Secular changes in the tropical stratospheric water vapour entry induced by the Indo-Pacific warm pool warming

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Highlights:
• The tropical lower stratosphere water vapour (SWV) experiences a drying process during 1984-2020 in both linear and nonlinear perspectives.
• The Indo-Pacific warm pool (IPWP) is the main factor in such drying of the tropical stratosphere.
• IPWP leads the coldest point region cooler modulating tropical SWV entry by enhancing equatorial waves.

ABSTRACT
A decreasing trend in the tropical (30°S–30°N) stratospheric water vapour (SWV) entry in recent four decades (from 1984 to 2020) is detected based on the Stratospheric Water and OzOne Satellite Homogenized (SWOOSH) measurements and the ERA5 reanalysis dataset using linear regression and Ensemble Empirical Mode Decomposition (EEMD) analysis. With the concurrent warming of the SST, the Indo-Pacific warm pool (IPWP) appears to be the most significant region among the tropical oceans based on correlation analysis. More than 43% of the decreasing tropical lower SWV trend is likely to be related to the IPWP sea surface temperature (SST) warming. To validate this relationship, two groups of idealized runs are carried out with version 4 of the Whole Atmosphere Community Climate Model (WACCM4) and version 5 of the Community Atmosphere Model (CAM5). Both simulations agree with the observational-based linkage. The IPWP-SST-warming forced simulations show that the temperature in the tropical tropopause has decreased at the rate of around 0.318 K per decade in the coldest point region, as the tropical convection over the IPWP has become more vigorous and excited stronger equatorial waves to produce adiabatic cooling around tropopause. This cooling tropical tropopause leads to a dehydrating tropical lower stratosphere at the rate of 0.025 ppmv per decade, as expected by the freeze-drying mechanism. These results imply the substantial warming trend of IPWP is an important factor for the long-term trend of the tropical SWV entry under climate change, and a better representation of this relationship in the model is critical for the SWV projection under future climate scenarios.

Keywords: Stratospheric water vapour; Indo-Pacific warm pool; Trend; Tropopause; Coldest point region

Introduction
The stratospheric water vapour (SWV) mainly originates from the troposphere: the moist air parcels at the bottom of the troposphere ascend, reaching the tropical tropopause layer (TTL) between 14–18.5 km, experiencing a severe dehydration process at the TTL (because the TTL has the coldest temperature in the lower atmosphere) (Gettelman and Forster 2002; Fueglistaler et al. 2009), then arriving in the stratosphere. The SWV is suggested to contribute significantly to global climate change by altering the infrared opacity of the atmosphere (e.g., Soden and Held 2006), providing a strong positive feedback at +0.3 W/(m²·K) to global warming (Dessler et al. 2013). When the SWV increases, it subsequently leads to warming in the
troposphere and cooling in the stratosphere, and the warmer troposphere will, in turn, increase the SWV (Rind and Lonergan 1995; de F. Forster and Shine 1999; Solomon et al. 2010; Dessler et al. 2013; Fu et al. 2015), and by this positive feedback, the increase of the SWV will accelerate the rate of increase in global surface temperature and vice versa. Meanwhile, the SWV participates in stratospheric chemical processes as the primary source of stratospheric hydrogen oxide radicals. For example, it strongly affects heterogeneous chemistry on cold sulfate aerosol and the formation of polar stratospheric clouds, which promote chlorine activation and polar ozone loss (Evans et al. 1998; Shindell 2001; Stenke and Grewe 2005; Tian et al. 2009). So, it is critical to understand the decadal and long-term SWV variability and the relevant physical processes.

Previous studies have already documented that the TTL temperature is very important for SWV variability. Because the TTL is the main area where air enters the stratosphere, changes in SWV are largely related to the tropical SWV entry and the TTL temperature largely determines the SWV entry values (Brewer 1949; Randel et al. 1998; Scaife et al. 2003; Fueglistaler et al. 2005; Rosenlof and Reid 2008; Schoeberl and Dessler 2011; Grise and Thompson 2012; Dessler et al. 2013). Therefore, the multi-timescale variations of the SWV ranging from daily to decadal timescales (e.g., Randel et al. 2004; Fueglistaler and Haynes 2005; Fujiwara et al. 2010; Hegglin et al. 2014) can be traced to TTL temperature variations (e.g., Randel et al. 2007; Rosenlof and Reid 2008; Randel 2010; Fueglistaler et al. 2013;Randel and Jensen 2013). As a layer between the stratosphere and troposphere at about 14–18.5 km (Fueglistaler et al. 2009), the TTL temperature is affected by both the stratospheric (top-down) and tropospheric (bottom-up) processes, including variability of the Brewer-Dobson circulation (BDC, a stratospheric mean meridional circulation), the quasi-biennial oscillation (QBO), and tropical convection (bottom-up). Because the TTL temperature and SWV entry values are generally the results of the interplay between the top-down and bottom-up processes, the SWV’s interpretation (e.g., Hegglin et al. 2014) and prediction (e.g., Gettelman et al. 2010) are complex. In the tropical troposphere, anomalous deep convection induces upward motion near the tropopause and thereby results in a cooling of the TTL (Highwood and Hoskins 1998). And deep convection is usually associated with the El Nino Southern Oscillation (ENSO), Asian Monsoon, and Madden-Julian Oscillation exert tropical planetary waves including the equatorial Rossby wave and Kelvin wave. In the stratosphere, the acceleration of the BDC causes the adiabatic cooling of the TTL through the enhanced large-scale vertical ascending motions, and vice versa (Holton et al. 1995; Thompson and Solomon 2005). Fu et al. (2010) also documented that the strength of the BDC is a main factor driving the seasonal variability of the TTL temperature. In short, the TTL temperature variability is driven by both the tropospheric (bottom-up) processes and the stratospheric (top-down) (Kumar et al. 2014).

By using balloon-borne water vapour profiles above Washington DC and Boulder, Oltmans et al. (2000) observed an increase of lower SWV by about 1% per year during the 1960s and 1990s. This agrees with the Third Assessment Report of the IPCC, which reported water vapour in the lower stratosphere is likely to have increased by about 10% per decade since the beginning of the observational record. Dessler et al. (2013) showed observational evidence for stratospheric water vapour feedback—a warmer climate increases stratospheric water vapour, and because stratospheric water vapour is itself a greenhouse gas, this leads to further warming. Lin et al. (2017) found that the tropical tropopause layer will become warmer in response to carbon dioxide increase and surface warming. A few numerical studies reported that a moist stratosphere occurs under global warming scenario by using the forcing of quadrupling CO2 in different general circulation models (Zhang and Huang 2014; Banerjee et al. 2019; Li and Newman 2020; Wang and Huang 2020; Xia et al. 2021b). Keeble et al. (2021) suggested that CMIP6 multi-model mean SWV mixing ratios in the tropical lower stratosphere have increased by 0.5 ppmv from the pre-industrial to the present-day period and are projected to increase further by the end of the 21st century. Keeble et al. (2021) further pointed out that the largest SWV increases (2 ppmv) are simulated under the future scenarios with the highest assumed forcing pathway (e.g., SSP5-8.5).

However, the increasing trend of the SWV seems stopped or becomes blurred after the 1990s. Although the SWV above Boulder is reported to increase during the periods of 1992 to 2002 in the balloon water vapour data (Randel et al. 2004). This increasing trend is not reproduced well by satellite data. Randel et al. (2004) also documented that the SWV near Boulder, Colorado (40degN) and the tropical mean (60degS-60degN)
SWV have no significant trend in 1992-2002 based on the HALOE data. Besides, the Fifth Assessment Report of the IPCC (IPCC5, 2014) documented that the near-global satellite measurements of SWV show substantial variability but small net changes for 1992-2011, i.e., the satellite data show no clear trends for the SWV. Randel et al. (2006) even reported that the near-global SWV after 2001 decreased (or had persistent low values beginning in 2001), and this near-global SWV decrease is attributed to the enhanced tropical upwelling after 2001. Hurst et al. (2011) analyzed the balloon-borne SWV over Boulder, Colorado, then reported the multi-decadal variability of the SWV; the SWV increased by an average of 1.0 ± 0.2 ppmv (27 ± 6%) during 1980-2010, but in 2001-2005, it has an opposite trend to other periods. Recently, another strong drop is reported in the tropical SWV (10°S-10°N, similar to the SWV drop observed in the year ~2000) was observed in 2011-2012 (Urban et al. 2014). Hegglin et al. (2014) using observation data revised by transfer function found a negative trend in the lower and mid-stratosphere. Dessler et al. (2014) revealed that water vapour entering the stratosphere has no firm evidence of trend. Konopka et al. (2022) suggested that the stratosphere has become wetter after 2000. Tao et al. (2023) found that SWV has a robust multi-decadal variation and short-term trends in SWV are closely related to this multi-decadal variation. These imply that there are great uncertainties in the trends of SWV and the trends are sensitive to the period focused on.

Many studies have suggested that tropical oceans have a crucial effect on the stratosphere (e.g., Hu et al. 2014; Hu and Guan 2018; Xie et al. 2020b; Xie et al. 2020a; Xia et al. 2021a). As an important component of the stratosphere, the SWV is no exception. Scaife et al. (2003) have pointed out that a positive trend in water vapour of around 0.1% per year and ENSO effects appear to explain no more than about one-tenth of the long-term trend by using model and observational data. Tropical SST variability, especially ENSO, has been known to be an important factor in determining the amount of water vapour being uplifted to the upper tropospheric region and the lower stratosphere by altering tropical convection (Su et al. 2006; Rosenlof and Reid 2008; Liang et al. 2011; Xie et al. 2012; Garfinkel et al. 2013a; Garfinkel et al. 2013b; Avery et al. 2017; Su et al. 2020). The tropical SST has been suggested to contribute to the drop of the lower stratospheric water vapour during 2000 (Brinkop et al. 2016; Ding and Fu 2018). The Indo-Pacific Warm Pool (IPWP) has been also documented as a vital region that affects the stratosphere and tropical lower SWV (Xie et al. 2014; Xie et al. 2018; Zhou et al. 2018). The warm phase of IPWP causes a drier lower stratosphere and vice versa. Zhou et al. (2021) further pointed out that such impact has seasonality and hemispheric differences. Almost the entire tropical ocean shows a warming long-term trend in SST over the last century (Deser et al. 2010). The tropical western Pacific is warm faster than the eastern Pacific in observations (Cane et al. 1997; Kanamitsu et al. 2002; Compo and Sardeshmukh 2010; Zhang et al. 2010; Li et al. 2017). There is widespread warming across the tropical Indian Ocean basin and SSTs have reached 28 degC in the western Indian Ocean, which has expanded the Indo-Pacific warm pool region defined by the 28 degC isotherm westward (Roxy et al. 2015). It is quite possible that the zonally asymmetric warming trend of tropical oceans will further influence the SWV entry and provide the principal source for its decadal trend. Previous studies have shown the impact of IPWP on interannual variability of tropical lower SWV and discussed its seasonal and hemispheric differences. However, the impact of IPWP on tropical SWV entry over longer time periods is unclear, especially when the IPWP is substantially warming in the past forty years. Therefore, in this study, we seek to understand the impact of IPWP continuous warming on tropical SWV entry in recent decades.

In short, the decadal or long-term changes of the tropical SWV during the past decades seem not to strictly follow the presumed long-term increasing trend under global warming. So, we try to revisit and interpret the decadal or long-term change of the SWV with longer observations for the period 1984-2020 and explore the potential impact of IPWP warming on it. The remainder of the paper is arranged as follows. The data, model, and methods we used are presented in Section 2. In section 3, we revisit the long-term trend of SWV for the period 1984-2020, then focus on its link with the warming of IPWP. Section 4 is a summary of the principal findings.
Data, model and methods

Water vapor data

Stratospheric Water and OzOne Satellite Homogenized (SWOOSH) is a merged data set that ranges from 1984 to the present containing multiple satellite data and it not only offers values of SWV but also provides some ancillary information like standard deviation, number of data points and others (Davis et al. 2016). In addition, it also supplies a combined product which is a weighted mean value from the available satellite measurements mentioned above and it has a fabulous advantage that when one satellite measurement is missing, others will be filled in by using different algorithms. SWOOSH has been used in some studies (Hardiman et al. 2015; Gilford et al. 2016). Our study used this combined product with 31 pressure levels from 316 to 1 hPa and the version of SWOOSH is v2.7.

In addition to SWOOSH, water vapour of ERA5 was also analyzed for comparison. ERA5 which covers the period from 1979 to the present, is the latest global atmospheric reanalysis product obtained from European Centre for Medium-Range Weather Forecasts (ECMWF). Based on the 4D-Var data assimilation scheme and Integrated Forecast System (IFS) CY41R2, it covers the earth with a 30 km horizontal grid and 137 hybrid sigma/pressure levels from the surface to 0.01 hPa (Hersbach et al. 2020). And the resolution we used is 0.25deg x 0.25deg in the horizontal and 37 levels from 1000 hPa to 1 hPa in the vertical. Because ERA5 has a cold bias in the lower stratosphere during 2000 and 2006, ERA5.1 is applied in this special time.

Meteorological data

Besides ERA5, the major meteorological data we also used is Japanese 55-year Reanalysis (JRA-55). JRA-55 is conducted by Japan Meteorological Agency (JMA) and JRA5 is a comprehensive climate dataset with the applicant of 4D-Var. It covers the period from 1958, coinciding with the establishment of the global radiosonde observing system. The resolution we used is 1.25deg x 1.25deg in the horizontal and 37 levels from 1000 hPa to 1 hPa in the vertical.

Another relevant meteorological data is sea surface temperature, and Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) data set was applied in our study. It is mainly from Met Office Marine Data Bank (MDB), and it also covers data from Global Telecommunications System (GTS) since 1982. To enhance the coverage of data, when data from MDB is missing, the monthly median SSTs for 1871-1995 from the Comprehensive Ocean-Atmosphere Data Set (COADS) (now ICOADS) are included (Rayner et al. 2003). And its resolution is 1deg x 1deg.

Model

The Community Earth System Model version 1 (CESM1), developed by National Center for Atmosphere Research (NCAR), can simulate the state of climate from the past to the future. It consists of several relatively independent component models, including atmosphere, ocean, land, land ice, sea ice, and so on, and all of them have their own spatial resolutions. Besides, CESM1 has a central coupler that can exchange energy and information between different component models (Hurrell et al. 2013). In our study, we used version 5 of the Community Atmosphere Model (CAM5) to design experiments, which is one of the vital component models of CESM1, to simulate global atmospheric activity. CAM5 can not only run as one of the component models of CESM1 but also run as an independent model. It applies 30 vertical levels from the ground to 3.64 hPa. Version 4 of the Whole Atmosphere Community Climate Model (WACCM4), a comprehensive numerical model based on CAM, was also used in the experiment design. It can extend from the surface to the thermosphere, namely, from the surface to 5.1x 10-6 hPa (about 140 kilometers) with 66 vertical levels. In our study, the finite-volume dynamical core was applied in both CAM5 and WACCM4. We used the 1.9deg x 2.5deg medium resolution version which includes 96 longitude and 144 latitude points.

CAM5 and WACCM4 are employed to investigate how and to what extent SWV entry changes in response to IPWP warming. WACCM4 can capture the negative relationship between the IPWP SST anomalies and the tropical SWV entry (Xie et al. 2018; Zhou et al. 2018). Two groups of experiments are carried out, which involve a control group forced by observed SST from 1955 to 2005 (E0, E1) and another forced by
the observed SST in the IPWP region only (E2, E3). Details of transient experiments can be referred to in Table 1. Due to the limitation of WACCM4, E0 and E2 run only from 1955 to 2005. So, although CAM5 in E1 and E3 run from 1900 to 2005, we use the same period as WACCM4 in E0 and E2. We evaluate the two modes using control runs (E0, E1) by comparing them with the observational data and reanalysis data. Both can represent the structures in SWV and tropical tropopause temperature, with the pattern correlations exceeding 0.7 between observed and simulated climatology (Fig. S1 and Fig. S2).

Table 1. The detailed design of experiments. For WACCM4, the experiments are based on F_1955-2005-WACCM_CN compset. The experiments of CAM5 are based on F_AMIP_CAM5 compset.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Designs</th>
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<tr>
<td>E0</td>
<td>Purpose: simulate historical climate from 1955 to 2005 in WACCM4. Forcings: HadISST used for SST; surface emissions scenario based on RCP4.5 emissions scenario from Coupled Model Inter-comparison project 5 (CMIP5); spectrally resolved solar variability; the SPARC CCMVal REF-B2 scenario recommendations applied to volcanic aerosols; Quasi-Biennial Oscillation (QBO) determined by the observed zonal wind.</td>
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<tr>
<td>E1</td>
<td>Purpose: simulate historical climate from 1900 to 2005 in CAM5. Forcings: HadISST used for SST; surface emissions scenario based on RCP4.5 emissions scenario from CMIP5; spectrally resolved solar variability; the SPARC CCMVal REF-B2 scenario recommendations applied to volcanic aerosols.</td>
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<tr>
<td>E2</td>
<td>Purpose: simulate climate from 1955 to 2005 under the influence of IPWP warming in WACCM4. Forcings: The same as E0, but HadISST used for SST, 12-month cycle climatological means from 1955 to 2005 used except IPWP (30°S to 30°N, 30°E to 180°) where based observed SST.</td>
</tr>
<tr>
<td>E3</td>
<td>Purpose: simulate climate from 1900 to 2005 under the influence of IPWP warming in CAM5. Forcings: The same as E1, but HadISST used for SST, 12-month cycle climatological means from 1900 to 2005 used except IPWP (30°S to 30°N, 30°E to 180°) where based observed SST.</td>
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Methods

In our study, the region (30°S-30°N, 30°E-180°) was used to represent IPWP. For observational data and reanalysis data, anomalies are calculated by subtracting the monthly mean. Linear trends were calculated by linear regression analysis in the least square method. Linear regression analysis was also used to remove the signal of IPWP. In addition, Ensemble Empirical Mode Decomposition (EEMD) was carried out to further study the nonlinear trends of SWV and tropical tropopause temperature. It is an improvement of EMD, which is an adaptive time-space analysis method that suits the non-stationary and non-linear time series (Salisbury and Wimbush 2002; Wu and Shen 2016). It can extract the Intrinsic Mode Functions (IMF) at different frequencies and obtain a residual series that can represent the non-linear long-term trend. To depict the relationship between tropical SWV entry and SST of IPWP, the correlation coefficients were calculated. Because the SWV entry and tropical tropopause temperature have large interannual variabilities, they have
been eliminated to some extent by the five-year running average on raw timeseries before calculating the correlation coefficient. The statistical significance is calculated by Mann-Kendall non-parametric test for trend. The statistical significance of correlation is using the Student’s t-test and the degrees of freedom are estimated as follows (Bretherton et al. 1999):

\[ N_{\text{eff}} = \frac{N(N-1)}{2} \frac{1 - 2r}{1 + r} \]  

(1)

Results

Observed reduction in SWV entry for the period 1984-2020

Fig. 1a shows the time series of SWV entry anomalies in the tropics from 1984 to 2020. A few facts are first reviewed to make sure the datasets used can capture recent SWV changes. The reportedly two severe drops which were registered around 2000 (Randel et al. 2006; Dhomse et al. 2008; Wang et al. 2017) and 2011 (Urban et al. 2014) respectively are also shown here. The interannual cycle is also well captured in the two datasets with an approximate 2-year cycle mainly controlled by QBO (Fuglstaler et al. 2005; Diallo et al. 2018; Diallo et al. 2022). Now, we assess the long-term trend in the lower SWV for the period 1984-2020. Both SWOOSH and ERA5 datasets show a significantly decreasing trend in SWV entry anomalies from 1984 to 2020. The linear decreasing rate is 0.106 \( \pm \) 0.021 ppmv per decade in SWOOSH and 0.037 \( \pm \) 0.022 ppmv per decade in ERA5. The decades-long decreasing trend is statistically significant at 99% confidence level. This decline is also manifested in their mean values. For SWOOSH, the SWV amount was about 3.62 ppmv in the first five years of 1984-2020 and it decreased to 3.43 ppmv in the last five years, with a drop of \( \sim 0.2 \) ppmv. A similar decadal drop with a smaller amplitude can be also seen in ERA5. But this drop amplitude is smaller than that estimated by linear tread. The reason for this disagreement will be explained later.
Fig. 1. (a) Time series of tropical (30°S-30°N) averaged SWV entry anomalies (solid lines) and their linear trends (dashed lines) based on SWOOSH (black lines, 82 hPa) and ERA5 (red lines, 70 hPa) from 1984 to 2020. The trends are shown in the dashed lines legend, and one asterisk denotes significance at the 90% confidence level and two asterisks denote significance at the 99% confidence level. The uncertainties are expressed by 2σ errors. The number in the top left-hand corner and top right-hand corner are the averages of anomalies over the first five years and the last five years. (b) The same as (a), but for the tropical tropopause temperature (30°S-30°N, 70 hPa) based on ERA5 (red lines) and JRA55 (black lines). (c) Vertical profiles of global SWV trend using SWOOSH (red line) and ERA5 (black line). (d) The same as (c), but for meridional variations of the global SWV (100-10 hPa) trend. Bold lines in (c) and (d) mean significance at the 90% confidence level.

The cooling trend in the lower stratosphere is captured by the tropical tropopause temperature (Fig. 1b). The linear cooling trends are 0.328 ± 0.083 K per decade in ERA5, while JRA55 has a relatively larger rate at 0.253 ± 0.08 K per decade. Coherently, the temperature average value also supports the SWV entry decrease but with a larger value in ERA5 than in JRA55. The free-drying regime works if it is assumed all air entering from the troposphere to the stratosphere passes through the extremely cold temperature. Thus, the decreased rate of SWV entry predicted by the Clausius-Clapeyron equation, for the linear cooling trend of the tropical tropopause at the value of 0.328 K per decade, is about 0.09 ppmv per decade, which is very close but slightly smaller than the observed value (0.106 ppmv per decade).

As the tropical SWV entry decreases, we can speculate that the global SWV may have the same change. So, the vertical and meridional resolved zonal-mean SWV trends are shown in Fig. 1c and 1d, respectively. The decreasing trends based on the two datasets are generally in agreement in the lower stratosphere,
showing significant dehydration in the lower stratosphere for the period 1984-2020 (Fig. 1c). Above 30 hPa, however, the positive trend is only seen in SWOOSH. This increase in water vapour is possibly induced by the increase of methane (le Texier et al. 1988) and its production of water vapour via oxidization. The meridional variation shows that the drying trend in the southern hemisphere is stronger than that in the northern hemisphere. This hemispheric difference has not been clarified yet. In general, the linear trends of SWV based on observations show a consistent decreasing trend for the period 1984-2020. And it is similar to the tropical SWV entry.

However, the tropical SWV entry time series show large interannual variability, which can degrade the linear estimation of its long-term trend. So, we apply a nonlinear algorithm, EEMD, to confirm the drying trend. Fig. 2 shows the original tropical SWV entry time series in the tropics and its decomposed modes using EEMD analysis. In the original time series, the tropical SWV entry shows large interannual variability with the magnitudes up to about 1.5 ppmv (Fig. 2 (a) and (b)). The first three components are corresponding to the irregular oscillations, annual cycles, and interannual variations, with the peak-to-peak amplitudes at around 0.2 ppmv, 0.6 ppmv, and 0.2 ppmv, respectively (Fig. 2 (c), (d), (e), (f), (g) and (h)). With the number of EEMD modes increasing, the frequency of the oscillations becomes lower. Finally, the residual term has only one extremum which can be used to diagnose the nonlinear long-term change (Fig. 2 (i) and (j)). The residual component shows a general decreasing trend in the tropical SWV entry and the level around 2020 is still much lower than that around 1980. And, one thing that should be noted is that ERA5 exhibits strong non-linearity in its residual with a turnaround in 2005. This turnaround may be related to the preceding inconsistency between the amplitude of the drop and the estimated linear trend. And this turnaround makes decreasing trends much weaker in ERA5. We also applied EEMD on the tropopause temperature time series, and the results are in good agreement with a residual term showing a decades-long cooling trend (Fig. S3).
In sum, a robust drying trend in the lower tropical stratosphere is confirmed by both the linear and nonlinear long-term trend analysis. The freezing-dry model is generally applicable in the decrease rate, indicating the dominating role of the tropical pathway in the process.

Decreasing SWV entry associated with IPWP

As a key factor modulating the transport through the tropical pathway, the SST long-term variations in tropical oceans, especially the tropical Pacific and tropical Indian Ocean, are further investigated on its linkage to the drying trend in the lower stratosphere. Fig. 3a shows the zonally resolved correlation coefficients between tropical SST anomalies and the tropical tropopause temperature and SWV. To remove the strong interannual variations, we apply a 5-year running mean on tropical tropopause temperature and SWV time series before the linear relationship analysis. A strong negative linear relationship is shown between the long-term change of SST of the IPWP and the tropical tropopause temperature, with a weak positive relationship over the Niño3 region. Because tropical tropopause temperature is a great indicator of SWV, the SST in IPWP also has a greatly negative correlation with SWV, for both the tropical and global averages from both data sources. During 1984–2020, the IPWP has been substantially warming, at a higher rate (0.12 °C per decade) than the eastern Pacific (Figs. 3b, 3c). The strong correlation between the SST in IPWP and SWV indicates that there may be some connection between the warming IPWP and the drying stratosphere.
tropical SWV entry anomalies and global SWV anomalies. The orange area indicates the IPWP region. The bold line indicates that significance at the 90% confidence level. (b) SST trends in the tropical Pacific and Indian Ocean from 1984 to 2020, with the black box indicating the area of the IPWP (30°S to 30°N, 30°E to 180°). Dots indicate significant trends at the 90% confidence level. (c) The time series of the IPWP averaged SST anomalies from 1984 to 2020. This solid line indicates SST anomalies in the IPWP. The dashed line is the linear regression line. The trend and uncertainty are shown in the top right-hand corner. The uncertainties are expressed by 2σ errors.

Fig. 4 shows the distribution of zonal mean SWV decreasing trends and tropical tropopause cooling trends, with the left column showing the raw trends and the right showing the trends after linearly regressing out the warming IPWP signal. In SWOOSH, the significant dehydration trends in the SWV below 30 hPa induced by the cooling trend in the tropical tropopause are coherent with that shown before, and the only decreasing trend is located above 30 hPa at high latitudes (Fig. 4a). And this is consistent with Hegglin et al. (2014). In ERA5, the distribution of the trend is significantly different. The decreasing trend is mainly in the southern hemisphere, while the decreasing trend in the northern hemisphere is weak (Fig. 4b). After removing the IPWP warming signal, decreasing SWV trends become weaker in both data sets and even increasing trend dominates the northern hemisphere in ERA5 (Figs. 4b, 4d). This implies that the recent decadal SWV trends may be connected with IPWP warming. The IPWP warming signal is also shown in the cooling trends of tropical tropopause. After removing the IPWP warming, the significant cooling trends in tropical tropopause are relatively weak in both ERA5 and JRA55 (Figs. 4f, 4h).
and (f) are from ERA5. (g) and (h) are from JRA55. The left column is the raw trend. The right column is trend removed IPWP by regression. Dotted regions indicate significance at the 90% confidence level. A five-year running average is used before calculating trends.

The importance of the warming IPWP for dehydration is further quantified in Fig. 5. What can be clearly seen in the bar plot is the dramatic decline in the dehydration rate after regressing out the IPWP warming. For SWOOSH, the drying trend in the tropical SWV entry reduces from 0.106 ppmv per decade to less than 0.06 ppmv per decade after linearly removing the IPWP warming signal. The decadal decrease rate of SWV associated with IPWP warming accounts for 43% of its tropical mean. In ERA5, the trend of tropical SWV entry is -0.036 ppmv per decade and the trend without IPWP is -0.014 ppmv per decade. IPWP warming contributes 61% of the decreasing trend of tropical SWV entry. It implies that global SWV is mainly controlled by the tropical SWV entry. In sum, the linear estimation based on SWOOSH for the contribution of IPWP warming to the drying trend in the tropical SWV entry is about 43%, highlighting a fundamental role of IPWP warming. However, as we have removed the interannual signal from the analysis, the relationship between SWV entry and IPWP may mainly be driven by secular trends. And there may be an overestimation of the contribution of IPWP. In the next part, we further present models to validate the effect of IPWP warming on SWV entry.

Fig. 5. Tropical (30°S-30°N; at 82 hPa in SWOOSH and at 70 hPa in ERA5) and global average trends of SWV for SWOOSH, and ERA5. Orange bars represent raw trends and green bars represent trends that have been removed from IPWP. Values of trends are presented around each bar. Red texts represent the trends caused by IPWP and their proportion of raw trends. One asterisk denotes significance at the 90% confidence level and two asterisks denote significance at the 99% confidence level. A five-year running average is used.
before calculating trends.

IPWP warming impacts in models

It is possible that the signal of IPWP warming is tangling with other internal variabilities, for example, the long-term trend of other oceans, which can make it difficult to provide quantification and a clear physical mechanism for the IPWP warming impacts. An alternative approach is to isolate the IPWP warming signal with the aid of models. So, here we employ WACCM4 and CAM5 to carry out transient experiments to isolate the IPWP warming signal. The details of the transient experiments can be found in Table. 1 E2 and E3.

The effect of IPWP warming on the tropical temperature is visualized in Fig. 6 which shows a cross-section of temperature trends and Fig. 7, which shows decadal changes in the tropical temperature profiles. As expected, tropical air in the troposphere becomes warmer due to latent heat caused by intensified convection, with a heating center at about 200 hPa (Fig. 6). Air in the stratosphere, however, becomes cooler due to adiabatic cooling caused by enhanced large scale ascent. Both WACCM4 and CAM5 share the general pattern in tropical temperature long-term changes, but WACCM4 has a relatively larger gradient in the upper troposphere and lower stratosphere (UTLS) region (seen as dense contours near the tropopause). We also note that there are zonal asymmetries in the temperature trend in the tropics, with both the heating center in the troposphere and the cooling center in the UTLS being located over the IPWP region (Figs. 6c, 6d). The two out-of-phase temperature changes in the troposphere and the stratosphere, together, lead to the change in the shape of the tropical temperature profile and a lower coldest point temperature (Fig. 7). The coldest point temperature at 85 hPa drops from 196.055 K to 195.343 K in WACCM4, with an estimated decrease rate at about 0.17 K per decade. In CAM5, however, the cooling rate is about half of the rate of WACCM4.
Fig. 6. (a), and (b) are trends of global zonally-averaged temperature. Black solid lines indicate the tropopause. (c), and (d) are trends of tropical meridional temperature (30°S-30°N). The left column is from WACCM4 and the right column is from CAM5. Dotted regions indicate significance at the 90% confidence level.

Fig. 7. (a), and (b) are vertical temperature profiles above the tropics (30°S-30°N). The coldest pressures are shown after labels. (c), and (d) are zoom temperature profiles in tropics (30°S-30°S). The coldest temperatures are shown after labels. Blue solid lines are 1955-1964 mean values and purple dash lines are 1996-2005 mean values.

Considering the zonal asymmetries shown above in the zonally resolved temperature trends, we provide fields of the trends in eddy geopotential height and stream function in Figs. 8a and 8b to further explain how the tropopause changes in a zonally resolved view. Climatologically, the zonally asymmetric patterns in tropopause temperature are dominated by equatorial planetary waves in a bottom-up regime (Grise and Thompson 2013). The dynamical regime also applies here. The trend fields for eddy geopotential height and stream function show a Gill pattern associated with Rossby-Kelvin waves, which lead to large ascent and adiabatic cooling in the tropopause (Figs. 8c, 8d). The zonally asymmetric patterns in circulation and temperature fields are more evident in CAM5 than those in WACCM4, which naturally leads to a lower decrease rate in the zonal mean tropopause temperature in CAM5 (Figs. 7, 8) (Fu 2013). We further proved the long-term changes in the coldest point regions (CPR) in response to the IPWP warming, which is defined as the coldest 10% between 30°S and 30°N (Garfinkel et al. 2013a; Zhou et al. 2021) and is a key factor for the water vapour entry in a zonally resolved aspect. The CPR temperature decreases at the rate of 0.318 K per decade and 0.347 K per decade in WACCM4 and CAM5 respectively. Because CPR decreases much
more in CAM5 than in WACCM4, it causes CAM5 SWV entry to decrease more with 0.025 ppmv per decade in WACCM4 and 0.037 ppmv per decade in CAM5 (Fig. 8e and 8f). Thus, the quantification of the IPWP warming impacts, using both models and observations, shows the fundamental contribution of the IPWP warming to the drying trend in the lower SWV entry.

Fig. 8. (a) and (b) are trends of eddy geopotential height (color shading) and trends of stream function (black contour lines, the values have been multiplied $10^{-6}$ units: m s$^{-2}$ 10yr$^{-1}$) at 100 hPa. (c) and (d) are trends of temperature at 85 hPa and green dash lines indicate the location of the CPR. The area average trends in the CPR are shown in the top right-hand corners. (e) and (f) are trends of SWV entry at 85 hPa and the area average trends in the tropics (30°S-30°N) are shown in the top right-hand corners. The left column is from WACCM4 and the right column is from CAM5. Dotted regions indicate significance at the 90% confidence level.

Conclusions

In previous work, we have demonstrated that SST in IPWP has significant impact on stratosphere and tropical lower SWV in interannual scale (Xie et al. 2014; Xie et al. 2018; Zhou et al. 2018). And in this study, we reveal linkage between the decades-long drying trend in the tropical SWV entry and the substantial warming of the IPWP based on observations and transient experiments. Using merged satellite measurements SWOOSH and the newest reanalysis data set ERA5 we show a significant decreasing trend in the lower SWV entry since the satellite era (1984-2020), with a rate at 0.106 ± 0.021 ppmv per decade according to SWOOSH. The two data sets have relatively good agreement in the lower stratosphere, although they have large discrepancies in global. The trend in tropical SWV entry is captured by the tropical tropopause...
temperature well, which is concurrently experiencing significant cooling at a rate of \(~0.32\) K per decade. We found that cooling tropical tropopause, as a primary role, determines the decrease in the water vapour entry. Correlation analysis shows a good relationship between the warming tropical SST and the drying trend in the lower stratosphere. Importantly, the strong negative correlation is in the IPWP region. The SST over IPWP is substantially warming, at a higher rate than that over the eastern Pacific. Meanwhile, the drying trend in the tropical lower stratosphere is significantly reduced by 43\% in SWOOSH and 61\% in ERA5 after regressing out IPWP warming. And for global SWV, this contribution is very similar. It implies that the tropical SWV entry is very important for the global SWV budget.

We further validate the relationship by carrying out two groups of transient experiments with WACCM4 and CAM5, accompanied by a comparison between the two models in representing the response of SWV entry. The simulations by both models agree with the observations that IPWP warming can significantly reduce the SWV entry through the tropical pathway in the long-term. The simulated drying trend caused by IPWP warming is about 0.025 ppmv per decade using WACCM4. This further confirms the vital role of IPWP warming in dehydrating the lower stratosphere for the period 1984-2020. We explain the physical process using the bottom-up regime. It shows that IPWP warming can enhance the equatorial waves due to intensified convection and thereby cool the tropical tropopause, especially in the CPR. And IPWP warming finally reduces the transport of water vapour through the tropical pathway.

Our results differ from previous work on global warming causing TTL warming (Keeble et al. 2021). Here we focus more on the IPWP and find that the IPWP warming can cause cooling of the tropical tropopause, resulting in less water vapour entering the stratosphere. This suggests that although global warming causes TTL warming, regional SST warming may have different effects than global warming.

We have demonstrated a possible relationship between IPWP and tropical SWV entry, which can partially interpret the decreasing trend of SWV in the past decades. Nevertheless, owing to the limited instrumental measurements since the satellite era and the control role of multi-decadal variation in SWV short-term trend (Konopka et al. 2022), the long-term trend in the tropical lower SWV still exists large uncertainty and needs to be investigated in the future. Moreover, it would be of interest to assess the long-term changes of the tropical SWV entry in different models and analyze the role of the IPWP in the future. In addition, because there are large uncertainties in the model simulations on the tropical SST impacts on the tropical SWV entry (Garfinkel et al. 2021), a caveat that the results might depend on the models.

CRediT authorship contribution statement

Yangjie Jiang: Formal analysis, visualization, writing – original draft; Xin Zhou: Conceptualization, funding acquisition, investigation, methodology, supervision; Quanliang Chen: Funding acquisition, writing – review&editing; Wuhu Feng: Writing – review&editing; Xiaofeng Li: Methodology, writing – review&editing; Yang Li: Funding acquisition, methodology, writing – review&editing.

Declaration of Competing Interest

All authors declare no conflicts of interest.

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Data availability

ERA5 reanalysis data can be obtained online from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=form. JRA55 can be downloaded online from NCAR RDA Dataset ds628.1 Data Access (ucar.edu) . HadISST can be accessed from https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html.
References


