Large Uncertainty in Observed Meridional Stream Function Tropical Expansion

Daniel Baldassare[1], Thomas Reichler[1], Piret Plink-Björklund[2], and Jacob Slawson[2]

- [1]Department of Atmospheric Sciences, University of Utah, Salt Lake City, UT 84112, USA
- [2]Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401, USA

Correspondence: Daniel Baldassare (daniel.baldassare@utah.edu)

10 **Abstract**

Recent tropical expansion rate estimates vary substantially, as a multitude of methods and reanalysis datasets yield conflicting results. Among the many methods of estimating the tropical width, the meridional stream function 500 hPa zero-crossing is the most widely used, as it is directly related to the poleward edge of the Hadley Cell (HC). Other common metrics use atmospheric phenomena associated with the HC as a proxy, for instance the zonal surface wind zero-crossing. As each of these metrics require different data, each with varying error, the level of data-driven uncertainty differs between each metric. While previous work has analyzed the statistical and dynamical relationships between metrics, to date no study has quantified and compared the uncertainty in different HC metrics. In this study, we use ERA5 ensemble members, which include small perturbations in atmospheric variables based on the data error, to quantify the uncertainty associated with six commonly used HC metrics as well as the range of their trend estimates. In the Northern Hemisphere, the tropical expansion rate calculated by the stream function is roughly 0.05 degrees per decade, while the Southern Hemisphere rate is 0.2 degrees per decade. Of the six metrics, only the meridional stream function and precipitation minus evaporation have substantial uncertainties. The stream function errors are large due to uncertainty in the underlying meridional wind data and the presence of large regions of near-neutral circulation at the poleward edge of

the tropics. These errors have decreased in recent decades because of improvements in the assimilated

observations. Despite these improvements, we recommended using the zonal surface wind zero crossing

to analyze tropical extent trends in reanalyses. This is particularly important in the Northern Hemisphere,

before the year 2000, and when studying individual seasons other than winter.

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Plain Text Summary

Using ensemble members from the ERA5 reanalysis, the most widely used method for estimating tropical

width trends, the meridional stream function, was found to have large error, particularly in the Northern

hemisphere and in the summer, because of weak gradients at the tropical edge and poor data quality.

35 Another method, using the latitude where the surface wind switches from westerly to easterly, was found

to have lower error and is recommended for future studies.

1   Introduction

Observed estimates of Hadley Cell (HC) meridional extent change in the last few decades vary

40 substantially in the literature, as a variety of methods and reanalysis datasets, as well as time periods,

yield conflicting results (Staten et al., 2018; Xian et al., 2021). During the 2000s, HC expansion rates

were estimated across a wide range of positive values as high as 3 degrees per decade, while recent

annual mean trend estimates have decreased to 0.2-0.4 degrees per decade (Grise et al., 2019).

Many methods have been created to determine the latitude of the poleward edge of the HC (Chen et al.,

45 2002; Fu et al., 2006; Hudson et al., 2006; Hu and Fu, 2007; Lu et al., 2007; Seidel and Randel, 2007;

Previdi and Liepert, 2007; Seidel et al., 2008; Hu et al., 2011; Staten et al., 2011; Zhou et al., 2011; Choi

et al., 2014; Karnauskas & Ummenhofer, 2014). Of these methods, the meridional stream function 500

hPa zero-crossing (SF) is the most frequently used due to its direct representation of the zonal-mean HC.

Other commonly used metrics such as the sea-level pressure maximum (PSL), the zonal surface wind

50   zero-crossing (UAS), the subtropical jet maximum (STJ), the eddy driven jet maximum (EDJ), and the

precipitation minus evaporation zero-crossing (P-E) are thought to measure the HC extent more indirectly

(Waugh et al., 2018). Previous research has studied the trends associated with the many HC extent

metrics as well as the correlation and physical links between metrics in reanalyses and climate simulation

(Davis and Birner, 2017; Seviour et al., 2018; Waugh et al., 2018). However, to date no study has

55   analyzed the quality and consistency of the data underlying each metric, or the impact of reanalysis data

error on HC width uncertainty. Without consideration of the reliability of the data used for each metric it

is not possible to determine the uncertainty in the trends or thoroughly analyze the disagreement between

metrics.

HC extent is typically studied using zonal mean data, which is then temporally averaged over either a

60   season or a year, removing the impact of longitudinal variation and short-lived storm systems (Staten et

al., 2019). Reanalysis data is often used to study observed circulation changes as it uses observational

data to estimate historical atmospheric conditions, spans multiple decades, and is spatially and temporally

continuous. Climate model data is commonly used as well, though some natural variation is not present,

and important forcings such as the Pacific decadal oscillation and aerosols are often not accurately

65   modeled (Allen et al., 2014). Despite this, the reliability of reanalyses in estimating tropical width has

also been questioned recently due to inaccurate estimates of tropical precipitation (Chemke & Polvani

2019).

In the present study we use data from ERA5, a modern high-quality, high-resolution reanalysis dataset

(Hersbach et al., 2020). The ERA5 reanalysis provides continuous data from 1950, though here we will

70   only use data from 1979 onwards to align with previous studies. ERA5 is one of the only reanalysis

products which is nearly mass conserving, avoiding the questionable meridional circulation found in other

reanalyses which are not mass-conserving (Davis & Davis, 2018). Since reanalyses combine observations

and modeling to produce estimates of atmospheric variables, observation density and quality impact the

reliability of reanalysis estimates. As a result, the reliability of a particular tropical extent metric depends

75   on the input data error at the relevant location. Moreover, each metric has a specific sensitivity to the

input data error which depends on the meridional gradient in the underlying data near the position where

the metric is defined. Weak gradients around the region of interest result in less robust estimates, as small

errors in the underlying data can result in large uncertainties in the position of the tropical edge.

Unlike most other reanalysis products, ERA5 includes several ensemble members to allow for a

80   quantification of uncertainty. The different ensemble members are produced by introducing slight

perturbations in observations and model parameters within their respective error ranges (Hersbach et al.,

2020). The spread between the members quantifies the uncertainty in the data, and when ensemble

members are used to calculate the tropical extent, the data-driven uncertainty for each metric can be

calculated. To date no study has quantified the impact of this reanalysis uncertainty in HC extent trend

85   estimates, resulting in a lack of information about the relative reliability of HC extent metrics. Due to this

knowledge gap, previous studies have not been able to consider the differences between metrics in data

quality or sensitivity to reanalysis data error. In the present study, we provide this information by

analyzing the ERA5 ensemble members, as this allows for a systematic analysis of data uncertainty and

its impact on HC estimates. In utilizing these ensemble members, we provide estimates of the uncertainty

90   in the reanalysis data used by each metric and the sensitivity of each metric to these data errors. This

study further aims to provide a range of observed HC extent trends for the various metrics in each

hemisphere and season using the modern ERA5 reanalysis dataset.

The structure of the paper is as follows. In Section 2 we describe the methodology, including the HC

extent metrics to be analyzed. In Section 3, we start by measuring the HC trend uncertainty of every

95   metric in each season. Next, we determine the annual variation in HC extent for all six metrics in each

season. Subsequently, we attempt to determine the causes of uncertainty in the SF estimates. Following

these results, in Section 4 we provide suggestions for determining the correct HC extent metrics to use in

future studies.

2 Data and methods

2.1 Data

ERA5 monthly averaged ensemble member data from March 1979 through February 2022 were acquired for use in this study. March is selected as the starting month as meteorological winter spans multiple calendar years, meaning that March 1979 is the start of the first complete season, while February 2022 is chosen as the final month to allow for the maximum number of complete seasons. ERA5 contains 9 ensemble members and one control member. Because the control member is produced through a more thorough data assimilation process than the other ensemble members, the control was excluded from the ensemble analysis. Acquired pressure level data includes the meridional and zonal wind fields, while surface level data included 10-m zonal wind, sea-level-pressure, precipitation, and evaporation. This data is used to compute the tropical extent for the six metrics described in the next sub-section. Data from these 9 ensemble members are regridded using a first-order conservational regridding to a 1-degree resolution using the Climate Data Operator (CDO) 'remapcon' function (Schulzweida, 2022). All ensemble members are then zonally and seasonally averaged into March-April-May (MAM), June-July-August (JJA), September-October-November (SON), and December-January-February (DJF). Separately annual means are calculated for each year from March-February.

2.2 Methods

Six different tropical width estimation methods are used, each covering different atmospheric regions near the HC edge or using different atmospheric variables. Each method is computed using the Python version of TropD, a module which estimates HC width from zonally averaged atmospheric data, yielding a latitude estimate for the poleward extent of the tropics in each hemisphere (Adam et al., 2018). All tropical width metrics use the standard configuration of TropD.

The meridional stream function 500-hPa zero-crossing (SF) is chosen as it is the most commonly used metric. This method uses the meridional wind to estimate the edge of the zonal-mean meridional circulation. The stream function values are calculated by integrating the zonal-mean meridional wind at

125 each latitude from the top of the atmosphere to the level of interest. From these stream function values, the 500 hPa zero-crossing poleward of the minimum (30 degrees) and equatorward of the maximum (60 degrees) is determined as the tropical extent.

The subtropical jet adjusted peak between 100 and 400 hPa (STJ) is presented here as it requires upper-troposphere zonal wind, which directly contrasts with the upper-tropospheric meridional wind used by the

130 SF method. Substantial issues exist with the STJ metric, and it has been shown to poorly correlate with other tropical extent metrics (Waugh et al., 2018).

The eddy driven jet maximum at 850 hPa (EDJ) uses lower-troposphere zonal wind data and is located substantially poleward of the other metrics, but has been shown to be closely linked to other metrics of tropical expansion (Davis and Birner, 2017).

135 The precipitation minus evaporation zero-crossing (P-E) utilizes surface-level precipitation and evaporation, which are both known to be poorly estimated by reanalyses. Furthermore, the P-E metric is not well connected to other expansion metrics (Seviour et al., 2018). Regardless, this metric is still occasionally used in the literature as it attempts to directly measure the most impactful societal effects of tropical widening.

140 The surface zonal wind zero-crossing (UAS) uses 10-m zonal wind data and has been shown to be well-correlated with and dynamically linked to the SF metric (Davis and Birner, 2017).

The subtropical sea-level-pressure maximum (PSL) reflects the surface pressure anomaly generated at the descending branch of the HC. This metric was found to be moderately correlated to SF, poorly correlated to P-E, and very highly correlated to UAS (Waugh et al., 2018).

145   Notably absent from these metrics are the tropopause break height, which is avoided because it is closely

related to the subtropical jet (Davis and Birner, 2017), and outgoing longwave radiation-based metrics,

which are avoided due to infrequent use in recent studies. As a result of these decisions, SF, STJ, EDJ, P-

E, UAS, and PSL will be analyzed in subsequent sections, with a particular emphasis on SF as it is the

most frequently used metric.

150   To quantify differences between ensemble members multiple statistical methods are used. The

intermember standard deviation (STD) is calculated by taking the STD of the nine ERA5 ensemble

members for a given quantity. In Section 3.3, a normalized intermember STD is calculated by

normalizing this quantity by the interannual STD of the intermember average, and then multiplying by

100 to present the ratio as a percent. This normalized intermember STD reflects the intermember spread

155   as a percentage of its interannual variability and is unitless, allowing for comparison between variables.

3   Results

In the first two results subsections, we analyze uncertainties in HC trends among the six metrics with the

goal of determining the reliability of each metric and the range of trend estimates. In the subsequent

160   sections, we examine the SF metric more in depth as it is the most commonly used metric in the literature.

3.1   HC trend uncertainty

To quantify the HC trend uncertainty, trends are calculated for each ensemble member using all six

metrics over the period from 1979-2022. From these trends, kernel density estimates are computed in

each season and the annual mean, for all six metrics in the Northern Hemisphere (NH) (Fig. 1) and

165   Southern Hemisphere (SH) (Fig. 2). The standard deviation of the smoothing kernel is determined using

Scott's Rule (Scott, 1992).
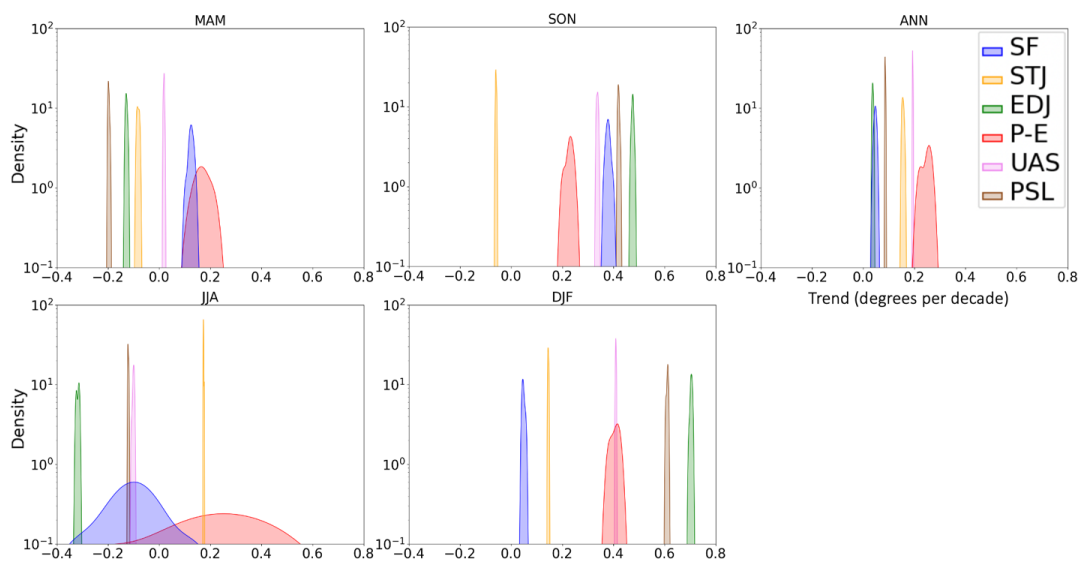
Figure 1 Tropical widening trends over the NH. Shown are kernel density estimate (y-axis) of tropical

extent trend (1979-2022) in degrees per decade (x-axis), computed from the nine ERA5 ensemble

members for all seasons and the annual mean. Note the logarithmic scale for density on the y-axis.

Positive x-axis values represent northward trend in tropical extent.

While in individual seasons the trends vary substantially between metrics, the annual mean trends are

typically more similar. The NH annual mean trend for SF is roughly 0.05 degrees per decade, while other

metrics estimate 0.05 to 0.3 degrees per decade. The SH annual mean trend ranges between 0.1 and 0.3

degrees per decade, with most metrics (including SF) estimating 0.2 degrees per decade. While these SF

trends are low and represent a substantial downward revision from the older studies which estimated rapid

expansion, the near-zero NH tropical expansion rate and weak SH expansion are similar to the generally

weak expansion found across multiple reanalysis datasets in Grise et al., (2019). It is also of note that the

rate of expansion for the annual mean of P-E in the NH is larger than all other metrics.
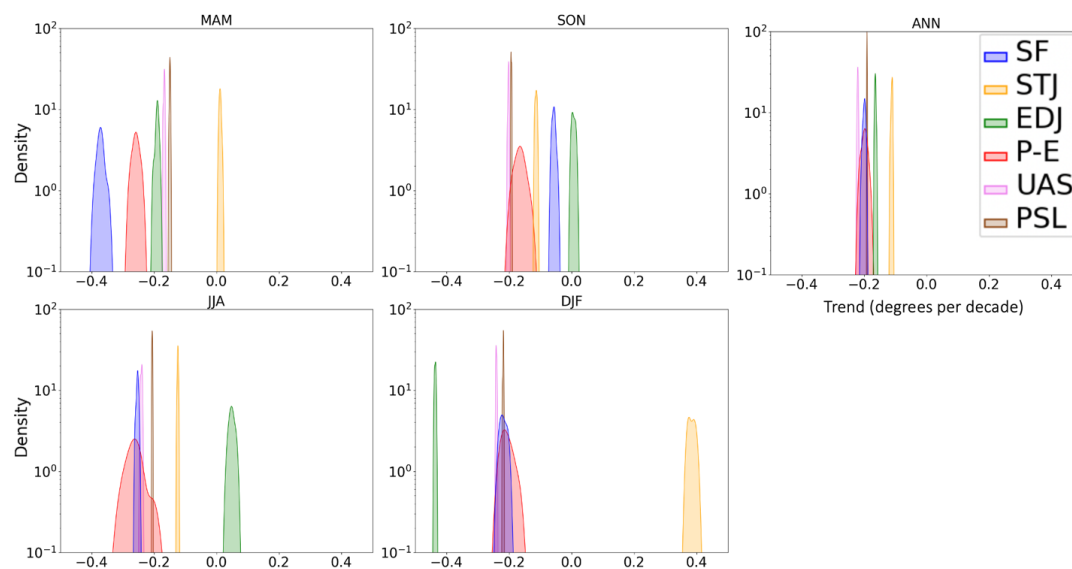
Figure 2 Same as Fig. 1 for SH. Note the different x-axis values, with negative values representing southward expansion.

185   On seasonal time scales, the trends and their uncertainty vary substantially between the different metrics, as shown by the kernel density estimates and the intermember trend STD; a table of the latter is presented in the Supplement (Table S1). P-E features the largest uncertainty, particularly In the NH and in JJA. Over the NH, the SF exhibits the second least certain trend in all seasons, particularly in JJA, where the range of estimates include both poleward and equatorward trends. Over the SH, SF estimated tropical

190   expansion is more robust, as shown by the consistency of the negative sign in all seasons as well as the smaller uncertainty. While the uncertainty over the SH is low for STJ and EDJ in most seasons, STJ in DJF and EDJ in JJA are substantial outliers, estimating tropical contraction while all other metrics record expansion.

We hypothesize that data uncertainty is a major contributor to the larger uncertainties in SF and P-E. SF is

195   based on poorly observed and poorly constrained meridional wind, and P-E uses imperfectly modeled

evaporation and precipitation data. On the other hand, STJ and EDJ are based on better observed and, constrained (through the thermal wind relationship) zonal wind data, and UAS and PSL are also well-observed and constrained quantities. Comparisons of the normalized intermember STD for zonal and meridional wind is included in Fig. S1, showing that the relative uncertainty for the zonal wind used by STJ and EDJ is much smaller than in the meridional wind used by SF. Larger normalized uncertainty in the data underlying the SF metric causes larger uncertainty in SF-derived HC expansion rates.

3.2 HC extent uncertainty

We next examine the HC extent uncertainty in individual years. In doing so, the impact of improved observations over time can be seen along with the potential influences of internal climate variability on tropical width estimates. The yearly intermember STD of tropical extent is calculated for each metric in the NH and SH (Fig. 3). P-E has the greatest STD in nearly all seasons and is particularly unreliable in the NH JJA. SF uncertainty is typically one order of magnitude larger than the four most reliable metrics and is particularly unreliable in the NH JJA. Over the SH, the SF extent uncertainty is largest relative to the other metrics. We also note that there is not much interannual variation in STD for the six metrics in either hemisphere, indicating that internal climate variability does not have a substantial impact on uncertainty. Counter to this observation are SF and P-E in the NH in JJA, which sometimes are even undefined in some years, resulting from P-E not recording a zero-crossing near the poleward edge of the tropics, and the SF not recording a closed circulation cell. Examples of the absence of a closed HC in 2019 and 2020 are included in the Supplement (Fig. S2). As a result, in these years the STD is calculated excluding undefined ensemble member values, resulting in imperfect estimates of variation. It is interesting that 2019 and 2020 are the only two years with some members not reproducing closed NH summer circulation cells, and it remains to be seen whether this is part of a systematic longer-term trend.
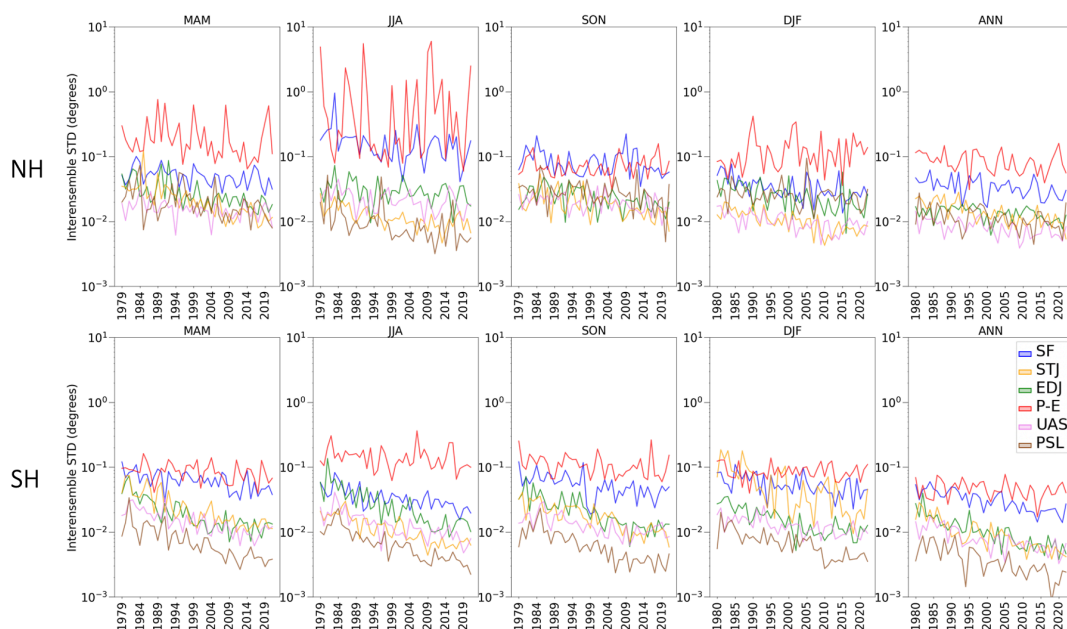
Figure 3 Interannual variation in tropical extent uncertainty. Shown are annual intermember STD of HC extent (degrees latitude) for NH (top) and SH (bottom) by season for all six metrics. Note the logarithmic scale for the y-axis. The start year for each season is the first available year.

Most notably, Fig. 3 shows a substantial reduction in uncertainty over the 40-year period in most seasons and for nearly every metric, likely due to the increased quantity and quality of observations assimilated into the reanalysis. Because the ensemble members are created by perturbing the model parameters along with observations, both a lack of observations and the presence of lower quality observations increase the data uncertainty. The metrics based on u-wind and sea-level pressure (STJ, EDJ, UAS, PSL) have consistently low uncertainty in all seasons, years, and hemispheres, though the variation for PSL especially in the SH is the lowest of all metrics. Despite the presence of more conventional observations in the NH, particularly in the earlier decades, the extent uncertainty is lowest in the SH for all metrics.

This is likely due to the abundance of ocean in the SH and topographic variability in the NH, both of which impact the atmospheric processes which are measured by the HC extent metrics.

235 ### 3.3 Spatial variability of SF data uncertainty

Because the SF is the most widely used metric, the following sections will take a closer look at the magnitude and impact of data error for just the SF. To quantify the spatial uncertainty of SF data, the intermember STD of SF is calculated for all years using zonally and annually averaged meridional wind data. These annual values are then averaged over two 20-year periods and normalized as described in the

240 Methods section. This results in the annual mean SF normalized intermember STD over two time periods (Fig. 4). The two time periods are 1979-2000 and 2001-2021, comparing the period with fewer observations to the better observed period following the deployment of many remote sensors (Hersbach et al., 2020). The normalized intermember STD during the earlier period is clearly larger than during the later period, indicating the role of improved observations in the reduced SF extent uncertainty in recent

245 decades seen in Fig. 3. As the SF metric used here calculates the tropical extent using the 500 hPa SF values between the Hadley and Ferrel cells, only the improvements in these regions are impactful, while the large decrease in normalized STD in other regions is not directly relevant. However, the improvements in observations in these regions, particularly the inner tropics, constrain the meridional circulation, likely contributing to reduced uncertainties in other regions of the Hadley circulation in recent

250 decades. As can be seen from Fig. 4, the normalized STD improves from roughly 6% to 4% at 500 hPa at the tropical edges in both hemispheres between the two time periods.
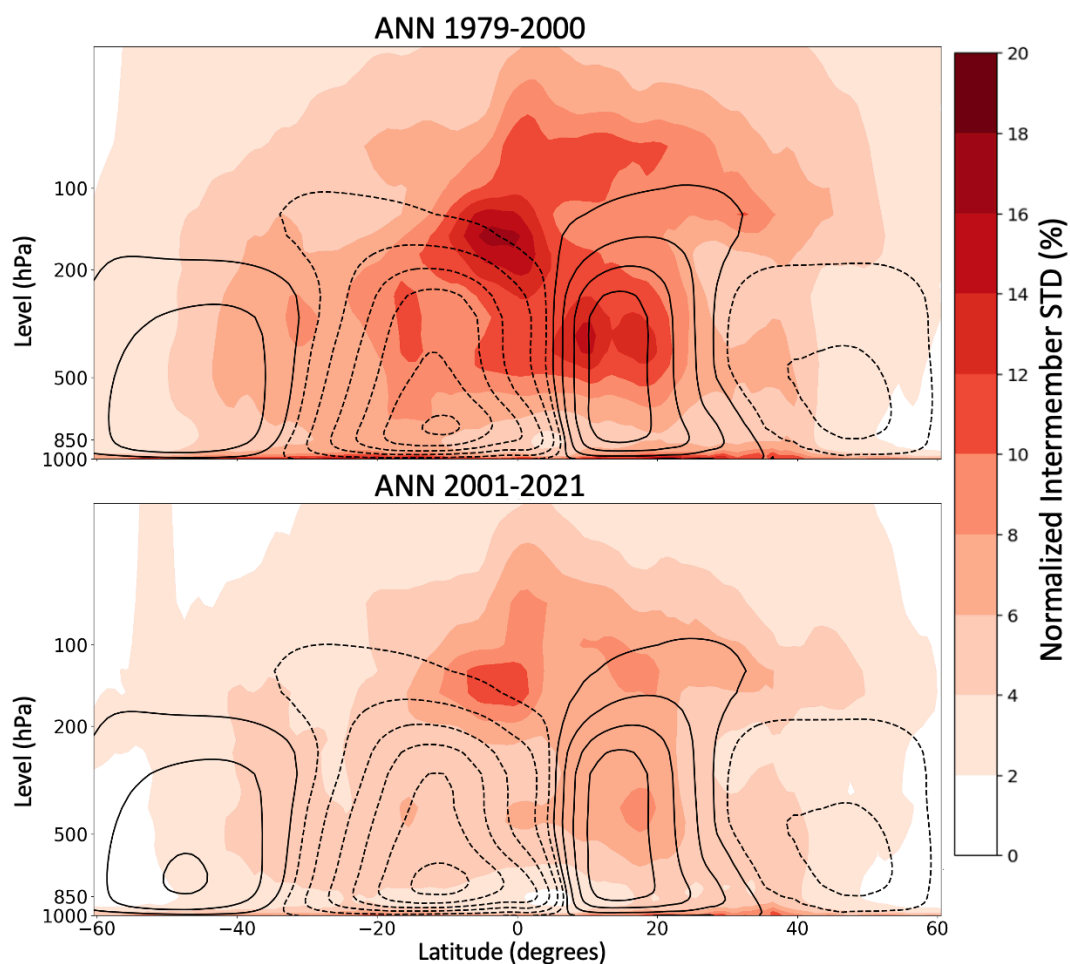
Figure 4 Meridional cross sections of SF uncertainty for 1979-2000 (top) and 2001-2021 (bottom), demonstrating improvement in SF estimates in recent decades. Shading shows the 20-year average of the annual mean SF normalized intermember STD (%). Dashed lines indicate negative (counterclockwise) circulation while solid lines indicate positive (clockwise) circulation.

3.4   HC extent errors due to weak SF gradients

As shown earlier in this study, in Section 3.2, the SF extent uncertainty is greater in the NH than SH and

260   is particularly pronounced in the NH in JJA. Here, we aim to investigate the impact of the HC structure

on SF extent uncertainty. In order to calculate the tropical extent, the latitude where the circulation

changes from clockwise to counterclockwise at 500 hPa must be determined. Observational errors will

have a larger impact on SF extent estimates if the region of near-neutral circulation between the Hadley

and the Ferrel cell is large, as small variations between the ensemble members can cause the zero-

265   crossing to occur over a larger latitude range. We define Δ in each hemisphere as the width in degrees

latitude of the region in the vicinity of the HC edge (poleward of 20 degrees and equatorward of 50

degrees) at 500 hPa where the SF is very weak ($\pm 5*10^9$ kg s^{-1}). This Δ is larger in the NH than SH and is

particularly large in NH JJA, coinciding with the seasons and hemispheres where SF trend and extent

uncertainty are greatest (Fig. 5).

270   As shown by Fig. 5, the HC over the NH has a smaller latitudinal extent and features a distinctive

narrowing in the middle and upper troposphere. This narrowing coincides with a large Δ, which is not

present in other seasons or in the SH. The wide Δ likely represents the impacts of large land masses and

greater longitudinal variation in meridional circulation in the NH (Hoskins et al., 2020). In both

hemispheres, however, the region of near-zero circulation in summer is larger than winter, suggesting a

275   possible relationship between the weak summer HC and meridional gradients at the poleward edge of the

HC. We speculate that Δ is impacted by both the zonal variation in circulation and the strength of the

meridional circulation. Hence, in JJA in the NH, the weak meridional circulation and large zonal variation

in circulation combine to create a persistent large Δ which causes the SF metric to perform poorly. It is

also worth noting that the latitudinal width of the near-zero circulation region does not change

280   significantly during the 40-year period, suggesting that this is a typical and quasi-permanent feature of the

atmosphere, and is unrelated to measurement errors.
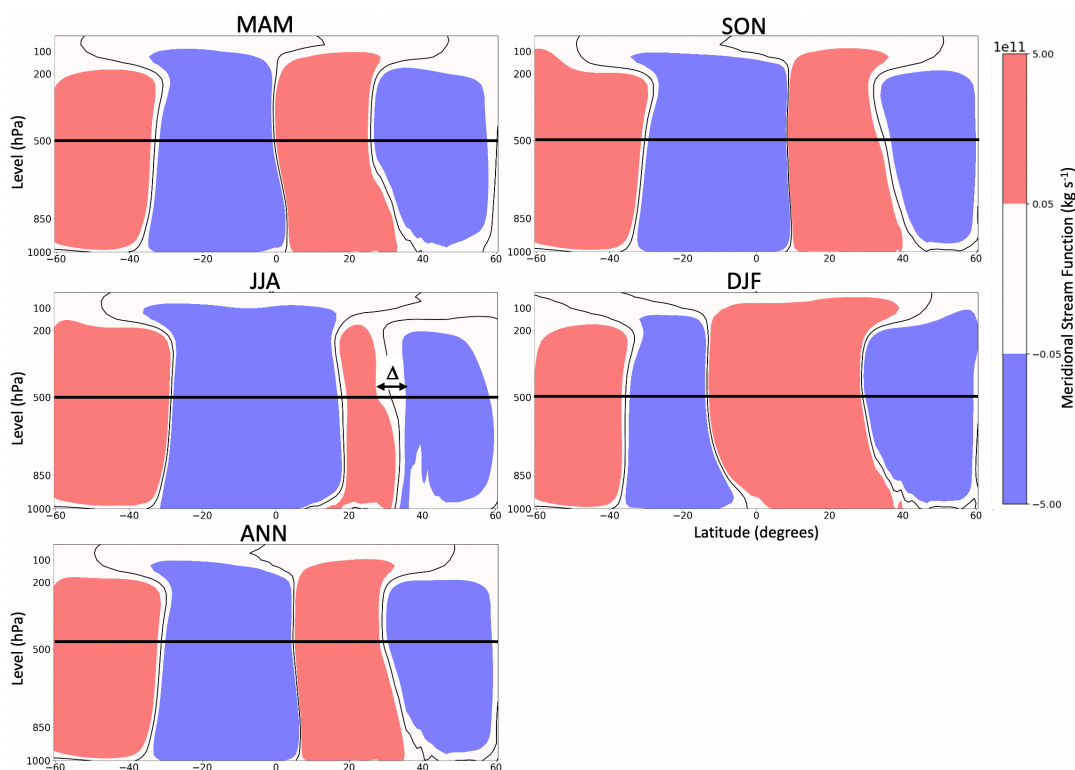
Figure 5 Climatological mean stream function, highlighting regions with values near zero. Red shading represents clockwise circulation stronger than $5*10^9$ kg/s, blue shading indicates counterclockwise motion

285   stronger than $5*10^9$ kg/s, and white shading the region of near-zero stream function values. Thin black contours denote a zero SF value, while the thick horizontal black line indicates the 500 hPa level where the tropical extent and Δ are calculated. In JJA an illustration of Δ is shown in the NH near 500 hPa.

3.5   Impacts of data error and weak gradients on SF uncertainty

290   In the previous sections, the SF extent uncertainty was shown to be related to both data error and weak meridional gradients. We next determine the impact of these two factors on seasonal and annual HC estimates. The 40-year means of the tropical extent uncertainty for each season and hemisphere are well-

approximated by a linear function of Δ (Fig. 6a). Here, Δ is computed from the 1-degree regridded ERA5 data, resulting in relatively coarse latitudinal estimates. NH JJA features both the greatest extent

295   uncertainty and the largest Δ, while NH SON has the second largest values for each. The high correlation demonstrates that Δ plays an important role when using the SF to estimate tropical width, particularly in the NH and in summer. Although data uncertainty, as shown earlier (Fig. 4), partially explains the poor performance of SF relative to other metrics (Figs. 1 and 2) as well as the improvement over time (Fig. 3), no significant relationship was found between the climatological averages of uncertainties in SF data and

300   SF-derived HC extent; a scatter plot showing the poor correlation is included in the Supplement (Fig. S3).

However, when looking at individual annual means, the uncertainty of the SF-based HC extent is well-approximated as a linear function of the SF uncertainty in the vicinity (± 2 degrees latitude) of the HC edge (Fig. 6b). In the NH, the extent uncertainty is larger than in the SH, likely due to the aforementioned complicating influences of the NH land masses. The extent uncertainty is well correlated with the SF

305   uncertainty and poorly correlated with Δ, indicating that the reduction in data error is the main reason for the decrease in SF extent uncertainty seen before (Fig. 3); a scatter plot showing the poor fit between Δ and the annual mean SF extent uncertainty is included in the Supplement (Fig. S4). The improved observations in recent decades thus result in more precise tropical width estimates relative to earlier decades.

310   The uncertainty of the SF-derived HC trend has no discernable relationship with the SF data uncertainty when comparing seasons (Fig. S5). However, the trend uncertainty is greatest in seasons and hemispheres where Δ is largest, though this is mostly noticeable in NH JJA (Fig. S6).

Following this analysis, we conclude that Δ represents a persistent factor for the uncertainty in the SF metric, which varies primarily by season and hemisphere, and is nearly constant over the years. As

315   discussed earlier, Δ can be seen as a sensitivity of the HC extent to the data uncertainty, as a larger Δ results in a larger range of latitudes where data error could cause SF to be zero. Δ in individual seasons

and hemispheres does not vary much from year-to-year as it is mostly a consequence of relatively fixed

meteorological and geographical factors that control the structure of the HC. As a result, Δ represents a

persistent amplification of data error, resulting in greater extent uncertainty in certain seasons and

320   hemispheres, in particular JJA in the NH.
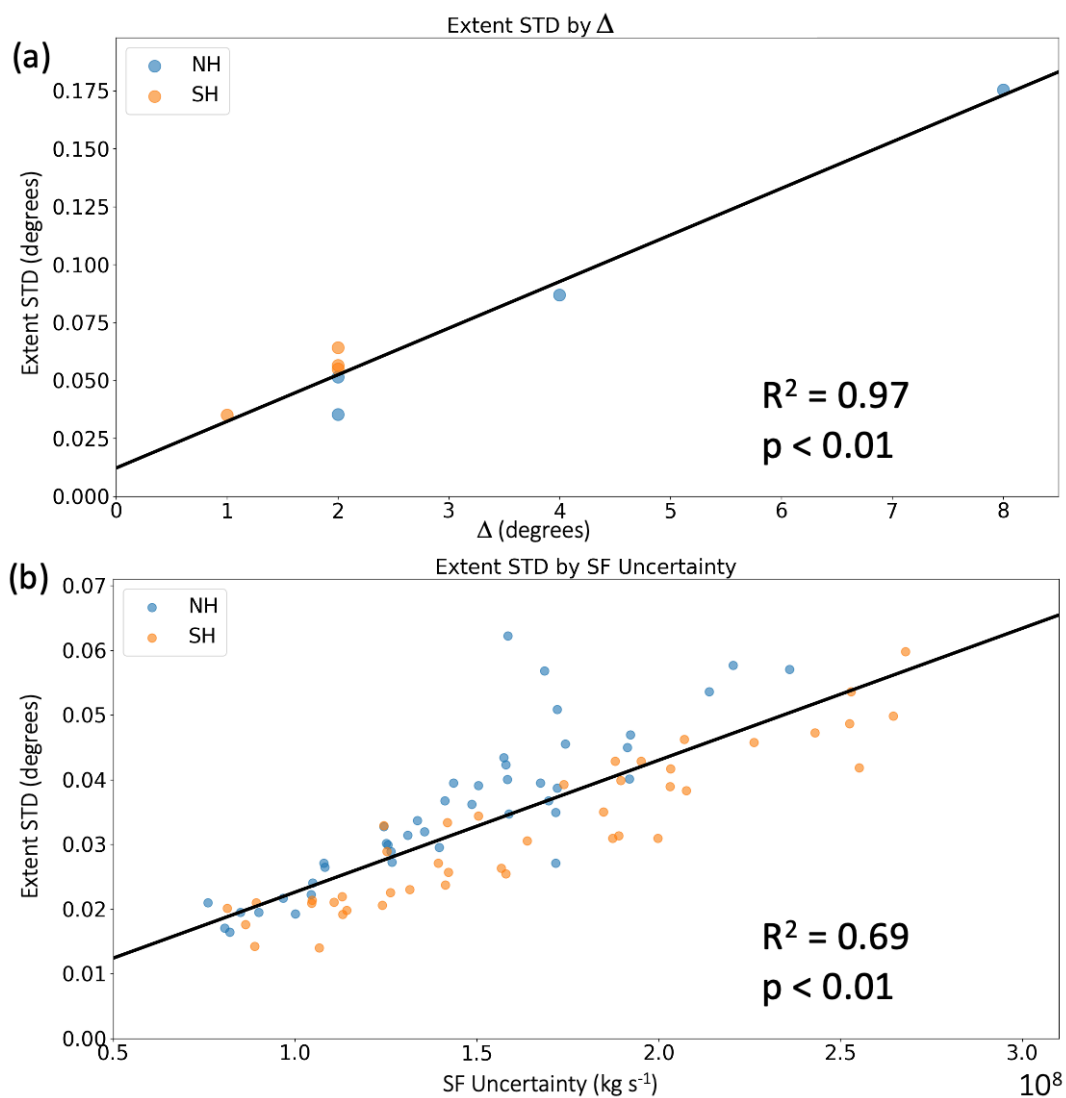
Figure 6 Linear best fit of the SF-based HC extent uncertainty. (a) climatological mean HC extent uncertainty (degrees latitude) by Δ (degrees) in all four seasons in both hemispheres. Δ is defined as the width of the near-zero circulation region at 500 hPa in the vicinity of the HC edge, as shown in Fig. 5. (b) annual mean HC extent uncertainty (degrees latitude) by the SF uncertainty at 500 hPa averaged within 2 degrees of the HC edge (kg s^{-1}).

4   Conclusions and discussion

In this study, we used ERA5 ensemble members from 1979-2022 to quantify the uncertainty and long-term trends of different Hadley cell (HC) extent metrics. The annual mean SF HC expansion rate in the NH was found to be approximately 0.05 degrees per decade in the NH, and 0.2 degrees per decade in the SH. The HC extent trend uncertainty analysis showed the high uncertainty of SF and P-E trends relative to the other metrics, particularly in the NH, and most prominently in JJA in the NH. Over the ~40-year-long reanalysis record, we found substantial improvements in HC extent error for all metrics (Table S2), especially in the SH, likely due to increases in the number and quality of observations assimilated by the ERA5 reanalysis system (Figs. 3 and 4). The seasonal and hemispheric differences in SF-derived HC extent uncertainties were well described by variations in the strength of meridional gradients in SF at the poleward edge of the HC (Figs. 5 and 6a). Differences in annual mean SF extent uncertainty were well correlated with the SF uncertainty near the poleward edge of the HC (Fig. 6b). The high sensitivity to data uncertainty combined with substantial SF data error suggests that the SF metric is not the most reliable method of determining the width of the HC in reanalyses.

In the following paragraphs, we discuss our findings to provide suggestions for future studies. For each

345   metric, the data-driven trend and extent uncertainty, agreement with other metrics, and findings from

previous studies will be considered.

Despite being the most widely used metric of tropical extent, SF was found to have much higher

uncertainty in both trend and extent relative to STJ, EDJ, UAS and PSL. The meridional wind used in the

SF metric is generally weak and likely less well-observed than the zonal wind used in other metrics.

350   Zonal-mean meridional flow is also not dynamically constrained by the temperature field through the

thermal wind relationship as is the case for the zonal wind field. As a result, meridional wind is less

accurately represented in reanalysis than zonal wind or surface variables, leading to larger uncertainties

relative to the variables used by other metrics. This issue is compounded by the presence of wide regions

of near-zero meridional overturning, resulting in a greater sensitivity of the HC edge latitude to the

355   already large data uncertainty. As a result of these two issues, and despite the near-ubiquitous usage in the

literature, the SF is not the most useful metric when analyzing tropical extent trends in reanalyses,

particularly if the time-period of interest is prior to 2000 or the focus is the NH summer. Over recent

decades, when analyzing annual averages, SF becomes a more reliable metric, particularly in the SH.

P-E is the least reliable metric of tropical extent by both trend and extent, in particular in the NH and

360   during JJA. P-E has high uncertainty mostly due to the well-documented issues in modeling precipitation

and evaporation in reanalyses (e.g., Simmons et al., 2010). This metric is further challenged by somewhat

poor correlations between meridional circulation and vertical moisture flux at the descending branch of

the HC, particularly over land masses (Schmidt and Grise, 2017). Despite P-E and related metrics such as

the precipitation minimum providing the most societally impactful information, the uncertainty in these

365   metrics is too high to be useful for HC trend analysis, particularly when other more reliable metrics exist

which can be used as proxies.

While STJ featured very low uncertainty, it is not well correlated with SF or P-E, the most direct and relevant metrics of tropical extent, and is therefore not recommended for analyzing tropical expansion (Davis and Birner, 2017).

370   PSL was shown in Davis and Birner (2017) to be moderately correlated with SF and poorly correlated with P-E, suggesting that it functions as a mediocre proxy for the societally impactful effects of HC extent change. However, in our study, the uncertainty for PSL tropical extent was found to be very low both in trend and extent. In light of these conflicting results, we conclude that PSL is reliable and potentially useful.

375   EDJ featured low uncertainty in most seasons and hemispheres in both trend and extent but resulted in trends outside of the range of the other metrics over most seasons. This indicates that the EDJ, though reliable and well correlated with SF, is also impacted by other processes that are not closely related to the width of the HC, particularly over individual seasons. We therefore suggest that the EDJ be used only when analyzing the mid-latitudes where changes to the EDJ are most relevant or studying annual mean
380   HC change.

For UAS, both the trend and extent uncertainties were found to be low in all seasons and hemispheres, and the trends were within the range estimated by other metrics. UAS has also been shown to be well correlated to SF and P-E (Davis and Birner, 2017). Because of these factors, we recommend using UAS when analyzing tropical extent trends in reanalyses.

385   This study focused on errors within a single reanalysis dataset, while many previous studies were based on data from multiple reanalyses, climate models, or observations. When analyzing multiple reanalyses, uncertainty arising from measurement error is likely to exist, as many of the issues highlighted in this study are present in all reanalyses. Some of these issues, such as the weak meridional gradients in SF are likely to be present in climate model data as well, while others such as observational uncertainty are

390 instead replaced by modeling error. Future work expanding on this topic should quantify the tropical

extent uncertainty in climate models, and in addition determine the most reliable metrics.

Code availability

The code for analysis is available at https://zenodo.org/record/7430530.

395 **Data availability**

This study uses monthly averaged ensemble members from the ERA5 reanalysis, which can be

downloaded at https://cds.climate.copernicus.eu (Hersbach et al., 2020)

Supplement

400 **Author Contributions**

DB and TR designed the study. DB performed the analyses and wrote the manuscript with

feedback from all authors.

Competing Interests

The authors declare that they have no conflict of interest.

405 **Disclaimer**

Acknowledgements

We acknowledge the European Center for Medium-Range Weather Forecasts (ECMWF) for

producing the ERA5 reanalysis dataset. We also thank Hans Hersbach and Paul Berrisford at

410   ECMWF for their communication on the ERA5 reanalysis dataset, and the Center for High

Performance Computing at the University of Utah for providing computing resources.

Financial Support

Thomas Reichler acknowledges funding from the National Science Foundation under award no.

2103013.

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