zonal mean ozone changes. Two model intercomparison projects[69,144] standardized experiments from multiple models. Comparison of the modeled 1980–1999 global mean temperature trends with observations[68,69] showed a large spread in model trends (about 1 K decade^{-1} in the upper stratosphere and LS and about 0.5 K decade^{-1} in the mid-stratosphere). The CCM temperature responses to the El Chichón and Mt. Pinatubo eruptions varied greatly among models, as also seen in comparison of GCMs.[149,150] However, the multimodel mean long-term global trends were in broad agreement with observations (Figure 5, right and Figure 7).

To distinguish LLGHG and ODS contributions to stratospheric temperature trends, studies have either used CCM simulations with LLGHG or ODS changes only,[86,151,152] or have applied regression analysis to simulations including both forcings.[152–154] The attribution of temperature trends to ODSs differs from earlier simulations, which applied prescribed ozone changes from whatever cause.[73,124,139,155]

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Identifying separate ODS- and LLGHG-attributable temperature change components results in less cooling being attributed to LLGHGs (as LLGHG-induced cooling leads to an increase in ozone through most of the stratosphere, which partly cancels the CO_2-induced cooling). It also results in more cooling being attributed to ODSs than to ozone (as the observed ozone depletion is a residual of a larger ODS-induced depletion, which has been partly cancelled by CO_2-induced ozone increases).[153,154] The distinction between the two approaches lies in whether the warming due to LLGHG-induced ozone increases is associated with ozone forcing[73,124,139,155] or with LLGHG changes.[86,151,152,154] Consistent with earlier results,[85] LLGHGs were the biggest contributor to modeled upper stratospheric cooling over this period, and ODSs were the biggest contributor to the cooling in the LS[73,124,139,155] (Figure 5).

In a related approach, Stolarski et al.[70] attributed their CCM stratospheric cooling to CO_2, methane, and ODSs, and accounted for the impact of methane on stratospheric water vapor concentrations (via methane oxidation) and HO_x levels, which lead to ozone destruction. At 1 hPa, the cooling attributed to methane between 1979 and 1998 (about 0.2 K decade^{-1}) is more than 50% of that due to CO_2; the calculations of Myhre et al.[156] indicate that around half of that CH_4-induced cooling is due to stratospheric water vapor increases.

Gillett et al.[86] used single-forcing CCM simulations[151] to assess the causes of observed 1979–2005 stratospheric temperature changes. Comparison of observed zonal mean MSU LS trends with the simulated response to combined anthropogenic and natural forcings in the CCMVal-2 simulations indicates broad consistency, although the models show enhanced annual mean cooling over Antarctica not found in the observations, which show a relatively uniform cooling at all latitudes.[86] (See *Latitudinal and Seasonal Structure of Trends* section for further discussion of the latitudinal variation of trends.) An attribution analysis identified a detectable influence of ODSs and natural forcings, but no detectable LLGHG contribution.[86] Higher in the stratosphere, the simulated SSU 26 cooling is stronger than that observed, while the SSU 27 cooling is somewhat weaker (Figure 5, right), although, as discussed earlier, the observed SSU trends are questionable.[69] The influence of natural and anthropogenic forcings could be detected in the SSU trends, but LLGHG and ODS influences could not be separately detected.[86]

Solar, ENSO, and Water Vapor Effects

Short-term stratospheric temperature variations influence detection and attribution of trends. An impact of solar variability on stratospheric temperature was shown decades ago.[43,157–159] With longer observational datasets now available, and CCMs that explicitly simulate the effect of solar variability, there has been renewed interest;[160] this has allowed better estimates of the strength of temperature variations associated with the 11-year solar cycle,[161] due to the direct effect of changing incoming solar radiation and the indirect effect of solar-cycle-induced ozone changes.[162] Randel et al.[21] using regression analysis on SSU and MSU data, found the average peak-to-peak amplitude due to the solar cycle increased from about 0.5 K in the tropical LS to over 1 K in the upper stratosphere. A similar method applied to ECMWF 40-Year Re-analysis (ERA) data[163] found a more marked vertical structure with a stratopause peak reaching 2 K, a mid-stratospheric minimum, and a secondary LS peak exceeding 1 K. Austin et al.[164] compared a range of CCM simulations, finding a response with a peak of around 0.8 K at the tropical stratopause, a relative minimum in the mid-stratosphere, and a secondary peak (not always statistically significant) in the tropical LS. However, the ability of CCMs to simulate the stratospheric temperature response to solar variability is heavily dependent on the specification of the wavelength dependence of that variability, which has recently been questioned.[84]

On shorter time scales, stratospheric temperature variability associated with ENSO has been better quantified through modeling and observational studies. Stratospheric cooling (above tropospheric warming) in the tropics during El Niños had been documented in the 1990s[112,165] and more recently, an Arctic wintertime response, modulated by the QBO, has also been identified in observations[166–169] and models[170–173] in association with changes in the strength of the polar vortex.

Given the sensitivity of temperature trends to stratospheric water vapor[85,127] (Figure 5, left), recent investigations of water vapor trends have a bearing on our understanding of temperature change. There have been updated analyses of trends in stratospheric water vapor[78,81] and particular attention to a marked and sudden decrease in stratospheric water vapor after 2001, and its relationship to tropical tropopause temperatures,[52,77–79] but no dedicated analyses of the influence of these changes on stratospheric temperature.

Latitudinal and Seasonal Structure of Trends

This review has focused on global and annual mean trends, and their height variation, but observed LS temperature trends have exhibited notable spatial and seasonal structure, particularly in high latitudes

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FIGURE 8 | Global map (left) and latitudinal variation (right) of Microwave Sounding Unit lower stratospheric (MSU LS) temperature trends during 1979–2010, based on Remote Sensing Systems (RSS) version 3.3 data. Error bars on zonal mean trends are 2-σ estimates of internal data uncertainties.[176] (Figure courtesy of Carl Mears, RSS)

(Figures 8 and 9), which may be explained by several mechanisms. First, model studies indicate that even a homogeneous change in LLGHG concentrations (and in the absence of atmospheric circulation changes) can lead to a significant meridional variation in temperature change.[64,134] Second, some changes in forcing agents have considerable spatial and seasonal structure (the springtime Antarctic ozone hole is an obvious example), causing local departures of temperature trends from their global and annual mean.[127,130] Third, changes in dynamical heat transport (e.g., because of changes in the strength of the winter polar vortex in the LS or in the Brewer-Dobson overturning circulation of the global stratosphere) can also lead to spatial and seasonal variations in temperature trends[65,66,174] sometimes reinforcing radiatively driven temperature trends.[175] Dynamical changes are not believed to be capable of generating appreciable globally averaged temperature changes at any given pressure level, because conservation of mass dictates that enhanced ascent at one latitude (and associated adiabatic cooling) must be balanced by enhanced descent at another (with associated adiabatic warming). Detailed modeling studies are generally required to infer if observed variations in temperature trends have a radiative or dynamical cause, or some combination of the two.

In the annual average, MSU LS data indicate that zonal mean 1979–2010 cooling trends have been largest in the Antarctic, associated with the maximum in stratospheric ozone depletion there (Figure 8). Note that this latitudinal structure was not apparent in 1979–2005 trends,[21,86] due in part to the anomalously warm conditions in the Antarctic LS during 2003–2006, which were followed by anomalously cold conditions during 2007–2010. Interpreting these latitudinal trend variations in MSU data is complicated by the broad MSU LS weighting function and the high tropical tropopause: MSU LS samples more of the upper troposphere in the Tropics than at higher latitudes (Figure 2).

Radiosonde data at 50 hPa (a stratospheric level at all latitudes) and MSU LS data for 1979–2009 show cooling of the tropical LS in all months, but it is largest between June and January (Figure 9). Fu et al.[177] suggest these seasonal differences in the tropics are related to changes in stratospheric circulation, but Free[179] notes that the seasonal variation in tropical 50-hPa trends found in multiple radiosonde datasets is mainly due to temperature changes in the mid-1990s.

The seasonal trend differences appear to be larger in the polar regions, with greatest cooling in the spring,[135] but trend uncertainties are larger here (Figure 9), due to the greater interannual variability in higher latitudes, poor sampling by radiosondes, and disparities among the available datasets. Hu and Fu[180] focus on a 1979–2006 warming observed in part of the Southern Hemisphere high-latitude LS in early spring. They attribute it to increased dynamical heating, which they reproduce in a simulation with prescribed SST changes; similarly, they find that early winter warming in the Northern Hemisphere is reproduced in simulations with prescribed observed SSTs, associated with a strengthened Brewer-Dobson circulation.[180]

Given the observational uncertainty, conflicting reported seasonal and latitudinal patterns of trends, and the complex evolution of LS temperature, further study is needed to clarify the nature of the trends and the possible role of stratospheric circulation changes.

SYNTHESIS AND CURRENT CHALLENGES

Since the advent in the 1960s of simple models showing the effect of changes in greenhouse gas concentrations on stratospheric climate, and accelerated by the increased attention to ozone depletion in the 1970s and 1980s, research has identified potential causes of past and future stratospheric temperature change and showed evidence of temperature trends in available observations over the past three to five

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FIGURE 9 | Lower stratospheric (LS) temperature trends during 1979–2009 as a function of latitude and month from Microwave Sounding Unit (MSU) LS observations (top) and radiosonde 50-hPa observations (bottom). Each panel shows a composite of trend estimates from different datasets, including the Remote Sensing Systems (RSS), University of Alabama in Huntsville (UAH), and NOAA Center for Satellite Applications and Research (STAR) Microwave Sounding Unit (MSU) datasets and the Hadley Centre Atmospheric Temperatures (HadAT), RAdiosonde OBservation COrrection using REanalyses (RAOBCORE), Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC), and Radiosonde Innovation Composite Homogenization (RICH) radiosonde datasets. Areas without stippling have trends that are statistically significant at the 95% confidence level in all datasets in the composite and all are of the same sign. (Updated and modified from Fu et al.,[177] Forster et al.[178] and Free.[179] Figure courtesy of Melissa Free, NOAA Air Resources Lab)

decades. But while tropospheric temperature trend research[1] focused on the rate of change, stratospheric investigations have concentrated on the causes, with greater reliance on model simulations and less attention to understanding observations (particularly in the middle and upper stratosphere).

Analyses of LS observations from radiosondes and AMSU/MSU all show cooling of about 0.4 K decade^{-1} over the past three decades (Figures 3, 5, 6, 8, and 9), and their differences suggest an uncertainty of about ±0.2 K decade^{-1}; however, the number of analyses is small and actual uncertainties may be larger (Figure 6). Recognition and adjustment of spurious signals in radiosonde data have yielded smaller cooling trends than in unadjusted radiosonde data, but greater cooling than MSU, and there is lingering concern as to whether these problems have been (or ever can be) fully resolved.

Models of several sorts indicate that stratospheric cooling trends have been driven largely by changes in greenhouse gases (mostly CO_2), ozone, and perhaps water vapor (Figure 5). In the LS, ozone depletion has been the dominant driver, and models reproduce the evolution of global mean temperature reasonably well, including the temperature spikes (~1 K) following major volcanic eruptions and the observed lack of significant global and annual mean trend since the mid-1990s (Figure 7).

A relatively recent development has been the attribution of temperature changes to particular causes, including their indirect effects (e.g., a CO_2 increase causing cooling that causes ozone increase and a partially compensating warming). The highly uncertain water vapor trends introduce considerable uncertainty into comparisons of simulated and observed stratospheric temperature trends. There is little hope of improving observational estimates of past trends in water vapor due to the paucity of high-quality observations in the upper troposphere and stratosphere.

Lessons learned about data problems at lower altitudes have heightened concerns over the robustness of estimated trends at higher altitudes, where, until quite recently, the community has largely relied on a single, poorly documented analysis of SSU data. Because there are no complementary global observations, characterizing structural uncertainty is more difficult than for the LS. The very recent release of a second SSU analysis has allowed a limited first comparison with the older methodology (Figure 4) and with model simulations (Figure 7), raising questions about all SSU datasets. Thus, observed temperature trends in the upper and middle stratosphere are considerably more uncertain than in the LS. Nevertheless, current analyses indicate global average temperature decreased from the late 1970s to the mid-1990s and has since stayed relatively constant.

The lack of temperature trend throughout the stratosphere for the past 15 years has not been the subject of detailed analysis, although stable LS

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temperatures since 1995 are also reproduced in simulations including observed variations in ODSs, LLGHGs, volcanic aerosol, and solar irradiance (Figure 7). Presumably, the combined and compensating effects of these changes explain the lack of global and annual mean trend, but quantitative attribution studies of this period, during which the stratosphere has been unaffected by volcanic aerosols, have yet to be made.

Stratospheric temperature variability associated with natural climate variations was recognized in early studies and has been more extensively analyzed over time. Major transient stratospheric temperature increases can result from volcanic eruptions (Figures 3, 4, and 7), at least into the middle stratosphere, but simulated warming spans a wide range of magnitudes. Solar variations become increasingly significant in the upper stratosphere. The role of ENSO in the stratosphere, in both the tropics and extratropics, and connections between stratospheric temperature and circulation changes are emerging topics in the overall understanding of stratosphere/troposphere linkages in interannual climate variability.

Reliable simulations of stratospheric temperature change are needed for accurate projections of stratospheric ozone and radiative forcing. Understanding of the nature and causes of stratospheric temperature changes has increased markedly in the past two decades, due to international climate and ozone assessments and intercomparison exercises as well as individual scientific papers. However, that work has revealed areas of considerable uncertainty in analysis of observations and in knowledge of the mechanisms that drive temperature changes. While overall the simulated evolution of middle and upper stratospheric temperatures in the latest coupled CCM simulations agrees reasonably well with observations, unless we can increase confidence in temperature trends derived from satellites, the extent of that agreement is difficult to assess (Figure 7). In the LS, the availability of several alternative observational datasets enhances confidence in the robustness of current understanding.

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