

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**DETECTION AND EVALUATION OF SUDDEN STRATOSPHERIC
WARMING : A CASE STUDY OF WATER VAPOR TRANSPORT**



Ph.D. THESIS

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Department of Meteorological Engineering

Atmospheric Science Programme

FEBRUARY 2026

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**STRATOSFERİK ANİ ISINMALARIN TESPİTİ VE DEĞERLENDİRİLMESİ:
SU BUHARI TAŞINIMI ÖRNEK OLAY İNCELEMESİ**

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To my spouse, child and family



FOREWORD

Since my childhood, I have wanted to be a doctor. This desire was not merely a career aspiration; it grew within me as a profound longing to know, to understand, to heal, and to be of service to humanity. I knew that my father had harbored the same dream in his youth. Life diverted both our paths in different directions; neither he could realize this dream, nor could I become a doctor in the classical sense. Yet, this dream never vanished; it only transformed.

At the point I have reached today, I may not be at a patient's bedside in a white coat; however, earning the title of 'doctor' at the end of this academic journey walked with patience, effort, and the guidance of science is not just a personal achievement for me. It is the quiet fulfillment of a dream shared with my father. This thesis is the tangible manifestation of a lingering desire, an ideal passed down through generations, and a persistent effort that never faltered.

'The truest guide for everything in the world, for civilization, for life, and for success, is science and knowledge.' This quote by the Great Leader Mustafa Kemal ATATÜRK has been the fundamental principle illuminating my path throughout my academic life. This faith in science has defined the intellectual foundation and the working discipline of this doctoral study, guiding me to adopt an approach that questions, research, and aims to produce. Many esteemed individuals have contributed their efforts and support to the completion of this doctoral thesis. First and foremost, I would like to express my sincere gratitude to my doctoral advisor, Asst. Prof. Dr. Deniz DEMİRHAN, for the academic guidance, mentorship, and constructive contributions provided throughout this process. I also consider it a duty to specifically thank Prof. Dr. İsmail GÜLTEPE, who contributed immensely to my work with his wealth of knowledge, experience, and scientific approach.

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ABBREVIATIONS

2D	: Two-dimensional
3D	: Three-dimensional
4D	: Four-dimensional
ACCESS1-3	: Australian Community Climate and Earth-System Simulator v1.3
AMIP	: Atmospheric Model Intercomparison Project
AO	: Arctic Oscillation
BDC	: Brewer-Dubson Circulation
CCM	: Chemistry–Climate Model
CDS	: Copernicus Climate Data Store
CMIP5	: Coupled Model Intercomparison Project Phase 5
DA	: Dipole Anomaly
DC	: Downward Control
DSMF-Net	: Deep Spatiotemporal Memory Flow Network)
ECHAM	: Middle Atmosphere - European Centre Hamburg Model Version 4
ECMWF	: European Centre for Medium-Range Weather Forecasts
EDA	: Ensemble of Data Assimilations
EMAC	: European Centre Hamburg Model Modular Earth Submodel System Atmospheric Chemistry
ENSO	: El-Niño Southern Oscillation
EP	: Eliassen-Palm
ERA-Interim	: ECMWF Re-Analysis Interim
ERA5	: Fifth Generation European Centre for Medium-Range Weather Forecasts Reanalysis
FGOALS-g2	: Flexible Global Ocean–Atmosphere–Land System Model, Grid-Point v2
GCM	: Global Climate Model
GFDL-ESM2G	: Geophysical Fluid Dynamics Laboratory Earth System Model v2G
GWD	: Gravity Wave Drag
H100	: Eddy Heat Flux at 100 hPa

HadGEM2-CC	: Hadley Centre Global Environmental Model v2 – Carbon Cycle
HARMONIA	: Harmonisation of Atmospheric Measurements and Models
hPa	: Hectopascal
IFS	: Integrated Forecasting System
ITCZ	: Intertropical Convergence Zone
IVT	: Integrated Vapor Transport
JAWARA	: Japanese Reanalysis for the Whole Atmosphere
K	: Kelvin
km	: kilometer
M*	: Residual Meridional Mass Streamfunction
MAX	: Maksimum
MDV	: Mean Doppler Velocity
MERRA-2	: Modern-Era Retrospective analysis for Research and Applications, Version 2
MESSY	: Modular Earth Submodel System
MIN	: Minimum
MJO	: Madden-Julian Oscillation
MLS	: Microwave Limb Sounder
MPA	: Main Phase Area
MPD	: Main Phase Duration
MPI-ESM-MR	: Max Planck Institute Earth System Model – Mixed Resolution
MPS	: Main Phase Strenght
MSF	: Meridional Mass Streamfunction
N	: North
N²	: Brunt-Väisälä Frequency
NAO	: North Atlantic Oscillation
NCAR	: National Center for Atmospheric Research
NCEP	: National Centers for Environmental Prediction
NH	: Northern Hemisphere
OGWD	: Orographic Gravity Wave Drag
OLS	: Ordinary Least-Squares
PPMV	: Parts Per Million by Volume
Pr	: Percentile Range
QBO	: Quasi-Biennial Oscillation

QBO-	: Easterly Phase of QBO
QBO+	: Westerly Phase of QBO
RC	: Residual Circulation
RCP	: Representative Concentration Pathway
RO	: Radio Occultation
RV	: Residual Velocity
S	: Wave Energy
SAO	: Semiannual Oscillation
Sd	: Standard Deviation
SH	: Southern Hemisphere
SPARC	: Stratosphere-troposphere Processes And their Role in Climate
SSW	: Sudden Stratospheric Warming
STE	: Stratosphere-Troposphere Exchange
SWV	: Stratospheric Water Vapor
TEA	: Threshold Exceedance Area
TEM	: Transformed Eulerian Mean
UTC	: Coordinated Universal Time
VAR	: Variance
WAACM3	: Whole Atmosphere Community Climate Model, Version 3
WMO	: World Meteorological Organization



SYMBOLS

$\bar{q}_{\text{high}}$	: Specific humidity in the Polar Region
$\bar{q}_{\text{trop}}$	: Specific humidity in the Tropical Region
$f_u(p)$	: Meridional Components of Horizontal Moisture Flux
$f_v(p)$	: Zonal Components of Horizontal Moisture Flux
$\vec{f}(p)$	: Horizontal Moisture Flux at a Specific Pressure Level
t_2, t_1	: End and Start Times
X_{t_2}, X_{t_1}	: Values of the Variable at Times t_2, t_1
Φ'_z	: Geopotential Thickness
%	: Percentage
°	: Degree
a	: Radius of Earth
CO_2	: Carbon Dioxide
$\cos$	: Cosines
g	: Acceleration Due to Gravity
H	: Scale Height
IVT_u	: Vertically Integrated Zonal Water Vapor Transport
IVT_v	: Vertically Integrated Meridional Water Vapor Transport
K'	: Kinetic Component
O_3	: Ozone
p	: Pressure
P'	: Potential Component
q	: Specific Humidity
$q(p)$	: Specific Humidity at Pressure Level p (kg/kg)
q'	: Specific Humidity Perturbation
R	: Correlation
S_{Ts}	: Linear Trend of Stratospheric Temperature
S_{Uh}	: Linear Trend of Zonal Wind
t	: Time

T_{amp}	: Amplitude of Stratospheric Temperature
T_{cli}	: Climatological Mean
T_{rng}	: Range-based Variability of Stratospheric Temperature
T_s	: Stratospheric Air Temperature
u	: Zonal Wind
$u(p)$	: Zonal Wind Component at Pressure Level p (kg/kg)
U_{amp}	: Amplitude of Zonal Wind
U_h	: Daily Mean Zonal Wind
U_{rng}	: Range-based Variability of Zonal Wind
v	: Vertical Wind
$v(p)$	: Meridional Wind Component at Pressure Level p (kg/kg)
$v'\theta'$	: Meridional Eddy Heat Flux
z	: Geopotential Height
ΔT	: Temperature anomaly
Δt	: Time Interval
ΔX	: Change in the Magnitude of Variable X
θ	: Potential Temperature
Σ	: Summation Operator
ϕ	: Geopotential
ω	: Vertical Velocity in Pressure Coordinates
ω'	: Vertical Velocity Perturbation
ω^*	: Residual Mean Vertical Velocity

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DETECTION AND EVALUATION OF SUDDEN STRATOSPHERIC WARMING : A CASE STUDY OF WATER VAPOR TRANSPORT

SUMMARY

Stratospheric Sudden Warming, (SSW), events represent the most dramatic and influential disruptions of the wintertime circulation in the Northern Hemisphere (NH). These phenomena are characterized by a rapid increase in polar temperatures and a subsequent weakening or reversal of the polar night jet, carrying profound implications for both stratospheric composition and tropospheric weather patterns. Furthermore, the modulation of these events by the Quasi-Biennial Oscillation (QBO) is evaluated, confirming that the easterly phase (QBO-) significantly enhances planetary wave activity and the probability of vortex breakdowns through the Holton-Tan effect. This thesis provides an comprehensive evaluation of SSW dynamics, their representation in modern climate models, and their critical role in the vertical transport of water vapor (WV). The primary objective is to move beyond simple statistical descriptions and characterize the evolution of these events through their feedback mechanisms within the global climate system. Given that NH winter conditions are heavily influenced by the coupling between the stratosphere and troposphere, understanding the physical triggers that lead to the breakdown of the polar vortex is essential for improving long-range seasonal predictability. The sudden surges in stratospheric temperature, often exceeding 30–40K at the 10 hPa level, are induced by the vertical propagation of large-scale Rossby waves from the troposphere, leading to intense wave-mean flow interactions and the collapse of the polar night jet.

A central methodological contribution of this research is the implementation of the Threshold Exceedance Area (TEA), method for identifying and classifying SSW events. Conventional detection methods, primarily based on the reversal of zonal mean winds at 60°N, often fail to capture the full thermodynamic evolution and the spatial extent of the warming. The TEA method addresses this gap by analyzing temperature anomalies at the 10 hPa level, requiring a 30 K threshold to be exceeded for at least 6 consecutive days. Using ERA5 reanalysis data for the 1980 to 2005 period, this study demonstrates that the TEA approach provides a more refined understanding of the Main Phase Strength (MPS). The MPS is calculated by multiplication the Main Phase Area (MPA) over the Main Phase Duration (MPD) of the event, allowing for a robust classification into Minor, Major, and Extreme categories. The findings indicate that during the peak of these events, the stratospheric temperature variance decreases by 44–54%, reflecting a fundamental reorganization of the polar vortex energy state. This variance reduction suggests that SSWs act as a critical stabilizing feedback mechanism, redistributing heat from the mid-latitudes to the over-cooled polar region.

With the ERA5 reanalysis dataset serving as the primary reference for validation, the evaluation of five specific climate models, namely ACCESS1.3 (M1), HadGEM2-CC (M2), MPI-ESM-MR (M3), FGOALS-g2 (M4), and GFDL-ESM2G (M5), reveals significant disparities in their ability to simulate stratospheric variability. While

models such as M1, M2 and M3 show a high degree of fidelity in reproducing the frequency and magnitude of NH SSWs relative to ERA5, others suffer from a persistent cold pole bias. This bias leads to a polar night jet that is too stable and strong, resulting in an underestimation of the frequency of vortex breakdowns. In particular, the vertical resolution and the height of the model top are identified as decisive factors in capturing the upward propagation of planetary waves. Low-top models like M4 and M5 fail to reproduce realistic SSW frequencies due to their limited representation of the upper stratosphere. Under the RCP 4.5 future climate scenario, the analysis suggests that while the absolute frequency of SSWs may not increase drastically, the duration and vertical depth of these events are projected to lengthen. These modifications in SSW characteristics are expected to influence the downward propagation of stratospheric anomalies, thereby affecting surface weather regimes and atmospheric oscillations in a warming climate.

Furthermore, this study investigates the hydrological implications of SSWs through a detailed case study of the January 2003 major warming event. This event is notable for a dramatic vortex split, which facilitated a significant injection of water vapor from the troposphere into the lower stratosphere. Quantitative analysis reveals a substantial +5.22% increase in the stratospheric moisture index (100–10 hPa), which is physically balanced by a –4.91% moisture deficit in the middle troposphere (500–100 hPa) due to the vertical hoisting mechanism. By analyzing vertical velocity fields and moisture flux, the research demonstrates that the mechanical disruption of the vortex creates pathways for moisture transport through the Upper Troposphere Lower Stratosphere (UTLS) region. Normal atmospheric barriers at the tropopause are breached during these extreme events, allowing moist air from lower levels to be injected into the dry stratospheric reservoir. This transport is not limited to large-scale circulation but also occurs through filamentous and spiral structures formed during the vortex fragmentation. The enhanced stratospheric water vapor alters radiative cooling rates and impacts the recovery time of the polar vortex, as the additional moisture acts as a radiative forcing agent that delays the return to a stable state.

A critical discovery of this research is the persistence of the hydrological response; while dynamical anomalies peak during the warming phase and the event concludes on 30 January 2003, stratospheric moisture concentrations remain elevated during the recovery phase. The role of the Brewer-Dobson Circulation (BDC) is central to explaining this transport mechanism. During an SSW, the BDC is significantly accelerated due to increased wave breaking in the stratosphere. This acceleration drives the upward motion of air at high latitudes, effectively pumping water vapor into the middle atmosphere. The case study of 2003 provides empirical evidence for this pump effect, showing that the moisture anomalies persist in the stratosphere for months after the initial warming has subsided. This suggests that SSWs are not merely dynamical events but are critical drivers of the stratospheric moisture budget and chemical composition. The persistence of these moisture anomalies provides a memory effect that can influence the radiative balance of the NH for an entire season.

In conclusion, this thesis advances the understanding of SSW events by introducing a robust detection algorithm and elucidating the physical mechanisms of stratospheric-tropospheric moisture exchange. The results highlight the necessity for improved stratospheric representation in climate models, particularly regarding vertical motion and UTLS interactions. By linking the dynamical classification of events via MPS with the hydrological consequences via BDC-driven transport, this research provides a holistic view of how the middle atmosphere responds to extreme forcing. These

findings are vital for refining future climate models, as the inclusion of accurate stratospheric water vapor feedback is essential for predicting the long-term stability of the global climate system. The results underscore that high-resolution vertical grids and accurate stratospheric water vapor feedback are essential prerequisites for improving long-range seasonal predictability and refining future climate projections. The mysteries of the NH stratosphere continue to be a focal point for meteorological research, and this work establishes a new framework for integrating dynamical warming events with the global hydrological cycle.





STRATOSFERİK ANİ ISINMALARIN TESPİTİ VE DEĞERLENDİRİLMESİ : SU BUHARI TAŞINIMI ÖRNEK OLAY İNCELEMESİ

ÖZET

Kuzey Yarımküre (KYK) kış mevsiminde orta atmosferin sergilediği en dramatik, en kaotik ve dinamik doğa olaylarının başında gelen stratosferik ani ısınma (SSW) olayları, stratosferik polar vorteksin termodinamik dengesinin temelinden sarsılmasıyla ortaya çıkan ve atmosferin dikey yapısındaki tüm dengeleri değiştiren son derece karmaşık süreçleri temsil etmektedir. Bu olaylar sırasında kutup bölgesindeki sıcaklıkların çok kısa bir zaman diliminde, bazen sadece birkaç gün gibi atmosferik ölçeğe çok dar bir aralıkta 30–40 K arasında ekstrem düzeylerde artması sadece stratosferin fiziksel ve kimyasal yapısını değiştirmekle kalmaz, aynı zamanda troposferle olan dinamik bağı üzerinden yer seviyesindeki hava sistemlerini, jet akıntılarını ve fırtına yollarını da doğrudan etkiler. Ayrıca, bu olayların Quasi-Biennial Oscillation (QBO) tarafından modüle edilmesi değerlendirilmiş ve doğulu fazın (QBO–), Holton-Tan etkisi aracılığıyla gezegensel dalga aktivitesini ve vorteks parçalanma olasılığını önemli ölçüde artırdığı doğrulanmıştır. Hazırlanan bu kapsamlı tez çalışması, söz konusu olayların tespitinden başlayarak küresel iklim modellerindeki temsil kapasitelerini, modellerin yapısal eksikliklerini ve bu süreçlerin stratosferik su buharı taşınımı üzerindeki dönüştürücü rolünü hem tarihsel reanaliz verileri hem de gelecek projeksiyon senaryoları ışığında çok boyutlu bir perspektifle analiz etmektedir. Atmosferin bu iki temel katmanı arasındaki etkileşimin doğru tanımlanması, sadece kısa vadeli hava tahmin modellerinin başarısını artırmakla kalmayıp, aynı zamanda iklim sisteminin uzun vadeli değişkenliğini ve küresel ısınma altındaki yeni denge durumlarını anlamak açısından da hayati bir öneme sahiptir. KYK genelinde kış şartlarının şiddeti, kar örtüsü süresi ve ekstrem soğuk hava dalgaları üzerinde belirleyici olan bu fenomenler, troposferden yukarı doğru yayılan gezegensel ölçekli Rossby dalgalarının stratosfere devasa enerji ve momentum taşıması sonucunda polar vorteksin zayıflaması, yer değiştirmesi veya tamamen parçalanmasıyla sonuçlanan bir enerji boşalımdır.

Çalışmanın metodolojik temelini oluşturan ve mevcut literatürdeki tespit kısıtlamalarını gidermeyi hedefleyen eşik aşım alanı yöntemi (TEA), geleneksel rüzgâr odaklı tespit kriterlerine çok daha hassas ve fiziksel bir alternatif sunmaktadır. Literatürde on yıllardır yaygın olarak kullanılan ve genellikle 60° K enlemindeki bölgesel rüzgarların yön değiştirmesini baz alan rüzgâr dönüşü yöntemleri, rüzgârın tam olarak doğulu rüzgâra dönmediği ancak stratosferin termal olarak büyük bir enerji birikimi yaşadığı pek çok ısınma olayını tespit edememekte veya yanlış sınıflandırmaktadır. Bu tezde geliştirilen TEA yöntemi ise 10 hPa basınç seviyesindeki sıcaklık anomalilerini merkeze alarak ısınmanın sadece şiddetini değil, aynı zamanda olayın zamansal sürekliliğini, kapladığı devasa coğrafi alanı ve atmosferik kütle üzerindeki etkisini matematiksel bir algoritma ile hesaba katmaktadır. ERA5 reanaliz verileri kullanılarak 1980 ile 2005 yılları arasındaki 25 yılı aşkın tarihsel dönem

mercek altına alınmış ve bir olayın gerçek bir SSW olarak tanımlanabilmesi için 30 K üzerindeki sıcaklık anomalisinin en az 6 ardışık gün boyunca kesintisiz olarak korunması şartı getirilmiştir. Bu yöntem sayesinde olayların ana evre gücü (MPS) üzerinden yapılan sayısal sınıflandırmalar, stratosferin termal hafızasını ve enerji boşaltım kapasitesini çok daha hassas bir şekilde ölçmeyi mümkün kılmıştır. MPS değerleri, ısınmanın kapladığı alan (MPA) ile süresinin (MPD) çarpımı üzerinden hesaplanarak olayları küçük, büyük ve ekstrem olmak üzere üç ana kategoriye ayırmıştır. İstatistiksel bulgular, SSW olaylarının gerçekleştiği kış aylarında stratosferik sıcaklık varyansında %44 ile %54 arasında değişen belirgin bir azalma yaşandığını ortaya koymuştur. Bu durum, stratosferin ekstrem ısınma yoluyla bir nevi kendisini stabilize etme, aşırı soğumuş kutup bölgesini çevre orta enlemlerle dengeleme ve atmosferik enerjiyi daha homojen bir yapıya zorlama çabası olarak yorumlanmaktadır.

Tezin model değerlendirme bölümünde, dünya genelinde iklim araştırmalarında referans kabul edilen ACCESS1.3 (M1), HadGEM2-CC (M2), MPI-ESM-MR (M3), FGOALS-g2 (M4) ve GFDL-ESM2G (M5) gibi beş farklı küresel iklim modelinin (CMIP5) performansları ERA5 reanaliz veri setiyle titizlikle kıyaslanmıştır. Modellerin tarihsel dönemdeki başarıları incelendiğinde, M1, M2 ve M3 modellerinin KYK polar vorteks dinamiklerini, Rossby dalga kırılma mekanizmalarını ve SSW frekanslarını ERA5 verileriyle uyumlu şekilde gerçeğe en yakın istatistiksel doğrulukla yakaladığı saptanmıştır. Özellikle dikey katman çözünürlüğü yüksek olan ve stratosferin üst sınırını 50 km'nin çok daha üzerinde tanımlayan modellerin bu uç olayları temsil etmede, dalga-ortalama akış etkileşimini doğru simüle etmede açık ara daha başarılı olduğu gözlemlenmiştir. Buna karşın, özellikle M4 ve M5 gibi modellerde kronik bir sorun olarak saptanan soğuk kutup yanlılığı durumu, polar gece jetinin olması gerekenden çok daha kararlı ve şiddetli simüle edilmesine yol açarak SSW olay sayısının istatistiksel olarak gerçek değerlerin çok altında tahmin edilmesine neden olmuştur. Bu durum, bu modellerin stratosferik değişkenliği eksik hesapladığını ve dolayısıyla yeryüzü iklim tahminlerinde de sistematik hatalar barındırabileceğini göstermektedir. M1 modeli tarihsel dönem ile gelecek projeksiyonları arasında belirli bir tutarlılık sergilese de rüzgâr şiddeti analizlerinde ve vorteksin geometrik şekil bozulmalarında sapmalar göstermiştir. Gelecek iklim senaryosu olan RCP 4.5 altında 2100'e kadar yapılan projeksiyonlar ise KYK stratosferinin genelinde beklenen ve sera gazı artışına bağlı olarak gelişen radyatif soğuma eğilimine rağmen SSW olaylarının fiziksel birer dengeleyici mekanizma olarak görev yapmaya devam edeceğini göstermektedir. Gelecekte bu olayların toplam sayısında radikal bir artış öngörülmesi de ısınma evrelerinin zamansal süresinin uzaması, ısınmanın dikey yönde troposfere daha derin nüfuz etmesi ve ısınma sonrası vorteksin toparlanma süresinin daha sancılı geçmesi gibi yapısal değişimlerin, stratosfer ile troposfer arasındaki etkileşimi çok daha kalıcı ve etkili hale getirme potansiyeli taşıdığı belirlenmiştir.

Bu araştırmanın kritik bir keşfi, hidrolojik tepkinin kalıcılığıdır; dinamik anomaliler ısınma evresinde zirve yaparken ve olay 30 Ocak 2003 tarihinde sona ererken, stratosferik nem konsantrasyonları toparlanma evresinde de yüksek kalmaya devam etmektedir. Tezin en özgün ve teknik derinliği en yüksek kısımlarından birini teşkil eden su buharı taşınımı analizi, 2003 yılının ocak ayında gerçekleşen ve atmosfer bilimleri literatüründe vorteksin tam ortadan ikiye ayrılmasıyla sonuçlanan büyük ölçekli ısınma olayı üzerinden detaylandırılmıştır. Bu örnek olay incelemesinde, polar vorteksin ikiye bölünmesiyle sonuçlanan dramatik dinamik süreçlerin üst troposfer alt stratosfer (UTLS) bölgesinden yukarı doğru alışılagelmişin dışında bir kütle ve nem

transferi başlattığı somut verilerle ortaya konmuştur. Nicel analizler, dikey yükselme mekanizması nedeniyle stratosferik nem indeksinde (100-10 hPa) %5,22'lik önemli bir artış olduğunu ve bunun orta troposferdeki (500-100 hPa) %4,91'lik nem açığı ile fiziksel olarak dengelendiğini ortaya koymaktadır. Normal şartlarda tropopoz seviyesi, bu iki atmosfer katmanı arasında kimyasal ve fiziksel geçişi engelleyen keskin bir bariyer görevi görürken, SSW sırasında oluşan ekstrem dikey hareketlerin ve dalga zorlamasının bu bariyeri mekanik olarak zayıflattığı saptanmıştır. Atmosferik dikey hız bileşenlerindeki ani ve şiddetli artışlar, tropopoz seviyesindeki nemli hava kütlelerinin, stratosferik kuru ve son derece steril olan rezervuara fiziksel olarak enjekte edilmesini sağlamıştır. Su buharının bu yukarı yönlü taşınımı sadece büyük ölçekli genel dolaşımla değil, aynı zamanda vorteks parçalanması sırasında kutup dairesi çevresinde oluşan ipliksi ve spiral yapılar vasıtasıyla, adeta bir pompa mekanizması gibi gerçekleşmiştir. Stratosfere bu yolla giren ilave nemin bölgedeki radyatif dengeyi kökten değiştirerek polar vorteksin kış sonundaki yeniden toparlanma sürecini önemli ölçüde geciktirdiği, stratosferi radyatif olarak daha fazla soğutarak termodinamik dengesizliği derinleştirdiği ve ısınmanın yarattığı anomalik etkilerin alt katmanlarda çok daha uzun süre hissedilmesine zemin hazırladığı tespit edilmiştir. Bu bulgular, SSW olaylarının sadece dinamik birer rüzgâr veya sıcaklık değişimi olmadığını, aynı zamanda atmosferin nem bütçesini ve ozon tabakası üzerindeki kimyasal yıkım süreçlerini etkileyen kritik hidrolojik sürücüler olduğunu ispatlamaktadır. Brewer-Dobson Dolaşımı (BDC), bu taşınım mekanizmasının merkezinde yer almaktadır. Bir SSW olayı sırasında KYK stratosferindeki dalga kırılmalarının artması BDC mekanizmasını adeta hızlandırarak troposferdeki nemli havayı yukarı doğru pompalamaktadır.

KYK genelinde yapılan bu derinlemesine analizler, SSW dönemlerinde polar stratosferin sadece termal olarak ısınmakla kalmadığını, aynı zamanda troposferden gelen yoğun kütle girişiyle kimyasal ve hidrolojik olarak da tamamen yeniden yapılandırıldığını göstermektedir. Bu araştırmanın kritik bir keşfi, hidrolojik tepkinin kalıcılığıdır; dinamik anomaliler ısınma evresinde zirve yaparken ve olay 30 Ocak 2003 tarihinde sona ererken, stratosferik nem konsantrasyonları toparlanma evresinde de yüksek kalmaya devam etmektedir. Özellikle 2003 yılındaki vorteks bölünmesi, stratosferin yalıtılmış yapısını bozarak nemli hava paketlerinin kutup dairesinin en derin noktalarına kadar sızmasına olanak tanımıştır. Bu sızma süreci, izentropik yüzeyler boyunca gerçekleşen yatay karışımlarla desteklenmiş ve ısınma olayının fiziksel olarak sona ermesinden sonra bile stratosferde aylarca süren kalıcı nem anomalileri bırakmıştır. Tezin sayısal veriler, spesifik nem grafikleri ve dikey kesit analizleriyle desteklediği bu mekanizma, gelecekteki iklim simülasyonlarında stratosferik nem bütçesinin neden çok daha hassas yöntemlerle hesaplanması gerektiğini açıkça ortaya koymaktadır. Mevcut modellerin birçoğunun bu dikey taşınım süreçlerini düşük çözünürlük kısıtları sebebiyle tam olarak yakalayamadığı, bu durumun da uzun vadeli iklim öngörülerinde, kutup buzullarındaki erime tahminlerinde ve mevsimsel tahminlerde ciddi belirsizliklere yol açtığı çalışmanın temel eleştiri noktalarından biri olarak öne çıkmaktadır.

Çalışmanın sonuç bölümünde, MPS değerleri üzerinden yapılan analizlerin stratosferik enerjinin nasıl dağıtıldığını ve bu enerjinin hangi mekanizmalarla troposfere geri besleme yaptığını anlamada vazgeçilmez bir araç olduğu kanıtlanmaktadır. Özellikle ekstrem sınıfa giren SSW vakalarının, KYK üzerindeki jet akıntılarını güneye doğru kaydırarak Avrupa ve Asya'nın kuzey bölgelerinde dondurucu ve uzun süreli soğuk dalgalarına, buna mukabil güney bölgelerinde ve

Akdeniz havzasında normalin çok üzerinde ekstrem yağış sistemlerine neden olduğu görülmüştür. TEA yönteminin sunduğu mekansal analiz kapasitesi, ısınmanın hangi boylamlar üzerinde yoğunlaştığını ve bu yoğunlaşmanın yeryüzündeki hangi yüksek basınç blokaj sistemleriyle doğrudan ilişkili olduğunu net bir şekilde ortaya koymaktadır. Sonuç olarak, geliştirilen TEA yönteminin stratosferik uç olayların karakterizasyonunda rüzgâr temelli geleneksel yaklaşımlara göre çok daha sağlam, fiziksel olarak tutarlı ve kapsayıcı bir çerçeve çizdiği sonucuna varılmıştır. Küresel iklim modellerinin stratosferik süreçleri temsil etme konusundaki yapısal eksiklikleri, gelecekteki model iyileştirme çalışmaları için somut veri setleri ve fiziksel parametrelendirme önerileriyle desteklenmiştir. 2003 yılına ait vaka analiziyle ortaya konan yukarı yönlü su buharı taşınım mekanizması, yüksek enlemlerdeki katmanlar arası kütle değişim süreçlerinin sanılandan çok daha karmaşık ve küresel iklim dengesi üzerinde etkili olduğunu ispatlamıştır. KYK stratosferinin bu gizemli ısınma olayları, gelecekte daha gelişmiş teknolojik imkanlar ve modellerle incelendiğinde, atmosferin dikey yapısındaki gizli geçitlerin çok daha net bir şekilde çözülmesine olanak tanıyacaktır.



1. INTRODUCTION

The stratosphere is a fundamental layer of the atmosphere located approximately between 16 and 50 km. Its vertical extent exhibits geographical variability, beginning at approximately 8–10 km altitude near the polar regions and reaching 15–20 km in the tropical regions, while extending to an average height of 50 km. This region corresponds to pressure levels of about 70 hPa to 1 hPa (Butchart, 2022). Due to the presence of cold and dense air masses, the stratosphere lies at its lowest level over the poles compared to other regions, especially during the winter months. During this period, the polar stratosphere is characterized by extremely low temperatures and the formation of a large-scale, cyclonic circulation system known as the Polar Vortex. This dynamic structure is stabilized by the westerly Polar Night Jet, which delimits the polar region throughout the winter, acting as a reliable isolation barrier against meridional transport (Nash et al., 1996). The lack of solar radiation during the polar night leads to strong radiative cooling, which is the primary driver for the formation of this low-pressure system and the associated eastward winds (Scheiben et al., 2011).

However, the structural integrity of the polar vortex is not uniform across winter seasons; it exhibits pronounced interannual variability driven by planetary wave forcing and complex atmospheric interactions. In the Northern Hemisphere (NH), approximately every 28 months, the established vortex suddenly warms up within a few weeks. During these episodes, the strong westerly zonal winds (U_h) suddenly cease, significantly weaken, or reverse to become easterly winds. In the scientific literature, these events are recognized as Sudden Stratospheric Warmings (SSW). The vertical propagation of large-scale Rossby waves from the troposphere leads to wave-mean flow interactions, inducing a substantial deceleration of the westerly winds. This wave forcing triggers the SSW phenomenon, characterized by the collapse of the polar night jet and the subsequent reversal of the U_h direction from westerly to easterly (Matsuno, 1971; Andrews et al., 1987). Monitoring these events has been markedly enhanced through the use of gridded daily mean fields verified by high-resolution radio

occultation (RO) data, providing a more consistent historical record since 1980 by accounting for both thermal and dynamical anomalies (Li et al., 2023).

The history of SSW research dates to early 1952, when Richard Scherhag identified a sudden and unusual increase in temperatures at the base of the stratosphere using radiosonde measurements in Berlin, Germany (Scherhag, 1952). Since then, satellite observations have provided monitoring of these events. While significant progress has been made in understanding the dynamical aspects of SSWs through both observations and simulations, evaluating their influence on both surface climate and the upper atmosphere remains a challenging and ongoing area of research. SSWs are defined by sudden surges in stratospheric temperature (T_s), particularly during winter, and are detectable in the middle stratosphere (at approximately 30 km or 10 hPa) by temperature increases often exceeding 30 to 40 Kelvin (K) (McInturff, 1978; Butler et al., 2015; Baldwin et al., 2020). These events are frequently accompanied by a corresponding cooling in the mesosphere, which can often be observed several days prior to the peak stratospheric warming, underscoring the significant vertical coupling within the middle atmosphere (Scheiben et al., 2011). Recent studies using the Deep Spatiotemporal Memory Flow Network (DSMF-Net), have further sought to improve the long-range predictability of these events, highlighting their non-linear complexity (Ma et al., 2025).

The morphology of SSW events varies, typically manifesting as either a vortex displacement or a vortex splits. The SSW event of January 2003 holds a distinctive position in the literature. Unlike majority of SSW events characterized by vortex displacement, the 2003 case involved as a vortex split event, resulting in a comprehensive breakdown of the stratospheric thermodynamic structure (Manney et al., 2005; Charlton and Polvani, 2007). This splitting process not only triggered an extreme temperature surge of 40–50 K but also led to a rapid and pronounced acceleration of the vertical branch of the global-scale Brewer-Dobson Circulation (BDC) (Holton et al., 1995). Recent reviews indicate that the BDC is expected to accelerate by approximately 2.0% to 3.2% per decade in response to greenhouse gas-induced climate change (Butchart, 2014). This intensification, however, may be partially attributed to an upward shift of the circulation under greenhouse gas forcing, rather than purely an increase in mass exchange, which has significant implications for the residence time of chemical species (Oberländer-Hayn et al., 2016).

In contrast to its role in the troposphere, water vapor in the extremely dry stratosphere serves as a sensitive tracer, delineating the pathways of stratospheric circulation. Stratospheric Water Vapor (SWV) is a significant greenhouse gas; even minor fluctuations in its concentration can perturb the Earth's radiative balance and catalyze chemical reaction chains leading to O₃ (Ozone) depletion (Solomon et al., 2010). During SSW events, the intensification of vertical motions in the polar region promotes the exchange between moist tropospheric air and dry stratospheric air masses. Research by Tao et al. (2023) indicates that SWV concentrations exhibit stable multi-decadal variations, often linked to temperature anomalies at the cold point tropopause, effectively segmenting the recent observational record into distinct wet and dry decades. Furthermore, longitudinal variations and zonal asymmetries in the BDC markedly influence the three-dimensional distribution of water vapor and O₃ in the northern middle atmosphere, suggesting that zonal mean approximations may overlook critical regional transport features (Bari et al., 2013).

To quantify this transport, this study utilizes a specific diagnostic index calculated as the difference between the average water vapor concentration in the subpolar region (70°N–50°N) and the tropical region (10°S–10°N). This index provides a proxy for the strength of the BDC, allowing for an examination of how moisture is redistributed from the tropics toward the poles during different phases of the SSW. By tracking this differential, the efficiency of meridional transport and the response of the stratospheric hydrological cycle to polar vortex disruptions can be effectively evaluated. The hydrological implications are supplemented by Integrated Vapor Transport (IVT) analysis. Horizontal moisture transport between mid-latitudes and the Arctic is often dominated by moisture intrusion events where transport exceeds the 90th percentile which are steered by large-scale circulation patterns such as blocking and Rossby wave breaking (Naakka et al., 2019). Since SSW events modulate the position and waviness of the tropospheric jet stream, they subsequently alter the pathways of IVT and can lead to anomalous precipitation patterns across the NH.

The Quasi-Biennial Oscillation (QBO) also plays a critical role in these dynamics. The QBO is a periodic shift between easterly and westerly winds in the tropical stratosphere occurring every 28 to 30 months near the equator (Alsepan et al., 2016). Typically, the westerly phase (QBO+) maintains vortex stability, while the easterly phase (QBO-) often enhances wave activity and the probability of SSW occurrences

through the Holton-Tan effect (Sunkara et al., 2024). During such events, planetary wave activity, including quasi-10-day and quasi-16-day waves, predominates in the stratospheric polar region, influencing the onset and persistence of the warming (Yang & Li, 2024). Recent findings also suggest that SSWs can modulate other tropical oscillations, such as the Semi-Annual Oscillation (SAO), by altering the momentum budget through filtered wave activity (Zhang et al., 2025, Ayarzagüena et al., 2018). The relationship between the QBO and SSWs remains a fundamental framework used to evaluate the dynamical consequences and interactions with adjacent atmospheric layers.

Historically, establishing a universal definition for SSWs has been difficult. Early monitoring programs like STRATALERT, launched by the World Meteorological Organization (WMO) in 1964, focused on sudden temperature increases detected using radiosonde and rocketsonde data (WMO/IQSY, 1964). Criteria proposed by McInturff (1978) used a temperature anomaly threshold of 25 K, while Charlton and Polvani (2007) defined Major SSWs as reversals of winds at the 10 hPa level at 60°N. However, research by Butler and Gerber (2018) demonstrated that annual SSW frequency can vary between 40% and 90% depending on the definition applied, highlighting the need for standardized metrics. Newer approaches such as the Threshold Exceedance Area (TEA) concept have been employed. In this framework, SSW intensity and duration are quantitatively assessed using Main Phase Duration (MPD), Main Phase Area (MPA), and Main Phase Strength (MPS) metrics (Li et al., 2023).

This study investigates observed and projected SSW events between 1980 and 2100. The analysis is conducted across two periods: a historical period (1980–2005) and a future period under the Representative Concentration Pathway 4.5 (RCP 4.5) scenario (2006–2100). SSW events interact significantly with other atmospheric layers, including the troposphere, mesosphere, and ionosphere. Therefore, the detection of SSWs is of particular importance in the context of climate change, as they serve as key indicators of polar winter variability and influence weather patterns on a global scale.

The analyses utilize the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA5) reanalysis and five Coupled Model Intercomparison Project Phase 5 (CMIP5) models as primary datasets, including ACCESS1.3 (Bureau of Meteorology and CSIRO, Australia; M1), FGOALS-g2

(LASG, Institute of Atmospheric Physics, China; M2), GFDL-ESM2G (NOAA Geophysical Fluid Dynamics Laboratory, USA; M3), HadGEM2-CC (Met Office Hadley Centre, UK; M4), and MPI-ESM-MR (Max Planck Institute for Meteorology, Germany; M5). While all five models are initially assessed, the study focuses primarily on M1, M2, and M3 to ensure consistency in capturing the evolution of the polar vortex and its sensitivity to thermal anomalies, as these models demonstrate a more reliable representation of the physical processes governing stratospheric variability. Hardiman et al. (2014) identified that while CMIP5 models generally project an increase in tropical upwelling, there are significant inter-model differences in the width of the upwelling region, particularly above and below 20 hPa. Models M2 and M3 are utilized as "high-top" models for their ability to simulate wave-mean flow interactions, while M1 is included due to its performance in simulating event counts comparable to observations.

TEA's are calculated by subtracting the multi-year daily climatological mean from the daily temperature fields, with the threshold value defined as anomalies exceeding 30 K. To define a discrete SSW event, this threshold must be exceeded for at least 6 consecutive days. Finally, each detected event is classified as Minor, Major, or Extreme based on the MPS value, which is derived from the MPA and MPD. These analyses are visualized in conjunction with QBO phases to understand the evolving dynamical and thermal connections within the atmosphere. Evaluation of these projections remains critical as reanalysis results are further refined through the integration of remote sensing and occultation observations (Li et al., 2023).

1.1 Purpose of Thesis

This research characterizes SSW conditions and evaluates their long-term evolution within the global climate system. Changes in the frequency, magnitude, and dynamical–thermal structure of these events are identified by comparing historical data (1980–2005) with future RCP 4.5 projections (2006–2100). The analysis examines T_s and U_h fluctuations at 10°N and 60°N latitudes, utilizing ERA5 reanalysis serves as the reference for validating CMIP5 model simulations over a continuous 120-year period.

The implementation of the TEA methodology provides a quantitative comparison for stratospheric variability. This approach addresses existing inconsistencies in SSW

classification by shifting the diagnostic focus from local wind reversals to multidimensional metrics. The spatial extent and temporal duration of warming are integrated into MPA, MPD, and MPS values, allowing for an objective assessment of event intensity and its response to anthropogenic forcing.

The diagnostic framework investigates atmospheric transport through a specific three-stage sequence. Initially, stratospheric moisture flux dynamics are quantified using Wave Activity Energy (S) and Vertical Eddy Moisture Flux ($\overline{w'q'}$) parameters to identify primary transport signals associated with vortex breakdown. This is followed by an assessment of IVT to determine the horizontal reorganization of moisture pathways and potential precipitation anomalies driven by tropospheric–stratospheric coupling (Naakka et al., 2019). The final stage evaluates the strength of BDC meridional transport using an index derived from the difference between subpolar (70°N–50°N) and tropical (10°S–10°N) water vapor concentrations. This integrated analysis explicitly identifies how extreme stratospheric events modulate the global hydrological cycle (Butchart, 2014; Tao et al., 2023).

A key objective involves the identification of systemic biases in climate models to improve long-range forecasting reliability. While the initial assessment includes five CMIP5 models (M1–M5), the analysis focuses on a primary ensemble consisting of M1, M2, and M3. These models are prioritized for their historical accuracy and, in the cases of M2 and M3, their "high-top" configurations, which are necessary for simulating wave–mean flow interactions. The exclusion of M4 and M5 from the primary group is due to their vertical resolution limitations, which result in a significant underestimation of stratospheric variability and a failure to reproduce realistic SSW frequencies. These findings emphasize the necessity of high-resolution vertical grids for accurate climate change projections.

1.2 Literature Review

In the study of Plumb and Eluszkiewicz (1999), recent developments in understanding stratospheric circulation dynamics have brought the notions of downward control and the extratropical transport. However, depending on certain assumptions, these notions cannot explain why mean stratospheric upwelling occurs largely in the tropics rather than the midlatitudes. A nonlinear two-dimensional model reveals that if the wave drag reaches close to the equator, within roughly 20°, a continuous and linear circulation

with an acceptable upwelling pattern may be attained. It is discovered that wave drag is the major mechanism driving the circulation by combining models of wave drag and diabatic heating into a nonlinear, zonally symmetric model. However, stratospheric heating might play a large role in net upwelling and help explain its structure. The role of viscosity in the model is yet unknown and has to be investigated further.

In the study of Limpasuvan et al. (2004), the life cycle of NH SSWs was examined using 44 years of National Centers for Environmental Prediction (NCEP)-National Center for Atmospheric Research (NCAR) reanalysis data. The research identifies that the incipient stage of a warming event is characterized by the preconditioning of stratospheric zonal flow and anomalous quasi-stationary wavenumber-1 forcing. It was discovered that as the life cycle intensifies, planetary wave driving causes a downward propagation of easterly winds and positive temperature anomalies toward the tropopause. The study concludes that the anomalous wave driving originates in the troposphere and determines the structural evolution of the vortex breakdown. This structural evolution, in turn, facilitates a downward coupling where stratospheric anomalies influence tropospheric circulation, leading to shifts in mid-latitude storm tracks and modulating surface weather patterns following the event.

Butchard et al. published (2006) a study titled "Simulations of anthropogenic change in the strength of the BDC." In the study, a number of middle atmosphere general circulation models were used to compare the effects of climate change on the BDC circulation and specifically on large-scale seasonal-mean transport between the troposphere and stratosphere. With a decrease in the extratropics, all models replicate the observed rise during the tropical tropopause. Some models interpret the rise's seasonal cycle as six months rather than a year. In every model, the BDC cycle quickened as greenhouse gas concentrations rose. With the exception of one model, the increase in mass change happened all year long, though this trend was usually stronger in the boreal winter. By applying the downward control principle, EP-flux divergence can account for over 60% of mean mass flux. The propagation of Rossby and gravity wave pseudo-momentum flows in the troposphere is assumed to be the cause of the BDC. The rate at which air moves from the tropical tropopause layer into the stratosphere in the tropics is determined by the strength of the BDC. The primary goal of the research is to comprehend the implications of climate change for the BDC, or the large-scale mass change from troposphere to stratosphere that is determined by

the BDC. According to every model, the northern winter will see the biggest rise in BDC. Our conclusion is that subgrid-scale processes contribute less from resolved waves but are still important to consider when analyzing how the BDC will react to a changing climate, so long as the downward control principle accurately describes seasonal mean stratospheric behavior. This has a significant implication for model parameterization to make sure that the parameters react to climate change appropriately, these processes' parameterization in models will need to be improved.

N. Butchart et. al. (2006), multiple middle atmosphere general circulation models have been used to study the influence of climate change on the BDC and large-scale transfer between the troposphere and stratosphere. Regardless of whether interacting O_3 chemistry is incorporated, these models consistently show that increasing greenhouse gas concentrations result in an increased mass exchange rate. All models successfully reproduce the observed upwelling and downwelling over the tropical tropopause and in the extratropics. However, the yearly cycle of upwelling differs amongst models, with some indicating a semi-annual rather than annual trend. The average trend in the mass exchange rate is predicted to be $11 \text{ kilotone s}^{-1}\text{year}^{-1}$, or around 2% each decade. However, this pattern differs greatly amongst models. The rise in mass exchange happens throughout the year in most circumstances, with a more prominent tendency found during the boreal winter. Using the downward control concept, it is discovered that the (Eliassen–Palm) EP-flux divergence can explain more than 60% of the mean mass fluxes. Furthermore, when the trends in the yearly mean mass fluxes calculated from the EP-flux divergence are averaged across all models, they account for approximately 60% of the trend in the troposphere-to-stratosphere mass exchange rate. Except for two models, there is a significant agreement between the downward control-derived and actual mass fluxes for the annual mean in terms of interannual variability. To summary, the models show that climate change increases the mass exchange rate between the troposphere and stratosphere, with more pronounced changes during the boreal winter. The models successfully reproduce observed upwelling and downwelling patterns, and the EP-flux divergence explains mean mass fluxes and trends.

In order to determine the seasonality of the change in the BDC, Austin and Wilson's (2007) study, "The Strength of the Brewer–Dobson Circulation in a Changing Climate: In Coupled Chemistry–Climate Model Simulations," examined the strength of the

circulation in a changing climate using Chemistry–Climate Model (CCM) between 1960 and 2100. In terms of the years 1960–2004 and 2005–2100, the model depicts the past and the future, respectively. reproduces the BDC's strengthening, albeit with a distinct seasonal cycle. Future simulations indicate that the upstream flow increase will be equal throughout the four seasons, whereas past simulations indicate that nearly half of the increase happens in December through February. The differential seasonality is primarily observed in the southern hemisphere, according to downward control analysis. According to this theory, the force of planetary waves in the sea is identified as the primary driver. Conversely, to previous solstice periods, this forcing reveals the long-term trends of those later periods. Analysis has revealed a strong correlation between the development of planetary wave activity in the southern hemisphere and the O₃ layer's expansion and contraction. Model results from the past indicate the decreased stratospheric mass. This indicates that the O₃ layer's thinning contributes roughly 60% of the flux increase. Greenhouse gas emissions are connected to the increase in mass flow. The reduction in stratospheric cooling and troposphere warming due to greenhouse gas increases and/or O₃ depletion is proposed as the cause of the decline in static stability in the lower stratosphere.

Simulations using the Whole Atmosphere Ensemble Climate Model were used in the research "Acceleration of the Brewer–Dobson Circulation due to Increases in Greenhouse Gases" by Garcia et al. (2008) to explain the mechanism that causes changes in the BDC under increasing greenhouse gas load. The study made use of the Stratosphere-troposphere Processes And their Role in Climate (SPARC), CCM, and Whole Atmosphere Community Climate Model, Version 3 (WAACM3) models. Due to variations in wave driving by resolved waves in the subtropical lower stratosphere and mesoscale gravity waves at higher altitudes, the BDC velocity in WAACM3 increases as greenhouse gas increases. It is clear from the simulations that the BDC is accelerating, and that this is because the lower stratosphere's tropical and subtropical regions have altered in terms of the zonal mean U_h structure, which permits the wind to continue spreading and dispersing. Wave activity in this area. Temperature trends brought on by an increase in greenhouse gases can ultimately be blamed for changes in the BDC since the U_h and T_s are in geostrophic balance.

"How does the northern-winter wave driving of the Brewer-Dobson circulation increase in an enhanced- CO₂ climate simulation?" was the title of a study by

Haklander et al. (2008). They brought the subject to light. In the study, BDC in an enhanced carbon dioxide (CO₂) climate were used to investigate it in detail. According to recent climate studies, if greenhouse gas concentrations rise, the BDC's Northern Winter wave will intensify. The paper reports on enhanced wave driving analysis using the Middle Atmosphere - European Centre Hamburg Model Version 4 (MA-ECHAM4) model in the doubled CO₂ experiment. A 12% increase in heat flux at 100 hPa, a gauge of stratospheric wave action, was discovered in a climate with doubled CO₂. The increase in the mid-latitude atmosphere is dominated by the stationary wave1 flow. Nearly all of the increase in heat flow at 100 hPa can be attributed to longitudinal temperature variability. It was discovered that doubling the CO₂ concentration caused a notable rise in Eddy Heat Flux at 100 hPa (H100) at the 100 hPa level as a result of wave1 increasing.

In Okamoto et al.'s (2011) paper "A study on the formation and trend of the Brewer-Dobson circulation," the meridional cross-section method was used to analyze the respective waves' contribution to the residual circulation. Verification was done using observational data and ECMWF Re-Analysis Interim (ERA-Interim) reanalysis data. As greenhouse gas concentrations rise, the warming balance is predicted to shift, resulting in warming in the troposphere and cooling in the stratosphere. In particular, above 30 hPa and at high latitudes, planetary waves are known to exist in the middle and upper stratosphere. Low- and mid-latitude regions of the lower stratosphere are the only locations where the synoptic scale wave effect occurs. Planetary waves and gravity waves both contribute similarly at mid-latitudes. Gravity Wave Drag (GWD) in the lower stratosphere is known to be useful in the development of BDC. Residual Circulation (RC) is a rough way to express BDC. It is acknowledged that body force caused by atmospheric waves breaking or dissipating is what drives it. The principle of downward control diagnoses the various wave types of contributions to resonance cancellation. In the lower stratosphere's low- and mid-latitudes, GWD, including Orographic Gravity Wave Drag (OGWD), significantly affects RC. GWD generates the winter circulation's low-latitude component in the summer hemisphere. When the resolved wave contribution is subtracted from the Residual Velocity (RV) using the Downward Control (DC) principle, the results align with estimates of the GWD contribution derived from reanalysis data. With OGWD shifting upward in the twenty-

first century, the net upward flux at 70 hPa seems to have strengthened. Based on these findings, the BDC is likely maintained in part by gravity waves.

Gabriel et al. (2011) published a study with the title "Zonal asymmetries in middle atmospheric O₃ and water vapor derived from Odin satellite data 2001–2010". Using data from the 2001–2010 Odin Satellite, startingary wave patterns were examined by calculating seasonal long-term averages of zonal-asymmetric components. In the NH, wave patterns intensify in the fall, hold steady throughout the winter, and then begin to wane in the spring. Between 10% and 20% of the zonal mean value is the maximum amplitude. Wave 1 in the O₃ layer has a double-peak structure in the winter, peaking over the North Pacific/Aleutians, troughing the North Atlantic/Northern Europe, and building in amplitude in the upper and lower stratosphere. Water vapor from Wave 1 moves from the lower stratosphere to the upper mesosphere, shifting westward as altitude rises and experiencing a phase shift at altitudes in the upper stratosphere. Similar wave patterns are seen in the southern spring in the Southern Hemisphere (SH). It is determined that the primary source of these wave patterns in O₃ and water vapor is zonally asymmetric transport by geostrophically balanced winds by comparing the linear solution of the steady-state transport equation for the zonally asymmetric tracer component with the observed wave patterns.

The study by Scheiben et al. (2011) investigated water vapor and O₃ anomalies during the 2010 major SSW using ground-based microwave radiometers and Aura Microwave Limb Sounder (MLS) satellite data. A significant increase in stratospheric water vapor was observed over mid-latitudes during the peak of the warming. This increase was attributed to the advection of moist air masses originating from the polar vortex. It was also found that O₃ concentrations in the upper stratosphere decreased by approximately 20% to 30% during the event. The research highlights the role of SSWs in the chemical and dynamical redistribution of middle atmospheric constituents.

The primary objective of Seviour et al.'s (2012) study was to diagnose BDC and tropical upwelling using ERA-Interim. Long-term trends were computed in the study using residual vertical velocity. Data from 6 hours were used (00-06-12-18 Coordinated Universal Time (UTC)). 37 pressure levels and 1.5 degrees of horizontal resolution were employed between 1989 and 2009. The region of the stratosphere for about one kilometer is represented by the uppermost 1 hPa. The study allowed zonal mean winds to be well-represented. The circulation's features were replicated in the

model. The yearly cycle is also effectively depicted. Understanding BDC's climatology necessitates at least six hourly periods. More accurate than the ERA-Interim's residual speed values. This gave a more complete diagnosis of the tropical rise's spatial structure. During the minimum year in the equator, it has been observed that the ascent rate, around 70 hPa, is the fastest in NH. Consequently, trend predictions may be insufficient even though ERA-Interim more accurately represents the data.

The study by Bari et al. (2013) investigated the effects of longitudinal changes in BDC, water vapor, and O₃ transport on regional asymmetries using the three-dimensional (3D) residual circulation approach. The study used general circulation model simulations with interactive chemistry (Harmonization of Atmospheric Measurements and Models (HARMONIA)), reanalysis (ERA-Interim), and satellite data (Aura/MSL) to obtain monthly average residual winds, including Eulerian Flow and eddy induced time-mean flow for January. A 3D circulation connected to zonal waves in the middle atmosphere, including residual winds that move both northward and downward, is revealed when the zonal mean two-dimensional (2D) BDC is. These winds are a major cross-polar transport from Asia to North America, downward winds over northern Europe/Asia towards the polar vortex over northern Siberia, and upward and southerly residual winds over the northern Pacific/Aleutians. The production of O₃ and water vapor advection occurs due to zonal asymmetries of residual mass transport, in which Eulerian and Eddy time-mean transports substantially outweigh the observed wave patterns of these gases. These asymmetries underscore how localized moisture advection can alter the stratospheric radiative balance and drive the vertical moisture injection mechanism observed during major warmings. The model underestimates the effects of planetary waves in comparison to observations. As the SSW forms in O₃ and water vapor, the phases of transient waves are estimated.

According to Hardiman et al. (2014), "The morphology of the Brewer–Dobson circulation and its response" Annual average vertical and latitudinal structure of the BDC in CMIP5 models was analyzed in the paper "to climate change in CMIP5 simulations". The strength of the tropical updraft was found to increase with stratospheric altitude as a result of climate change. The tropical upwelling's width increases above 20 hPa and decreases below at that point. This demonstrates that various processes are involved in the various regions. Relative to the extratropics, the

70 hPa level is low enough to avoid mixing issues while still being high enough to be above the stratosphere-troposphere exchange. The study examines how the models' tropical upwelling zone width and upwelling structure respond to climate change. Waves on the planet Its dissemination has been studied in relation to changes. Additionally examined has been the tropical upwelling region's seasonal cycle. Tropical upwelling widens above 20 hPa and narrows below. This demonstrates the distinct roles that various mechanisms play across the regions. Specifically, the analysis has focused on how changes in extratropical downwelling balance out changes in tropical upwelling. Residual vertical velocity is typically used to analyze BDC, however CMIP5 does not include this variable. Because of this, the modeling group had to be contacted directly for the data. Data on monthly averages were applied. The models utilized are either up to 1 hPa or stratosphere resolved. Reanalysis shows that BDC is still weak below 1 hPa. As a result, 5 degrees north and south latitude, which is frequently used to diagnose QBO, shows 20% of the total mass rise. Twenty degrees north and south of latitude are where 60% of the total mass rise is observed. In this area, the number of tropical upwelling is growing and decreasing. This demonstrates that various physical processes are in play.

N. Butchart published (2014) a review titled "The Brewer-Dobson circulation." The study analyzes historical developments in observations, theory, and climate model projections. It was found that greenhouse gas-induced climate change results in an acceleration of the global mass circulation by approximately 2.0% to 3.2% per decade. The research explains that this circulation is characterized by air rising in the tropics, moving poleward, and descending in the middle and high latitudes. The study concludes that while the trend is reliable in models, the physical mechanisms driving the BDC acceleration are not yet fully understood and require further investigation of wave-mean flow interactions.

In the study titled "What Drives the Brewer-Dobson Circulation?" by Cohen et al. (2014), the interactions between resolved Rossby waves and parameterized gravity waves were explored. Using an idealized atmospheric model, the study identified that perturbations to parameterized wave driving are often compensated by opposite changes in resolved wave driving. Three specific interaction mechanisms were identified: a stability constraint, a potential vorticity mixing constraint, and a nonlocal interaction driven by modifications to the refractive index of planetary wave

propagation. The findings suggest that wave-driving compensation is a critical factor to consider in model parameterization.

The 2013 SSW event was the subject of a case study by Milas (2014). The research focused on the effects of planetary wave propagation on the general circulation of the atmosphere. Using EP-flux theory, the study analyzed the forcing applied to the NH circulation pattern. It was found that the 2013 vortex breakdown was strongly associated with tropospheric blocking events. The analysis showed that the evolution of eddy momentum and heat fluxes directly determined whether the polar vortex would experience a displacement or a complete split.

The relationship between the rise in circulation and the BDC trend was pointed out in the Oberländer et al. (2016) study. F_{top} , or tropical upwelling mass flux, at 100 hPa is opposite in the tropopause, as was highlighted in the study using CCM. For the past ten years, F_{top} has increased by 1-2%, but in the tropopause, it has declined. Other tools used in the study included ECHAM, Modular Earth Submodel System (MESSy), and European Centre Hamburg Model /MESSy Atmospheric Chemistry (EMAC). From 1960 to 2100, it was simulated. Utilized were RCP 4.5–6 and 8.5. As for other CCMs, similar findings have been made. The conclusion is that, rather than increasing, changes in BDC are better characterized as upward shifts. It was shown that ascent dominates changes at constant pressure levels, with relatively little change in mass transfer into and out of the stratosphere.

In the research by Alsepan et al. (2016), the equatorial QBO was analyzed using ERA-Interim data from 1981 to 2010. The study quantified the alternating regimes of easterly and westerly winds, finding an average period of 27.7 months. It was discovered that the maximum amplitude of U_h occurs at the 20 hPa level, whereas the maximum temperature amplitude is located at 30 hPa. The results demonstrate that the phase of the QBO significantly modulates total column O_3 concentrations in the tropical stratosphere, which has implications for the overall radiative balance.

In the study by Naakka et al. (2019), a study using moisture transport between the Arctic and mid-latitudes is discussed. Emphasizing the importance of atmospheric water vapor in the Arctic climate system, it is stated that it functions as a greenhouse gas and affects radiative transfer, cloud formation and fog formation. The study focuses on the period 2003-2014 by analyzing regional, seasonal and vertical aspects

of moisture transport. In particular, reanalyses such as ERA-Interim are used to obtain a comprehensive representation of the atmosphere. The results of the study provide insights into the spatial and temporal characteristics of moisture transport between the Arctic and mid-latitudes. Emphasizing the importance of Transient Eddys in net latitude moisture transport, it reveals the influence of different factors such as Stationary Eddys and mean circulation. Crucially, these findings highlight the role of water vapor as a primary greenhouse gas in the Arctic, where its vertical distribution and regional transport patterns shape the polar radiative environment and hydrological feedback loops. The findings contribute to a better understanding of the interactions of moisture transport patterns and moisture profile with physical processes.

A study by Bushell et al. (2020) evaluated the representation of the QBO in 13 global climate models as part of the SPARC QBO-initiative. The results showed that while most models simulate a QBO period close to the observed 28 months, the meridional extent of the simulated oscillation is often too narrow. It was found that amplitudes at the 50 hPa and 70 hPa levels are frequently underestimated in current simulations. The study identifies that parameterized non-orographic gravity waves are responsible for the majority of the total wave forcing required to maintain the QBO in these models.

In a study by Weifu Sun et al., (2022), using the ERA5 reanalysis tool, the researchers examined the spatiotemporal features of atmospheric and energy flow towards the Arctic from 1979 to 2020. The Chukchi Sea, Baffin Bay, the North Atlantic, and central Siberia were identified as the primary entry points for atmospheric transport into the Arctic. Summer is featured by strong moisture transfer, whereas winter and spring show a large decrease in energy transmission. Summer and fall energy transport, on the other hand, is on the rise. The research also looked at the connection between air transport and large-scale atmospheric circulation patterns including the Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and Dipole Anomaly (DA). The Dipole Anomaly was found as the most prominent pattern related with moisture and energy entry into the Arctic among these patterns. As a result of the Dipole Anomaly, surface air 10^{-3} rises are more apparent throughout most of the central Arctic. Overall, no apparent pattern in moisture movement was identified, although winter and spring showed a decreasing trend in energy transfer and summer and fall showed a rising trend in energy transport.

The study "multi-decadal" variability controls short-term stratospheric water vapor trends" by Tao et al. (2023). The study combined the use of Lagrangian transport model simulations with satellite observations. The majority of the stratosphere exhibits a significant multi-decadal variation in water vapor concentrations, as shown by satellite observations and atmospheric model simulations. For the past 40 years, two wet decades have been used: 1986–1997 and 2010–2020. It was decided that the years 1998 through 2009 were a dry decade. A strong and significant Mean Doppler Velocity (MDV) appears to affect stratospheric water vapor. MDV has little effect on the four decades' worth of SWV trend calculations. Overall, there is no statistically significant trend for SWV between 1980 and 2020. Regionally, SWV trends were discovered to be predominantly positive in the lowermost stratosphere, weakly positive in the upper stratosphere, negative in the SH from the lower to middle stratosphere, and nearly neutral in the NH from the lower to middle stratosphere.

The study of Li et al. (2023) introduced a new methodology for monitoring SSWs under climate change using the TEA method. The research utilized ERA5 reanalysis data verified by high-resolution RO observations from 1980 to 2021. It was discovered that the duration of the main warming phase has increased by approximately 50% since the 1980s. The study concludes that this increased duration is a major factor contributing to the overall rise in SSW strength observed in recent decades. The TEA method was found to provide a more consistent historical record than traditional point-based metrics.

Sunkara et al. (2024) investigated the roles of the QBO and Madden-Julian Oscillation (MJO) in major SSW events during 2018, 2019, and 2021. Using Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis, the case study analyzed polar cap temperature surges and U_h reversals. It was found that westerly QBO phases facilitate stronger upward planetary wave propagation, while easterly phases tend to dampen the heat flux into the polar stratosphere. The research highlights the 2019 event as particularly significant due to its occurrence during a period of anomalous tropical convective activity, which amplified the wave driving.

In the study by Yang and Li (2024), planetary wave activity during the 2019 minor SSW in the SH was analyzed. Frequency-wavenumber spectral analysis revealed that quasi-10-day and quasi-16-day waves dominated the stratosphere during the event.

EP-flux diagnostics showed that these waves possessed both poleward-propagating components from tropical convection and equatorward components excited by barotropic instability. The results suggest that these specific wave modes played a critical role in the onset and persistence of the 2019 Antarctic warming event.

The study titled "DSMF-Net: A Spatiotemporal Memory Flow Network for Long-Range Prediction of SSW Events" by Ma et al. (2025) proposed a deep learning framework for atmospheric forecasting. By utilizing a spatiotemporal memory flow network, the researchers successfully predicted polar vortex structures up to 20 days in advance. It was found that the model outperforms traditional recurrent neural network baselines in capturing the non-linear dynamics of both vortex displacement and split events. The research emphasizes the potential of deep learning for improving the lead time and accuracy of extreme stratospheric event warnings.

Ermakova et al. (2025) analyzed stratospheric polar vortex strength under different QBO and El-Niño Southern Oscillation (ENSO) phases using a nonlinear general circulation model. The findings indicate that the polar vortex and EP flux divergence are most intense during La Niña and QBO+ conditions. It was found that SSW development is most favorable during the QBO– phase in January and the QBO+ phase in February under El Niño conditions. The results underline the complex interaction between tropical oscillations and the stability of the winter polar vortex.

In the study of Zhang et al. (2025), the modulation of the SAO by SSW events was examined using high-altitude Japanese Reanalysis for the Whole Atmosphere (JAWARA) re-analysis data. The research shows that early winter SSWs intensify the westward phase of the stratospheric SAO, while late winter events weaken the eastward phase. This modulation was attributed to the meridional temperature changes during the warming events, which act through thermal wind balance to alter the SAO structure. The study concludes that SSW-induced variations in filtered wave activity are the primary drivers of these changes in the middle atmosphere.

1.3 Data

1.3.1 Integrated dataset framework

The empirical and numerical foundation of this study is based on a combination of high-resolution atmospheric reanalysis and Global Climate Model (GCM) outputs.

Specifically, the research utilizes ERA5 and simulations from five global climate models participating in CMIP5. These datasets, accessed via the Copernicus Climate Data Store (CDS), provide a robust reconstruction of past atmospheric states while allowing for the evaluation of future climate projections under standardized forcing scenarios (Copernicus Climate Change Service, 2024a; 2024b). By integrating observational data with predictive simulations, the study establishes a continuous 120-year timeline for analyzing stratospheric variability. As summarized in Table 1.1, the analysis is structured across a historical period (1980–2005) and a future period (2006–2100) governed by the RCP 4.5 scenario.

1.3.1.1 The ERA5 reanalysis

ERA5 serves as the definitive reference dataset for historical validation and stratospheric process analysis. As the technical successor to the ERA-Interim reanalysis, ERA5 provides a significant advancement in spatial and temporal resolution, which is critical for capturing the rapid onset of SSW events.

The reanalysis is produced through a sophisticated four-dimensional (4D) variational data assimilation system within the ECMWF Integrated Forecasting System (IFS). This system integrates vast quantities of global observations including satellite radiances, radiosonde profiles, and surface measurements with numerical model data to create a physically consistent and spatially complete atmospheric record (Hersbach et al., 2023).

For the purposes of this investigation, the study utilizes the "ERA5 hourly data on pressure levels from 1940 to present" dataset. To maintain consistency across the comparative analysis, the native resolution has been regridded to a standard latitude-longitude grid of $0.25^\circ \times 0.25^\circ$ (Table 1.1). ERA5 resolves the vertical structure of the atmosphere using 137 model levels reaching up to 0.01 hPa. However, this study focuses on a subset of 37 standard pressure levels ranging from 1000 hPa at the surface to 1 hPa at the stratopause.

A distinctive feature of ERA5 is the inclusion of an uncertainty estimate generated by a 10-member ensemble every three hours. This Ensemble of Data Assimilations (EDA) reflects the information content of the evolving observing system and identifies flow-dependent sensitivity zones, providing a consistent measure of confidence in the stratospheric fields.

1.3.1.2 Numerical model data: CMIP5

The CMIP5 initiative serves as the standardized framework for the climate projections analyzed in this study. The data are extracted from the "CMIP5 daily data on pressure levels" archive provided by the CDS. Accessing multiple vertical pressure levels is essential for diagnosing the 3D structure of the polar vortex and the vertical branch of the BDC.

The research incorporates three primary categories of simulations. First, historical experiments (1850–2005) are analyzed to evaluate the proficiency of GCMs in replicating known stratospheric phenomena against modern observations. Second, an ensemble of experiments from the Atmospheric Model Intercomparison Project (AMIP) is employed; these prescribe oceanic variables to simplify the climate system by excluding the complexity of ocean-atmosphere feedback. Third, the study focuses on climate projection experiments aligned with the RCP 4.5 scenario (2006–2100). RCP 4.5 represents a medium-level stabilization pathway where greenhouse gas concentrations are projected to plateau in the latter half of the 21st century, reaching a radiative forcing level of 4.5 W/m² by 2100. This stabilization assumes the implementation of emissions mitigation policies, making it a viable baseline for moderate climate trajectories (IPCC, 2013).

1.3.2 Model selection and vertical resolution justification

Based on a critical review of the literature (Taylor et al., 2012; IPCC, 2013), five models were selected from the CMIP5 ensemble: M1, M2, M3, M4, and M5.

The models were chosen according to stringent criteria, including full temporal coverage across both historical and RCP 4.5 periods, data completeness for the required stratospheric variables, and the ability to adequately resolve the vertical profile up to at least the 10 hPa pressure level. The technical specifications and institutional origins of these models are presented in Table 1.1.

The selection is categorized into Primary (High-top) and Secondary (Low-top) groups based on their capacity to simulate stratospheric variability. The Primary group consists of M1 from Australia, M2 from the UK Met Office, and M3 from the Max Planck Institute. Models M1, M2 and M3 are categorized as high-top models, resolving levels up to 1 hPa or higher. This vertical extent is essential for accurately simulating planetary wave propagation, wave-mean flow interactions, and the complex

coupling between the QBO and SSW events. High-top models prevent artifacts associated with upper-boundary absorbing layers that frequently occur in low-top models, where wave activity is artificially dampened at the top of the domain. In contrast, the secondary group includes M4 from China and M5 from USA features a lower model top compared to M1, M2 and M3, it is included in the primary group due to its demonstrated success in replicating SSW frequencies that align with observational records.

Table 1.1 : Technical specifications, institutional origins, and spatial-temporal resolutions of the ERA5 reanalysis and selected CMIP5 models (Climate Data Service 2018, Climate Data Service 2023).

Full Model Name & Abbreviation	Institution / Country	Spatial Resolution	Temporal Coverage (Periods)
Reference Data			
ERA5 Reanalysis (ERA5)	ECMWF, Europe	$0.25^{\circ} \times 0.25^{\circ}$	Hourly (1980–2005)
Primary Climate Models			
Australian Community Climate and Earth-System Simulator v1.3 (ACCESS1-3 / M1)	CSIRO-BOM, Australia	$1.875^{\circ} \times 1.25^{\circ}$	Daily (Hist: 1980–2005 / RCP4.5: 2006–2100)
Hadley Centre Global Environmental Model v2 – Carbon Cycle (HadGEM2-CC / M2)	Met Office, UK	$1.25^{\circ} \times 1.25^{\circ}$	Daily (Hist: 1980–2005 / RCP4.5: 2006–2100)
Max Planck Institute Earth System Model – Mixed Resolution (MPI-ESM-MR / M3)	MPI-M, Germany	$1.875^{\circ} \times 1.875^{\circ}$	Daily (Hist: 1980–2005 / RCP4.5: 2006–2100)
Secondary Climate Models			
Geophysical Fluid Dynamics Laboratory Earth System Model v2G (GFDL-ESM2G / M4)	NOAA-GFDL, USA	$2.5^{\circ} \times 2.5^{\circ}$	Daily (Hist: 1980–2005 / RCP4.5: 2006–2100)
Flexible Global Ocean–Atmosphere–Land System Model, Grid-Point v2 (FGOALS-g2 / M5)	LASG/IAP, China	$2.8125^{\circ} \times 2.8125^{\circ}$	Daily (Hist: 1980–2005 / RCP4.5: 2006–2100)

In contrast, M4 and M5 are categorized with in the Secondary group. These models feature shallower model tops and coarser vertical resolutions in the middle atmosphere.

Technical evaluations indicate that these vertical limitations often restrict the models' ability to consistently reproduce realistic QBO-SSW interactions and the full magnitude of stratospheric warming events. While M4 and M5 serve as valuable comparative references for assessing inter-model variability and resolution-induced biases, their results are primarily utilized to highlight the impact of vertical grid density on stratospheric forecasting.

1.3.3 Scientific criteria for variable and diagnostic selection

The detection and analysis of SSW events focus primarily on the 10 hPa pressure level where the dynamical signals of the polar vortex breakdown are most pronounced. For both ERA5 and the CMIP5 models, a specific suite of atmospheric variables is extracted to support both dynamical and hydrological diagnostics.

The U_h components are utilized to identify the cessation or reversal of the polar night jet and to calculate wave-driving diagnostics such as the EP-flux. Correspondingly, T_s is essential for quantifying the magnitude and spatial extent of warming anomalies through the TEA method.

To analyze the stratospheric hydrological cycle and moisture transport, the study incorporates vertical velocity (ω) and specific humidity (q). These variables serve as tracers for assessing the strength of the BDC meridional transport and calculating IVT. By examining the relationship between ω and q , the study identifies how polar vortex disruptions reorganize global moisture flux patterns. The use of standardized pressure levels ensures a direct quantitative comparison between reanalysis data and model projections, facilitating an understanding of the stratospheric response to climate change.



2. METHOD

The definition and classification of SSW events have constituted a gap in the literature for many years. Extensive research on SSW has yielded various criteria for detection, such as stratospheric U_h reversal and temperature anomalies at specific latitudes and durations. However, the diversity among these definitions has significantly impacted the frequency and intensity of detected events. In fact, Butler et al. (2015) compared the results of nine different “extreme SSW” definitions and concluded that the annual SSW frequency varies between 0.4 and 0.9 depending on definition applied. Such large variations underscore the need for standard and physically meaningful metrics. Butler and Gerber emphasized that an ideal SSW definition should fully capture the characteristics of stratospheric warming without being overly sensitive to the dataset or specific latitude and pressure levels. Considering all these, the methods developed in recent years have tended to define the intensity of the event with metrics that consider both duration and area. In particular, Li et al. (2023) have achieved significant standardization by using the TEA concept and the MPD and MPA metrics related to it for the quantitative assessment of SSW intensity. In light of all these, the methods in the study include the detection, classification and comparison of SSW days using TEA and metrics.

Daily mean temperature data at the 10 hPa level were used in the study. SSW events occurring in the stratosphere were analyzed with these data. The dataset used in the analyses are ERA5 reanalysis data and five different GCM within the scope of the CMIP5. Analysis is divided into two periods as historical and future. While the 1980–2005-year range is used for historical data, the 2006–2100 year range is preferred for future data. The ERA5 data set is reduced to daily average due to its hourly resolution. For the entire data set, the data space is limited to the 0–90° NH at the 10 hPa level. To capture the full seasonal range of occurrences, the analysis focuses on the November–April window, as more than 60% of SSWs typically occur during the January–February period. Additionally, while five CMIP5 models were initially considered, only the first three (M1–M3) are utilized for dynamical analysis. Models M4 and M5 are excluded due to their poor performance in identifying significant

stratospheric results, while M1 is kept only for general frequency comparisons (Sections 4.1–4.3) but excluded from coupling diagnostics because it cannot replicate coherent thermal-dynamical feedback mechanisms.

2.1 Calculation of Threshold Value

One of the methods used in SSW detection is the classical wind rotation criterion. In this study, instead of the wind reversal criterion, which is one of the widely used methods, a method based directly on temperature anomalies was followed. This method, designed as TEA, is based on detecting SSW events with a certain temperature anomaly threshold value (Li et al., 2023). In addition to the threshold value, exceeding this threshold for 6 days or more is another criterion of this method. This method was first developed by Butler and Gerber (2015) and later used with different versions in studies such as Palmeiro et al. (2015), Garfinkel et al. (2010). With this selected method, the geographical area where a certain temperature anomaly is observed and the duration corresponding to this anomaly are determined, and the spatial and temporal spread of the event is converted into a numerical value. As a result, TEAs represent the total surface area of the regions where temperature anomalies exceeding the threshold value determined on that day and a certain number of days or more are observed. The threshold value for temperature anomalies used in the analysis process was selected as 30 K in the light of literature and calculated using daily average temperature data at 10 hPa pressure level.

Following earlier classifications, models M1, M2 and M3 are grouped as higher-top models (extending above ~ 1 hPa), allowing a realistic representation of planetary wave propagation. In contrast, lower-top models like M4, and M5 terminate at 10–30 hPa, which may result in a systematic underestimation of Major and Extreme events due to limited vertical wave–mean flow coupling. This value is consistent with the limit values frequently used in studies such as McInturff (1987), Labitzke (1981) and Baldwin & Thompson (2009) and is widely used to detect large-scale SSW events occurring in the middle stratosphere (approximately 30 km, 10 hPa).

The analyses were performed using MATLAB software. To identify SSW events accurately, temperature data must be processed to remove seasonal cycles and model-specific mean-state biases. In this study, temperature anomalies were calculated relative to a daily climatological baseline, established independently for the ERA5

reanalysis and each individual CMIP5 model simulation. This independent baseline approach is essential for ensuring that model-specific systematic errors do not interfere with the detection of dynamical warming events (Butler et al., 2017).

The calculation proceeds on a per-day basis for the entire calendar year. For example, to determining the temperature anomaly for January 1st of a specific year, the climatological mean of all January 1st data points within the reference period was subtracted from that day's value (Table 2.1). This process evaluates each date within its own historical or projected context, isolating transient dynamical signals through seasonally adjusted anomaly values (Charlton & Polvani, 2007, Blume et al., 2012).

Table 2.1 : Threshold Exceedance Area Temperature Anomaly Formula.

Parameter	Mathematical Formulation	Description / Definition
Temperature Anomaly (ΔT_s)	$\Delta T_s = T - T_{Cli}$	Represents the daily deviation from the long-term mean, typically expressed in K.
Observed Temperature (T)	T	The instantaneous or daily mean temperature value extracted from CMIP5 climate model outputs or ERA5 reanalysis profile data.
Climatological Mean (T_{Cli})	T_{Cli}	The long-term collocated climatic average temperature value at the same geographic location, used as the reference baseline.

A critical aspect of this methodology is the use of period-specific baselines to account for long-term climate trends. For the historical period (1980–2005), anomalies are derived from the mean state of that 26-year window. Similarly, for the future projections (2006–2100), a distinct baseline is established over the entire scenario window. By treating these two eras independently, the methodology effectively isolates SSWs from the background signal of long-term, greenhouse-induced stratospheric cooling. This approach ensures that any identified anomaly represents a true departure from the "climate normal" of that specific era, providing a consistent reference level to evaluate changes in dynamical variability relative to the projected state of the 21st-century stratosphere.

In order for an event to be defined as SSW, temperature anomalies above the selected threshold value of 30 K must persist uninterruptedly for at least 6 consecutive days.

This method distinguishes individual and sustained SSW events from transient warming fluctuations. The selection of this 30 K threshold is motivated by the necessity to isolate high-amplitude dynamical disturbances from background interannual variability, aligning with the classic 'Major Warming' criteria established by Labitzke (1981) and later refined for climatological robustness by Charlton and Polvani (2007). Unlike more relaxed thresholds (e.g., 25 or 28 K), the 30 K limit ensures that the identified events represent substantial polar vortex disruptions rather than minor thermal pulses (Butler et al., 2015). Furthermore, the requirement of 6 consecutive days of persistence is implemented to verify the dynamical memory of the event, as sustained warming is essential for establishing the downward coupling necessary to modulate the stratospheric-tropospheric exchange (Manney et al., 2015). Each SSW event was analyzed independently in terms of duration and area, and the point where it fell below the 30 K threshold value was accepted as the end point of the SSW event. This criterion aligns with the fundamental definitions widely employed in the existing literature (Charlton & Polvani, 2007; Blume et al., 2012).

In this context, all SSW events in the analyzed time series were determined according to these criteria and the event start and end dates were found. Once SSW days are identified, the surface area covered by temperature anomalies exceeding the threshold value on SSW days was determined in latitude-longitude coordinates. The geographical area (km^2) where temperature anomalies spread for each SSW event is calculated by taking the surface sum of the grid cells exceeding the threshold value.

Specifically, the process first identifies the grid cells where temperature anomaly values at the 10 hPa level exceed 30 K for each SSW day. Subsequently, the latitude and longitude coordinates of these grid cells are extracted to calculate the surface area for each individual cell. The sum of these areas constitutes the TEA value for the selected day. This approach enables a precise numerical measurement of the daily spatial evolution of SSW events.

2.1.1 Statical diagnostics and trend analysis

To quantify intra-annual variability and long-term changes in T_s and U_h , three statistical diagnostics are derived from the monthly mean series using a 12-month moving averaging window. First, range-based variability (T_{rng} , U_{rng}) is computed as the monthly maximum-minimum spread divided by 12. Second, the amplitude of

variability (T_{amp} , U_{amp}) is defined as the standard deviation of the windowed values. Third, long-term tendencies are expressed through trend slopes (S_{T_s} , S_{U_h}) calculated using ordinary least-squares (OLS) regression on monthly means, reported in K.yr^{-1} and $\text{m.s}^{-1}\text{yr}^{-1}$, respectively (Eq 2.1). The trend slope is defined in its basic finite-difference form as:

$$S = \frac{\Delta X}{\Delta t} = \frac{X_{t_2} - X_{t_1}}{t_2 - t_1}, \quad (2.1)$$

where X denotes the respective variable (T_s or U_h). These notations are used consistently throughout the analysis to assess the significance of stratospheric changes.

2.2 MPD, MPA and MPS Calculation

Table 2.2 presents a summary of the key quantitative metrics used to assess the intensity and spatial extent of SSW events. These metrics originated from the TEA framework, which jointly evaluates the horizontal spread and temporal persistence of each event. MPD denotes the number of consecutive days during which the temperature anomaly exceeds a predefined threshold, while the MPA represents the average daily area where the anomaly surpasses this threshold throughout the event. The product of MPD and MPA yields the MPS, a scalar measure that captures the overall spatiotemporal magnitude of the warming event.

MPS enables consistent comparison across events of differing duration and extent. Based on this metric, SSW events are classified as Minor ($<90 \times 10^6 \text{ km}^2 \cdot \text{days}$), Major ($90\text{--}180 \times 10^6 \text{ km}^2 \cdot \text{days}$), or Extreme ($>180 \times 10^6 \text{ km}^2 \cdot \text{days}$), following thresholds established in previous studies (Butler & Gerber, 2015; Palmeiro et al., 2015; Hitchcock et al., 2013). The examples listed in the table are drawn from both reanalysis and model simulations covering the 1980–2005 historical period. This classification framework not only identifies the occurrence of SSW events but also facilitates evaluation of their intensity and model performance in reproducing observed stratospheric variability. The relationship between stratospheric anomalies and tropical variability is further examined by focusing on U_h data averaged between $\pm 10^\circ\text{N}$ latitude at the 10 hPa level to isolate the QBO phases and their structural variations across models.

Table 2.2 : Definitions, areas of use and examples used in SSW analysis.

Metric / Category	Operational Definition & Calculation	Physical Significance
TEA (Threshold Exceedance Area)	Geographic area where the daily temperature anomaly exceeds a predefined threshold.	Quantifies the horizontal extent of the warming anomaly on a specific day.
MPD (Main-Phase Duration)	Total number of consecutive days where the Main-Phase TEA remains above the minimum area threshold (TEA Min).	Represents the temporal persistence and stability of the warming event.
MPA (Main-Phase Area)	The time-averaged TEA calculated over the entire duration of the event ($\sum \text{TEA} / \text{MPD}$).	Provides the mean spatial coverage of the warming throughout the event's lifecycle.
MPS (Main-Phase Strength)	The integrated product of the event's duration and its mean area ($\text{MPD} \times \text{MPA}$).	Measures the total magnitude and "heat energy" footprint of the SSW.
SSW Class: Minor	Events characterized by localized or short-lived stratospheric disturbances.	Low intensity warming with minimal vortex disruption.
SSW Class: Major	Canonical events that significantly impact the polar vortex structure.	Standard major warming typically associated with wind reversals.
SSW Class: Extreme	Exceptional events with massive spatial extent and prolonged duration.	Highly anomalous events with potential for deep tropospheric impacts.

2.2.1 Main Phase Duration (MPD)

MPD is the metric value that expresses how many days the threshold degree-dependent warming lasts in an SSW event. In the calculations, first of all, consecutive days where the TEA values are above a certain lower limit are determined. In the study conducted by Li et al. (2023), the limit value determined for a significant warming was determined as $3 \times 10^6 \text{ km}^2$. If these conditions are met, the number of consecutive days is defined as MPD. MPD determines the effect and duration of stratospheric warming.

A high MPD value is an indication that the warming is effective in the atmosphere for a long time. This shows that the anomalies in the circulation and vortex structure occur for a longer time. MPD SSW includes a threshold duration criterion by definition. In

the literature, this value is mostly taken as 6 days and above. In this way, it is possible to eliminate random short-term sudden fluctuations and detect real SSW events.

2.2.2 Main Phase Area (MPA)

MPA is a quantitative metric that describes the average horizontal area over which temperature anomalies exceed a predefined threshold during the main phase of a SSW event. Technically, MPA (Eq 2.2) is calculated as the mean of daily TEA values over the duration of the main phase, as determined by the MPD. The calculation follows the formula:

$$\text{MPA} = \Sigma \text{TEA} / \text{MPD} \text{ (Li et al., 2023)} \quad (2.2)$$

MPA reflects the typical spatial extent of significant warming throughout an SSW event. A higher MPA shows that the warming anomaly is widespread rather than localized, affecting larger portions of the polar stratosphere. For example, in the well-documented January 2009 SSW event, the MPA reached $8.64 \times 10^6 \text{ km}^2$, indicating that, on average, over 8.6 million square kilometers exceeded the threshold each day during the event's main phase.

While MPA is sometimes misinterpreted as a peak value, it represents a mean spatial coverage, instead of the maximum extent. In many cases, the TEA peaks near the midpoint of the main phase and declines afterward, making MPA a useful proxy for the characteristic horizontal reach of the warming around its peak intensity. Previous researches also indicates a positive correlation between MPA and the maximum temperature anomaly, reinforcing its importance in quantifying the horizontal magnitude of stratospheric warming.

2.2.3 Main Phase Strenght (MPS)

After SSW events are detected and TEA values are calculated, the next step is the classification step. The MPS value is used when performing the classification. Daily TEA values are collected for each detected SSW event, and this is recorded as the total MPS value. In short, MPS reflects the overall magnitude of SSW events. It is determined quantitatively by combining the spatial magnitude and temporal spread of the SSW event and is calculated to provide a basis for advanced classification. This metric value used to evaluate the intensity and scope of SSW events expresses the

magnitude, duration and spatial spread of each event holistically. This parameter quantitatively represents the overall intensity of each event by considering both the impact area and duration. The MPS value,

$$\text{MPS} = \text{MPD} \times \text{MPA} \quad (2.3)$$

It is calculated with the formula. As can be seen from the above formulation, it is an indicator of the total area-time in which the threshold is exceeded during the main event (Eq 2.3). Its unit is $\text{km}^2 \times \text{day}$. As a result of these calculations, the total values of the threshold exceeding areas made daily during the start and end dates of the event are obtained. In other words, the total impact size ($\text{km}^2 \times \text{day}$) is obtained by adding the TEA values calculated for each day of each SSW event (Li et al., 2023).

As a result of the TEA calculations, SSW events that are short-term but affect large areas and SSW events that are long-term but affect small areas are made comparable with a single scale. For example, the SSW MPS value calculated for January 2009 is found to be $164.2 \times 10^6 \text{ km}^2 \times \text{day}$. In fact, this value is equal to the product of MPD (19 days) and MPA ($8.64 \times 10^6 \text{ km}^2$). From a physical perspective, the MPS value can also be defined as a measure of the total energy contained in the SSW event.

In the last step of the classification, the MPS value obtained using TEAs is taken into account and classified under the titles of Minor, Major, and Extreme. The classification criteria are carried out based on the information obtained as a result of the literature review and the studies of Butler et al. (2015) and Palmeiro et al. (2015) (Table 2.2). With this classification, in addition to the detection of events, their potential impact on the climate system is also be assessed, and the extent to which climate models and reanalysis data defines SSW events in similar classes could be compared (Hitchcock et al., 2013).

In addition to the magnitude of the temperature increase, it also provides a more holistic assessment due to the evaluation of the duration of the event and the area it affects together. While minor SSW events are generally shorter-term and/or affect small areas, extreme SSW events are longer-term and/or affect large areas.

As a result of the classification, SSWs have become comparable in terms of both time and magnitude on a model-based or periodic basis. In the analyses used in the study, MPD, MPA and MPS values are defined consistently with each other and all these

metric values are based on TEA values. While the time integral of the TEA values calculated daily gives the MPS value, the components of this integral are separated as MPA and MPD metric values. Butler et al. (2015) emphasize in their study that an ideal SSW definition should reflect both the sudden and comprehensive heating of the event and the following stages.

2.3 Calculation of Horizontal Moisture Flux and Vertical Integration (IVT)

The methodology for calculating atmospheric moisture transport follows the framework defined by Naakka et al. (2019). This process is initiated with the calculation of the horizontal moisture flux at each pressure level, followed by its vertical integration to determine the total column transport. While the primary focus of Naakka et al. (2019) is on meridional transport, this study expands the analysis by incorporating the zonal moisture flux component to provide a more comprehensive assessment of the transport dynamics.

The horizontal moisture flux at a specific pressure level (p), denoted as f_q , is treated as a vector quantity representing the mass of water vapor passing through a unit area per unit time. The components of this flux are calculated by multiplying the specific humidity (q) with the respective wind components (u, v):

$$f_{qu} = qu, \quad (2.4)$$

$$f_{qv} = qv, \quad (2.5)$$

In these equations, q is the specific humidity at pressure level p (kg/kg), while u and v are the zonal and meridional wind components (m/s), respectively. To capture the total moisture transport across the entire depth of the atmosphere, these level-by-level fluxes are integrated from the surface (1000 hPa) to the lower stratosphere (10 hPa). This vertical integration, known as IVT, provides the total column transport of water vapor. By substituting the level-by-level fluxes into the integration, the zonal (IVT_u) and meridional (IVT_v) components of the IVT vector are obtained:

$$IVT_u = \frac{1}{g} \int_{p_{top}}^{p_{surf}} q u dp, \quad (2.6)$$

$$IVT_v = \frac{1}{g} \int_{p_{top}}^{p_{surf}} q v dp, \quad (2.7)$$

In these formulations, g is the gravitational acceleration (9.80665 m/s^2). The integration is performed numerically using the trapezoidal rule on 6-hourly ERA5 data.

To identify the spatiotemporal reorganization of moisture pathways during SSW events, a superimposed visualization technique is applied. In this approach, the IVT_v is presented as a scalar field (background color), while the total IVT vector field is overlaid to indicate the direction and magnitude of the flow. The results are visualized on a polar projection centered over the NH, where a rotation offset aligns the 90°E meridian vertically. This methodology allows for a holistic determination of how moisture intrusions are redirected into the Arctic as the stratospheric circulation undergoes significant changes.

2.4 Transformed Eulerian Mean (TEM)

The investigation of the vertical coupling and wave-mean flow interaction during SSW events is conducted within the Transformed Eulerian Mean (TEM) framework. This methodology provides a physically consistent representation of the residual circulation and the net transport of tracers, such as water vapor, by isolating the net effect of atmospheric eddies on the background flow. A fundamental prerequisite for these diagnostics is the determination of the Brunt-Väisälä frequency (N^2), which characterizes the static stability and vertical stratification of the atmosphere. The stability parameter is formulated as the relationship between the vertical gradient of potential temperature (θ) and g :

$$N^2 = \frac{g}{\bar{\theta}} \frac{\partial \bar{\theta}}{\partial z} \quad (2.8)$$

In this expression, N^2 serves as a critical factor in modulating the vertical propagation of planetary waves and determining the vertical levels at which wave-driven circulation changes are most pronounced.

To quantify the mechanical forcing exerted by atmospheric disturbances on the stratospheric polar vortex, the S is calculated. This diagnostic represents the sum of kinetic and potential perturbation energies and is obtained via the following equation:

$$S = \frac{1}{2} \left(\overline{u'^2} + \overline{v'^2} + \frac{\overline{\Phi_z'^2}}{N^2} \right), \quad (2.9)$$

By evaluating S , the methodology identifies the regions of intense wave activity where planetary waves dissipate their momentum, leading to the weakening or reversal of the zonal mean flow. The resulting reorganization of the stratospheric mass transport is evaluated through the residual vertical velocity (w^*). Unlike the standard Eulerian mean vertical velocity, $\overline{w^*}$ incorporates the effect of meridional eddy heat flux divergence to represent the net vertical motion within the BDC. Following the framework proposed by Kinoshita et al. (2010) and Demirhan Bari et al. (2013), $\overline{w^*}$ is defined as:

$$\overline{w^*} = \overline{w} + \frac{1}{a \cos \phi} \frac{\partial}{\partial \phi} \left(\cos \phi \frac{\overline{v' \Phi_z'}}{N^2} \right), \quad (2.10)$$

This metric effectively captures the enhanced polar downwelling that characterizes the warming phase of SSW events. Finally, the direct impact of these dynamical changes on the moisture distribution is determined by calculating the vertical eddy moisture flux ($\overline{w'q'}$). This component isolates the transport of water vapor specifically driven by large-scale atmospheric waves, separate from the background mean circulation. The flux is expressed as the time-mean product of the vertical velocity and specific humidity anomalies:

$$F_{q_eddy} = \overline{w'q'}, \quad (2.11)$$

In this formulation, w' and q' represent the departures from the time-mean w and q respectively. The simultaneous assessment of $\overline{w^*}$ and $\overline{w'q'}$ facilitates a comprehensive understanding of how moisture pathways are reorganized through the

interaction of residual circulation and localized eddy mixing throughout the SSW lifecycle.

2.5 Formulation and Rationale of the Meridional Moisture Transport Index

The quantitative assessment of the stratospheric transport efficiency and the structural response of the BDC requires a consistent metric capable of capturing the moisture exchange between the primary tropical reservoir and the polar sinks. To achieve this, a specialized diagnostic, the BDC_{Index} , is formulated within the scope of this study. While the research primarily examines NH dynamics, the tropical moisture source is defined by extending the latitudinal domain to 10°S. This extension is physically necessary to fully encompass the core of the equatorial moisture reservoir and the Intertropical Convergence Zone (ITCZ), ensuring that the moisture entering the stratosphere through the ascending branch of the BDC is accurately accounted for. The index is defined as the gradient in zonal mean specific humidity ($\bar{q}$) between the high-latitude belt (50°N–70°N) and this equatorial reservoir (10°S–10°N):

$$BDC_{\text{Index}}(p) = \bar{q}_{\text{high_lat}}(p) - \bar{q}_{\text{tropics}}(p) \quad (2.12)$$

In this formulation, the high-latitude band is strategically chosen to align with the climatological position of the polar night jet and the primary zone for stratospheric wave breaking, where the most significant moisture anomalies are expected to manifest. By subtracting the tropical baseline, the index isolates the anomalous poleward moisture signal from the dominant seasonal background. To further characterize the structural reorganization of the moisture field during the event's lifecycle, a Vertical Profile Correlation Analysis is performed. This step utilizes the R to measure the structural similarity between a steady-state reference profile established on 14 January 2003, prior to the circulation reversal, and subsequent daily profiles throughout the analysis window. A sustained reduction in the R value serves as a definitive numerical indicator of the departure from the steady-state circulation and the degree of structural deformation in the vertical moisture distribution. This multi-parametric approach enables a precise determination of the depth and efficiency of the cross-tropopause transport pathways, providing numerical evidence of how stratospheric dynamical anomalies modulate the global redistribution of water vapor.

2.6 Data Processing, Standardization, and Scaling Protocols

To ensure a globally consistent diagnostic and to resolve moisture gradients that span several orders of magnitude, a specialized data processing protocol is implemented. Although the analytical focus remains on the NH, the spatial domain selectively includes the 10°S to 90°N region. This extension is physically essential to accurately characterize the tropical moisture reservoir, ensuring that the moisture transport originating from the ascending branch of the BDC is fully captured within a unified mass-balance framework.

For all stratospheric diagnostics, q is converted from the standard mass mixing ratio (kg/kg) to Parts Per Million by Volume (PPMV) using a scaling factor of 10^6 . This conversion follows the standard convention in middle-atmosphere research, providing a physically intuitive scale for trace gas concentrations in the dry stratosphere. Furthermore, to prevent the extreme moisture content of the lower troposphere from masking the subtle structural details of the stratospheric moisture budget, a Logarithmic Transformation ($\log_{10}(q)$) is applied to the zonal mean fields. This transformation facilitates the simultaneous visualization of moisture injection zones and cross-tropopause intrusions, providing a high-resolution mapping of the hydrological redistribution throughout the entire depth of the atmosphere from 1000 hPa to 10 hPa.



3. RESULTS

This section presents an evaluation of SSW events with a focus on their frequency, energy intensity, and temporal evolution, primarily within the NH winter stratosphere. This region is governed by a complex balance between radiative cooling and dynamical wave forcing, which defines the seasonal cycle of the polar vortex. As emphasized by Nash et al. (1996), the structural integrity of this vortex is maintained by the westerly Polar Night Jet, acting as a critical isolation barrier that prevents the mixing of cold polar air with warmer mid-latitude airmasses.

However, this radiative-dynamical equilibrium is frequently disrupted by the vertical propagation of planetary waves from the troposphere, leading to significant stratospheric perturbations. These events involve an abrupt disintegration of the polar vortex, characterized by extreme T_s anomalies and a substantial deceleration or reversal of the U_h at the 10 hPa level, which serves as the standard isobaric surface for diagnosing such disturbances.

To systematically evaluate these processes, the study employs ERA5 reanalysis as a reference baseline to assess the performance of models M1 through M5. The investigations encompass the historical period (1980–2005) and future climate projections (2006–2100) under the RCP 4.5 scenario, utilizing a dataset of daily U_h and T_s fields. By comparing these datasets, systematic biases in model dynamics are identified, particularly regarding the ability of high-top versus low-top configurations to resolve the downward coupling of stratospheric signals. This comparative approach provides granular insights into stratospheric internal variability and its long-term response to increasing greenhouse gas concentrations, ensuring a robust assessment of how anthropogenic forcing influences the persistence of stratospheric disturbances.

The quantitative identification and classification of SSW are performed using the TEA method, following the approach outlined by Charlton and Polvani (2007) and Butler et al. (2015). Following the criteria established by Li et al. (2023), each identified event is categorized into Minor ($MPS < 90 \times 10^6 \text{ km}^2 \cdot \text{days}$), Major ($90 \times 10^6 \leq MPS \leq 180 \times 10^6 \text{ km}^2 \cdot \text{days}$), or Extreme ($MPS > 180 \times 10^6 \text{ km}^2 \cdot \text{days}$) phases based on the MPS value, which is the product of MPA and MPD. This classification ensures that the detected frequency is not biased by specific

latitude or pressure choices. In addition to categorical counts, the subsequent phase of the results analyzes U_h trends near 60°N to examine the correspondence between temperature-based classifications and wind variability across both historical and future periods.

The evaluation encompasses the teleconnections and hydrological impacts associated with SSW events, specifically the modulatory role of QBO phases via the Holton-Tan mechanism. The QBO, the dominant mode of equatorial variability is characterized using U_h data averaged over $\pm 10^\circ$ latitude at 10 hPa to assess phase transitions and their dynamical linkages to SSW occurrence. Furthermore, the stratospheric hydrological cycle is examined using q and w as tracers for moisture redistribution. These diagnostics quantify the strength of the BDC and the efficiency of STE processes, with a focus on $w'q'$ induced by turbulent fluctuations.

A meridional transport index, defined as the gradient in q between the subpolar (70° – 50°N) and tropical (10°S – 10°N) regions, is utilized to evaluate cross-latitude exchange. The study further assesses the components of total moisture transport, including IVT, culminating in a mechanistic case study of the January 2003 SSW event. This case study provides a detailed characterization of the vertical transport mechanisms and diagnostic indices that define extreme stratospheric disruptions.

3.1 Selection of Numerical Models

The initial stage of the analysis involves a systematic validation of the CMIP5 models against the ERA5 reanalysis to assess their ability to capture the frequency and total duration of SSW events. This evaluation is fundamental to establishing a consistent physical and statistical framework, as the annual frequency and intensity of identified events are highly sensitive to the internal dynamics and vertical resolution of each model.

Figure 3.1 illustrates the total number of SSW days identified during the historical period (1980–2005), categorized by intensity (Minor, Major, and Extreme). In this period, ERA5 serves as the primary comparison, identifying 29 SSW events with a total duration of 337 days. These events exhibit a distribution of 37% Minor (126 days), 17% Major (57 days), and 46% Extreme (154 days). The calculated mean event duration is 11.6 ± 4.1 days, highlighting a significant degree of variability in the persistence of vortex disruptions. The seasonal window for this evaluation is restricted to the November–April period, as more than 90% of the total SSW days in both ERA5 and the model ensemble occur within these months.

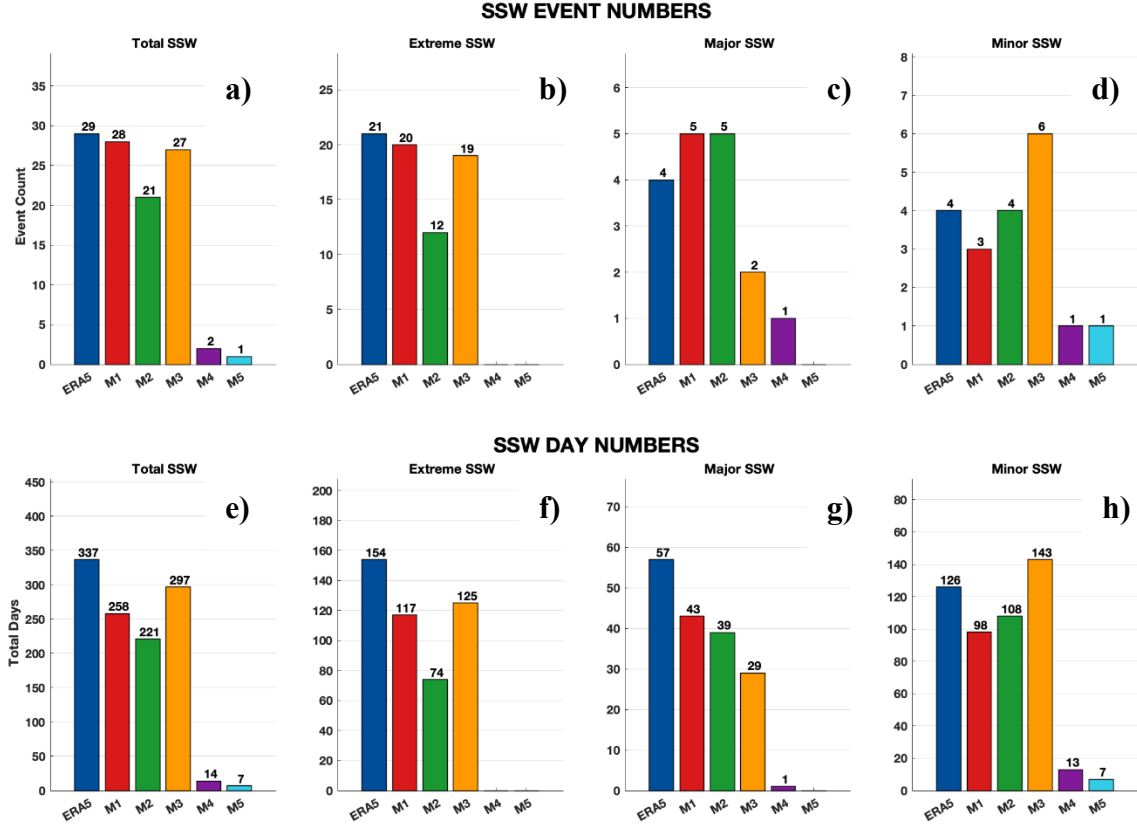


Figure 3.1 : Comparative analysis of identified SSW event frequencies and total durations across ERA5 reanalysis and the CMIP5 model ensemble (M1–M5) for the historical period (1980–2005). The top row illustrates SSW Event Numbers categorized as (a) Total, (b) Extreme, (c) Major, and (d) Minor events. The bottom row displays SSW Day Numbers, representing the cumulative duration in days for (e) Total, (f) Extreme, (g) Major, and (h) Minor categories. Bar colors differentiate the datasets: dark blue (ERA5 reanalysis), red (M1), green (M2), orange (M3), purple (M4), and cyan (M5).

In Figure 3.2 depicts the temporal and seasonal distribution of these events, providing a basis for evaluating how well each model captures the mid-winter warming signal. During the historical period (1980–2005), ERA5 reanalysis indicates that peak SSW occurrence is concentrated in the January–February window (62%), followed by November–December (31%) and March–April (7%). Among the evaluated models, M1, M2, and M3 are selected as the core ensemble for this study due to their superior handling of dynamical and thermodynamical processes. Specifically, M1 closely reproduces the seasonal pattern of the reanalysis (58%, 34%, and 8%, respectively), while M5 provides the most accurate seasonal match with 64% of events occurring in mid-winter. In contrast, although M4 presents a robust total event count, it exhibits a systematic bias toward shorter-lived and early-winter warmings, with a seasonal distribution of 49%, 39%, and 12%, and a mean duration of 8.7 ± 3.7 days.

The classification provided in Figure 3.2 offers further insights into the performance of high-top versus low-top models. M1 demonstrates the highest fidelity in terms of the total number of events, closely followed by M2 and M3. These models are recognized in the literature as high-top models that accurately represent stratospheric wave processes. Conversely, models M4 and M5 underperform in simulating the frequency of SSW events. This discrepancy is attributed to an overly stable and resilient polar vortex in their respective stratospheres, where only the most intense wave-breaking events can exceed the identification thresholds. These results are consistent with Charlton-Perez et al. (2013) and Rao and Garfinkel (2021), who demonstrate that low-top models with restricted stratospheric lids systematically underestimate SSW frequency.

Overall, this comparative evaluation confirms that SSW analysis is highly model-sensitive, and the inclusion of high-resolution stratospheric layers is a prerequisite for reliable results. While the majority of events across the successful models occur in the Minor category, the representation of Extreme events in M1, M2, and M3 remains compatible with the observed comparisons in ERA5. Consequently, these three models provide the reliable dynamical foundation required to analyze the coupling between T_s and U_h , as well as the resulting changes in the q and w fields during vortex disruptions. Under the future RCP 4.5 scenario (Figure 3.3), these selected models continue to show consistent seasonal oscillations, reinforcing their suitability for long-term climate projections.

The vertical extent of pressure height serves as a fundamental criterion for grouping these numerical models. Following established literature, high-top models (M1, M2, M3) extend into the upper stratosphere or lower mesosphere, typically above 1 hPa. This extended vertical range facilitates a more realistic simulation of planetary-wave propagation and vortex breakdown. In contrast, lower-top models (M4, M5) terminate at much lower altitudes, between 10–30 hPa. This lower lid limits the vertical wave–mean-flow coupling, frequently leading to a systematic underestimation of stratospheric variability.

The timing of SSW events is critical for understanding the interaction between planetary-scale waves and polar vortex stability. Historical observations indicate that more than 60% of these events occur during the NH mid-winter maximum. During this interval, planetary waves are most effectively transmitted from the troposphere into the stratosphere, enhancing the dynamical instability of the vortex. Figures 3.2 and 3.3 provide the visual framework for this assessment, illustrating the historical period (1980–2005) and projected distributions under

the RCP 4.5 scenario (2006–2100), respectively. In both visualizations, the horizontal axis denotes the progression of months while the vertical axis represents years from 1980 to 2100.

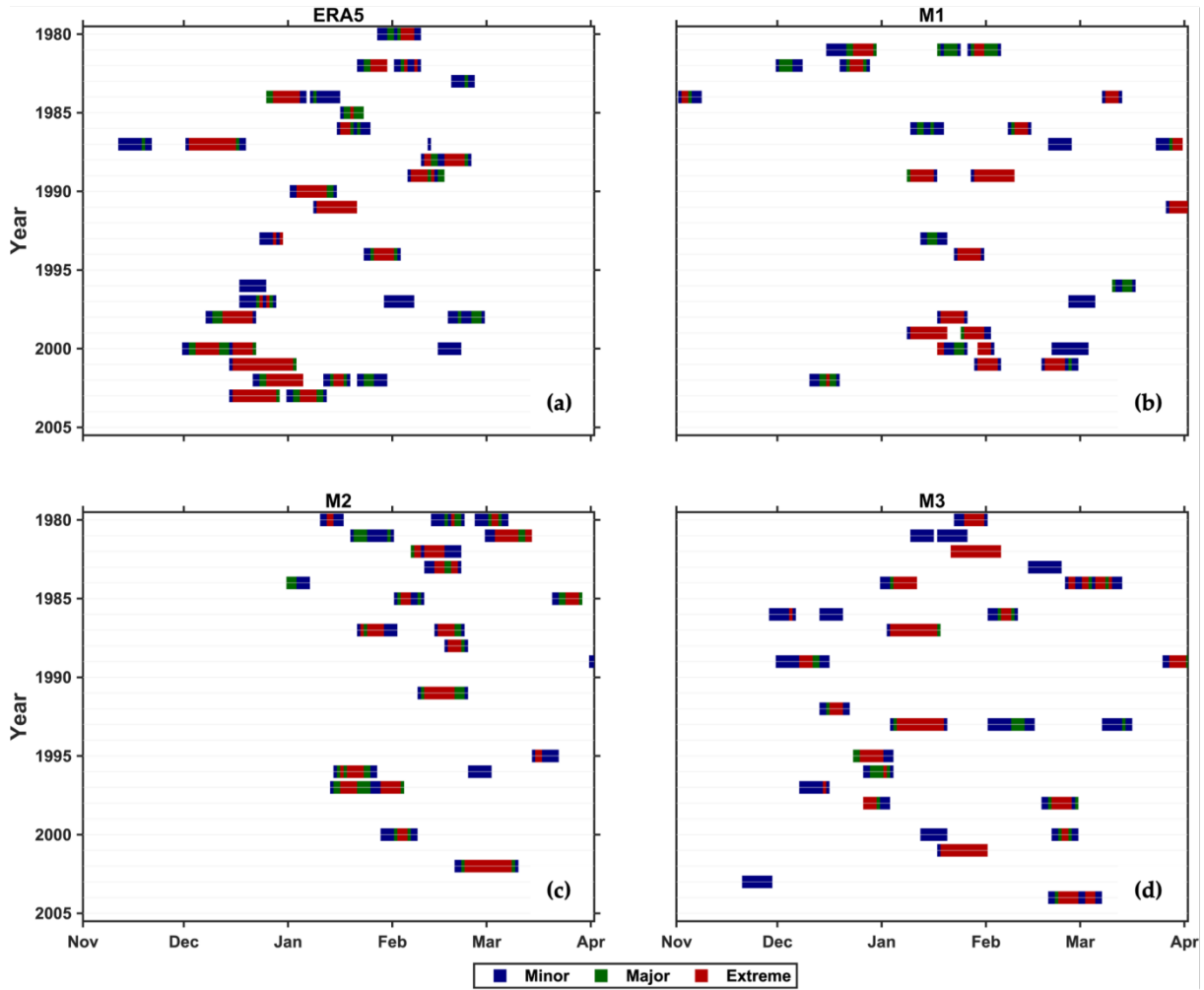


Figure 3.2 : Classification of SSW events at 10 hPa based on ERA5 reanalysis and CMIP5 model historical (1980–2005) data. Panels show the timing and intensity of events across different datasets: (a) ERA5 reanalysis, (b) M1, (c) M2, and (d) M3. Event categories are marked as Minor (blue), Major (green), and Extreme (red) (Durmus et al., 2026).

The persistence of these events also varies significantly; the mean event duration in ERA5 is 11.6 ± 4.1 days. While M1 (9.2 ± 3.3 days) and M5 (11.0 ± 3.9 days) reproduce the observed seasonality within a $\pm 5\%$ accuracy range, M5 remains the most consistent in terms of duration. Future projections under the RCP 4.5 scenario reveal that SSW seasonality remains confined to the November–April window. M1 maintains remarkable stability in the 21st century, with 57% of events in January–February, suggesting a stable stratospheric variability regime under climate change.

Conversely, M2 demonstrates a more pronounced early-winter bias under RCP 4.5 forcing, with January–February events falling to 46% while November–December occurrences rise to

42%. Quantitatively, M2 projects a 20% reduction in Extreme events and produces the shortest mean duration in the ensemble at 8.6 ± 3.8 days. This intensified shift highlights the sensitivity of particular models to anthropogenic forcing and underscores the necessity of high-resolution stratospheric representation. While M1, M2, and M3 remain within a 5–10% margin of the ERA5 comparison, it is noteworthy that event durations across the entire model ensemble are consistently 15–25% shorter than those identified in reanalysis.

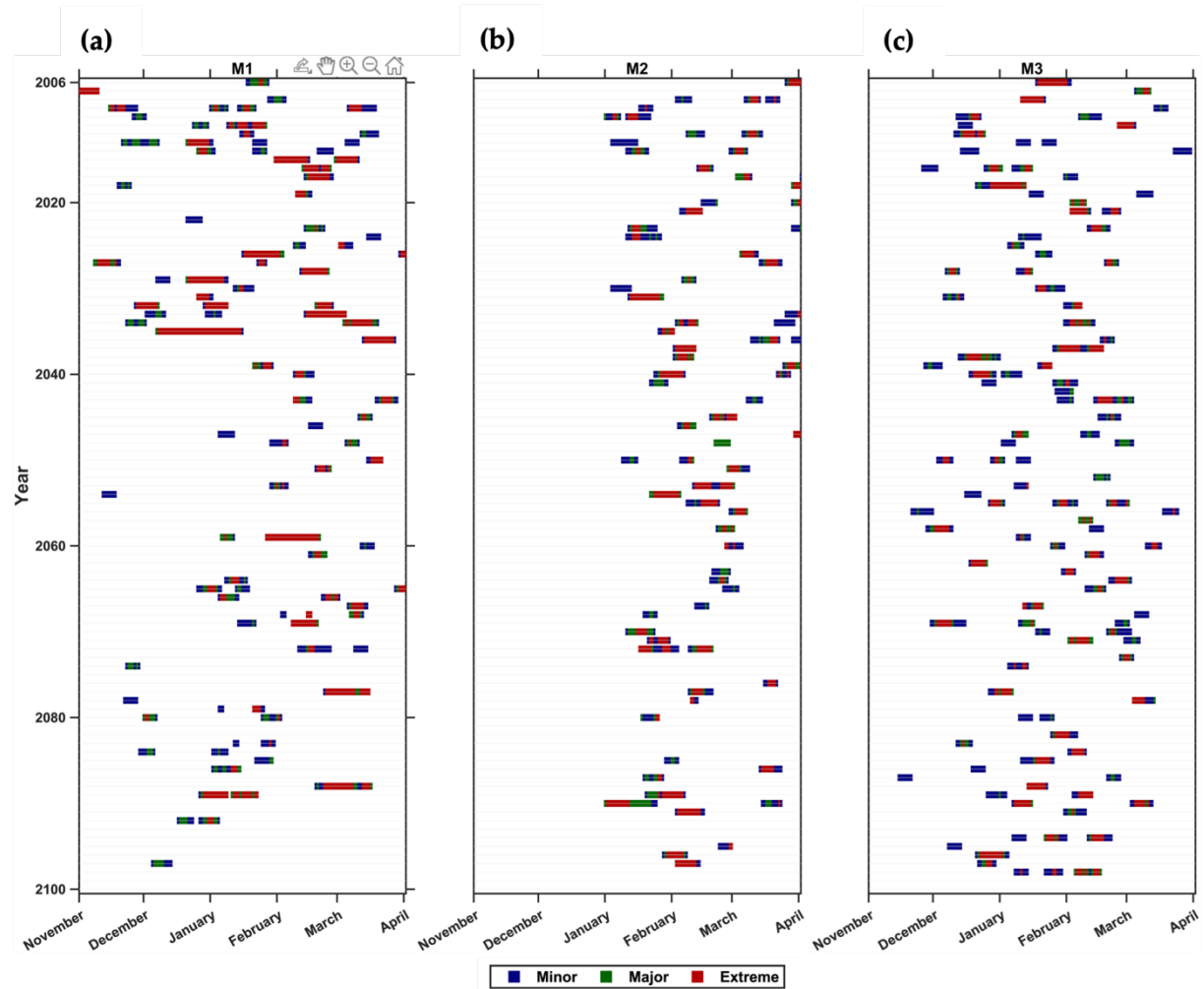


Figure 3.3 : Classification of SSW events at 10 hPa based on CMIP5 RCP 4.5 (2006–2100) data. Panels show the timing and intensity of events across different datasets: (a) M1, (b) M2, and (c) M3. Event categories are marked as Minor (blue), Major (green), and Extreme (red) (Durmus et al., 2026).

3.2 SSW and QBO Analysis

3.2.1 Temperature time series

This section evaluates the long-term evolution of the thermal structure in the polar stratosphere and the quantitative impact of SSW events. The analysis focuses on the 10 hPa pressure level

at 60°N latitude, utilizing ERA5 reanalysis as a comparison for validating CMIP5 model simulations (M1–M3) across two distinct periods: the historical period (1980–2005) and the future projection period under the RCP 4.5 scenario (2006–2100). To assess stratospheric thermal variability, key statistical diagnostics including T_s , standard deviations (sd), percentile ranges (P_r), and linear trends S_{T_s} are employed. According to Table 3.1, historical data reveal that the polar stratosphere is characterized by a weak but persistent cooling trend and significant interannual variability (Durmus et al., 2006).

Table 3.1 : Statistical comparison of daily stratospheric temperature (T_s) series at 10 hPa 60°N for ERA5 and CMIP5 models (M1–M3) over the historical (1980–2005) and future period (2006–2100). The metrics include mean T_s , standard deviation (sd), percentile range (P_r), linear trends (S_{T_s}), and variance reduction during SSW events (Durmus et al., 2026).

Period	Historical (1980–2005)				RCP 4.5 (2006–2100)		
Metric	ERA5	M1	M2	M3	M1	M2	M3
Mean T_s (K)	225.94	227.9	227.13	227.76	225.85	224.69	225.6
Std. Deviation (sd) (K)	9.55	11.69	7.68	9.45	11.99	7.38	9.04
Percentile Range (P_r) (K)	29.37	35.18	23.83	28.43	35.87	22.77	27.16
Trend (S_{T_s}) (K /decade)	-0.298	-0.85	-0.69	-0.316	-0.21	-0.26	-0.24
SSW Days Mean T_s (K)	226.19	224.96	229.22	228.81	222.95	228.68	225.75
Non-SSW Days Mean T_s (K)	225.93	227.96	227.07	227.72	225.95	224.69	225.93
SSW Variance Reduction	46%	54%	50%	44%	49%	52%	49%

A critical finding is the substantial reduction in temperature variance (approximately 44% to 54%) during SSW events, confirming their stabilizing effect on the mid-winter thermal structure. Future projections suggest that while moderate cooling will continue throughout the 21st century, the thermal characteristics and intensity of SSW events remain largely consistent with the historical baseline, with variance reductions projected at 49% to 52%.

3.2.1.1 Historical period of T_s

The analysis of T_s time series at the 10 hPa pressure level is chosen to characterize the background climatology and the transient thermal perturbations associated with SSW events. By examining daily S_{T_s} at 60°N latitude, the study aims to evaluate the consistency of

the seasonal cycle and the stochastic nature of polar vortex disruptions. This visualization serves as a vital diagnostic framework for validating the performance of CMIP5 numerical models (M1, M2, and M3) against the ERA5 reanalysis comparison, facilitating an assessment of the models' capacity to replicate the magnitude, frequency, and duration of observed warming anomalies within the historical period (1980–2005).

Figure 3.4 illustrates the historical temporal evolution of daily T_s , where the continuous blue lines represent high-frequency thermal oscillations and colored markers denote identified SSW categories: yellow circles for Minor, green triangles for Major, and red squares for Extreme events. In the ERA5 reference (Figure 3.4a), the stratosphere is characterized by a well-defined annual cycle where winter cooling is periodically interrupted by pronounced, high-amplitude thermal pulses that signify the abrupt warming characteristic of the polar vortex breakdown. In contrast, the simulation from Model M1 (Figure 3.4b) displays a significantly higher degree of inter-annual variability, with temperature excursions that frequently exceed the peak magnitudes recorded in the reanalysis. Model M2 (Figure 3.4c) presents a visually suppressed variability regime, where the seasonal range appears compressed and the warming peaks are markedly lower and more uniform, suggesting an overly stable stratospheric state. Model M3 (Figure 3.4d), however, exhibits a thermal profile that aligns most consistently with the reanalysis, effectively replicating both the seasonal amplitude and the episodic distribution of warming events observed in the historical record.

The visual characteristics identified in the time series are quantitatively substantiated by the historical diagnostics summarized in Table 3.1. The ERA5 reanalysis establishes a historical mean T_s of 225.94 K and a sd of 9.55 K. A critical finding in the reanalysis is the 46% reduction in temperature variance during SSW days compared to non-SSW periods, confirming that these events are the primary drivers of wintertime stratospheric variability. The historical S_{T_s} observed in ERA5 is -0.298K/decade . Conversely, M2 systematically underestimates variability, yielding a narrow thermal range of 23.83 K compared to the reanalysis baseline of 29.37 K, which correlates with the suppressed thermal peaks observed in Figure 3.4c. M3 provides the most accurate representation of the historical state, with a standard deviation of 9.45 K and a cooling trend of -0.316K/decade that aligns closely with the observational record. Despite individual biases in T_{cli} , all models successfully replicate the characteristic thermodynamic structure of SSW events, with variance reductions ranging from 44% to 54%. This underscores the stabilizing role of these disturbances in governing polar stratospheric thermal processes.

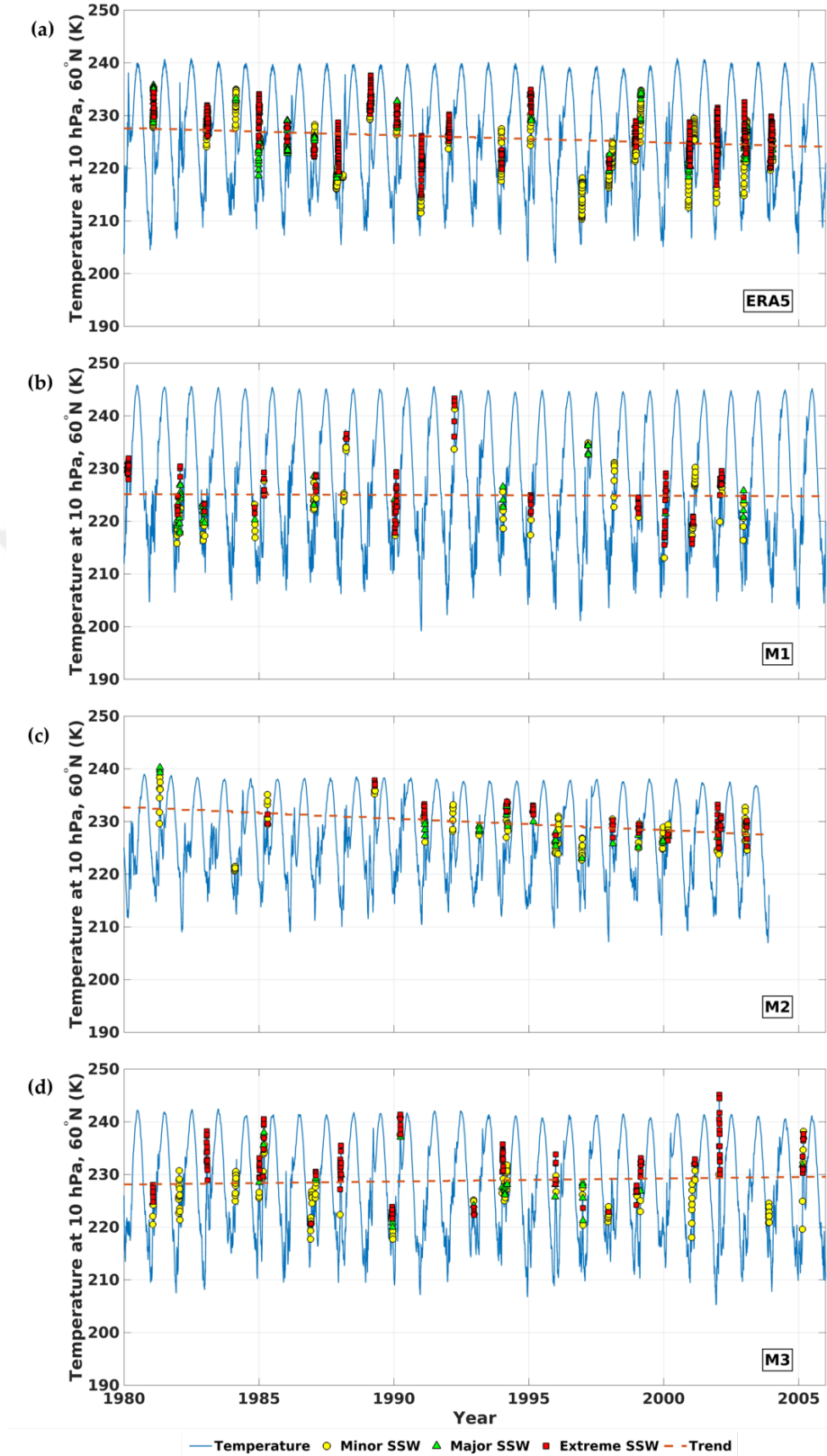


Figure 3.4 : Stratospheric temperature (T_s) time series at 10 hPa and 60°N for the historical period (1980–2005) based on (a) ERA5 reanalysis and (b) M1, (c) M2, and (d) M3 models. Daily T_s are overlaid with SSW classifications: minor (yellow circles), major (green triangles), and extreme (red squares). The dashed line reveals the trend in SSW days over time (Durmus et al., 2026).

The comparative analysis reveals that M1 overestimates thermal variability ($sd = 11.69$ K) and produces a cooling trend of -0.850 K/decade, nearly three times the magnitude of the 0.298 .

3.2.1.2 Future period of T_s

The evaluation of future stratospheric conditions under the RCP 4.5 climate scenario is conducted to determine how anthropogenic forcing modifies the fundamental characteristics of the polar vortex through the end of the 21st century. This analysis utilizes the same diagnostic framework as the historical period, focusing on changes in T_s , sd , P_r , and S_{Ts} . By projecting these variables from 2006 to 2100, the study aims to identify potential shifts in the frequency and intensity of SSW events and the overall thermal stability of the polar stratosphere in response to increased greenhouse gas concentrations.

Figure 3.5 illustrates the projected daily temperature time series at 10 hPa for the 2006–2100 period, following the same classification logic as the historical analysis. Visual inspection of these projections reveals that the polar stratosphere maintains a pattern of variability consistent with the historical record, characterized by a seasonal cycle interrupted by sharp, episodic warming peaks.

Notably, certain years exhibit a total absence of classified SSW events, while other periods show clusters of disturbances. A distinctive feature in the future projections, particularly visible in Figure 3.5, is the morphological broadening of the warming peaks. This morphological change in the temperature spikes confirms findings in recent literature suggesting that the duration of SSW events may extend under climate change conditions (Li et al., 2023). The statistical findings summarized in Table 3.1 provide a quantitative basis for these projections. Long-term cooling trends are projected to remain negative but weak, indicating that radiative cooling in the polar stratosphere continues at a moderate pace.

Model M1 (Figure 3.5a) maintains a thermal structure similar to its historical baseline but shows a significant stabilization in its long-term trend, with the cooling rate weakening by approximately 76% compared to the 1980–2005 period. Similarly, Model M2 (Figure 3.5b) exhibits a cooling rate that is 60% weaker than its historical prediction, despite showing slightly higher variability within a narrower percentile range. Model M3 (Figure 3.5c) continues to demonstrate high fidelity, with simulations for the future scenario closely resembling the historical ERA5 climate in terms of both mean temperature (225.6 K) and variability ($sd=9.04$ K).

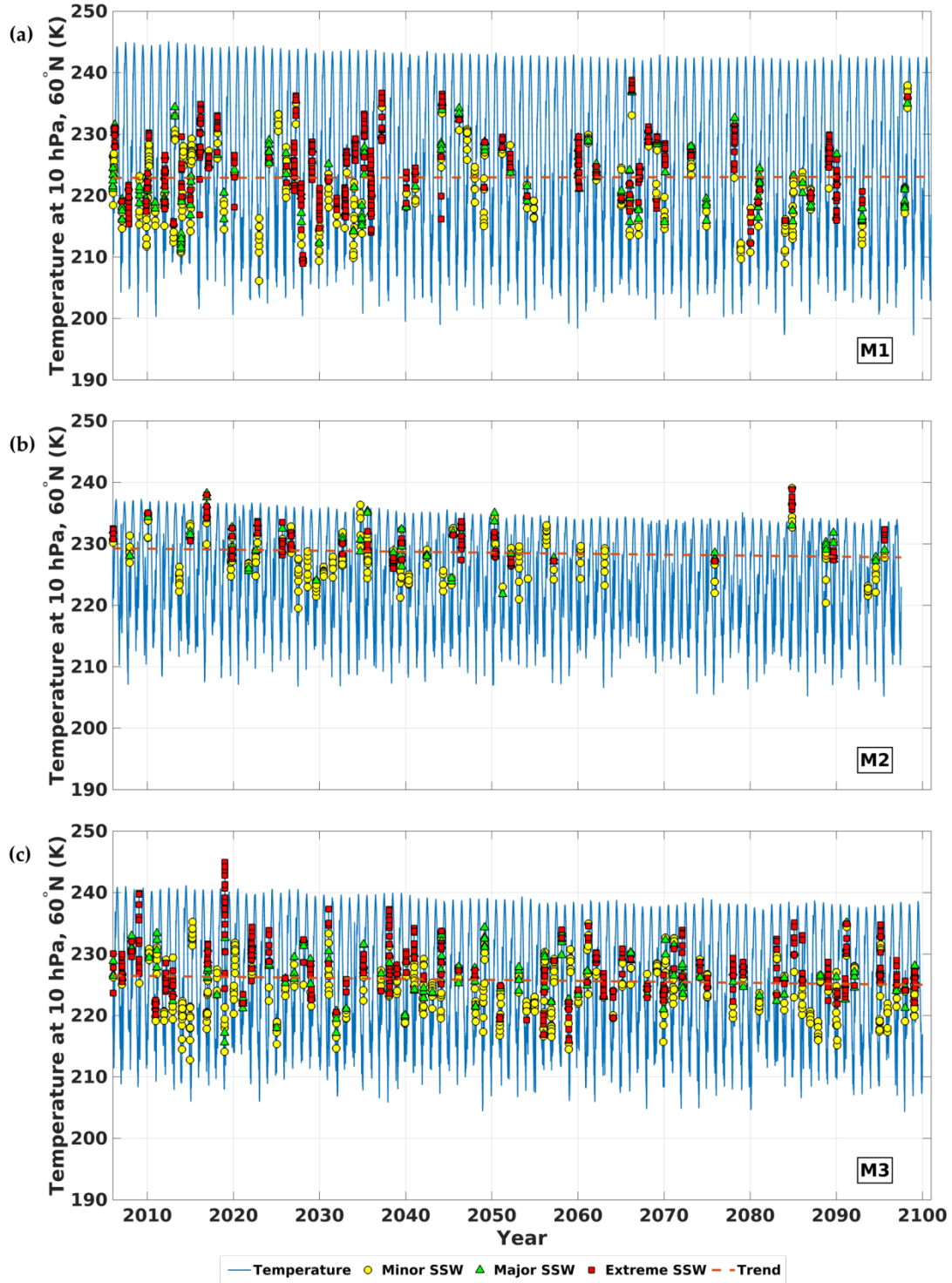


Figure 3.5 : Stratospheric temperature (T_s) time series at 10 hPa and 60°N for the future period (2006–2100) based on (a) M1, (b) M2, and (c) M3 models. Daily T_s are overlaid with SSW classifications: minor (yellow circles), major (green triangles), and extreme (red squares). The dashed line reveals the trend in SSW days over time (Durmus et al., 2026).

In summary, the transition from historical to future climate scenarios does not indicate a disappearance or a drastic reduction in the frequency of SSW events. The estimated reduction in temperature variance during warming events remains consistent at 49–52% across all models

(Table 3.1), suggesting that the thermodynamic structure of the polar vortex breakdown remains consistent. While the increase in greenhouse gases promotes a general radiative cooling trend in the stratosphere, the results support the diagnosis that SSW frequency does not undergo significant shifts (Ayarzagüena et al., 2018). The primary adjustment observed in the simulations is the temporal extension of the events themselves, as evidenced by the wider base of the warming peaks in the projected time series, indicating that while the frequency remains stable, the persistence of these stratospheric disturbances may increase.

3.2.2 Zonal wind time series

The analysis of U_h at the 10 hPa pressure level and 60°N latitude is fundamental for diagnosing the dynamical stability of the polar vortex and the intensity of the polar night jet. Consistent with the thermal analysis detailed in the previous section, the characteristics of U_h are evaluated using ERA5 reanalysis and CMIP5 models (M1–M3) to assess the representation of dynamical variability during both the historical (1980–2005) and future projection (2006–2100) periods. The focus remains on the detection of sudden decelerations or reversals of the westerly flow, which serve as primary indicators of stratospheric disturbances.

3.2.2.1 Historical period of U_h

The primary objective of examining the daily U_h time series for the 1980–2005 period is to evaluate the performance of the CMIP5 models in simulating the dynamical variability of the polar night jet and its response to SSW forcing. This visualization provides a diagnostic framework for assessing how well numerical simulations capture the abrupt shifts from strong westerly winds to the weakened or easterly flow characteristic of vortex breakdowns. Statistical assessments, including mean U_h , sd, and S_{U_h} , are utilized to quantify model fidelity against the reference dataset.

Figure 3.6 illustrates the historical temporal evolution of daily U_h at 60°N, where the continuous blue lines depict high-frequency dynamical oscillations and colored markers denote identified SSW categories. In the ERA5 reanalysis (Figure 3.6a), the polar stratosphere exhibits significant seasonal and interannual variability, with strong westerly winds frequently undergoing sharp decelerations. Notable points where the wind speed drops below 0 m.s^{-1} indicate complete wind reversals, coinciding with the most intense Major SSW events. In contrast, Model M1 (Figure 3.6b) exhibits a positive bias in the magnitude of the polar night jet, producing an amplified range of variability with peak velocities exceeding those recorded in the reanalysis. Model M2 (Figure 3.6c) reproduces the dynamical amplitude and mean state

with moderate skill, though the distribution of wind speeds appears more uniform. Model M3 (Figure 3.6d) exhibits the strongest visual correspondence with ERA5, successfully capturing the magnitude and structure of the westerly fluctuations and the timing of major decelerations.

Table 3.2 : Statistical comparison of daily zonal wind (U_h) series at 10 hPa 60°N for ERA5 and CMIP5 models (M1–M3) over the historical (1980–2005) and future period (2006–2100). The metrics include mean U_h , standard deviation (sd), percentile range (P_r), linear trends (S_{U_h}), and variance reduction during SSW events (Durmus et al., 2026).

Period	Historical (1980–2005)				RCP 4.5 (2006–2100)		
Metric	ERA5	M1	M2	M3	M1	M2	M3
Mean U_h ($m.s^{-1}$)	10.62	16.22	9.34	10.83	17.6	9.73	10.8
Std. Deviation (sd) ($m.s^{-1}$)	19.19	21.66	18.17	19.19	23.51	18.13	18.88
Percentile Range (P_r) ($m.s^{-1}$)	58.33	65.72	57.6	59.71	70.44	55.95	57.64
Trend (S_{U_h}) ($m.s^{-1}/decade$)	−0.87	+0.64	+0.80	+0.34	+0.11	−0.04	+0.17
SSW Days Mean U_h ($m.s^{-1}$)	14.5	17.61	12.78	11.9	19.66	13.1	31.75
Non-SSW Days Mean U_h ($m.s^{-1}$)	10.45	16.18	9.26	10.8	17.53	9.69	10.11
SSW Variance Reduction	24%	37%	54%	13%	43%	31%	4%

The visual characteristics identified in Figure 3.6 are quantitatively validated by the historical diagnostics summarized in Table 3.2. The ERA5 reanalysis defines a historical mean U_h of $10.62 m.s^{-1}$ and a sd of $19.19 m.s^{-1}$. A critical metric for dynamical assessment is the 24% reduction in U_h variance during SSW events compared to non-SSW periods, which confirms that vortex breakdowns lead the stratosphere into a state of reduced dynamical variability. The comparative analysis reveals significant model biases regarding long-term trends; while ERA5 shows a deceleration trend of $-0.871 m.s^{-1} decade^{-1}$, both M1 and M2 simulate a spurious intensification of the westerly jet with positive trends of $+0.643$ and $+0.803 m.s^{-1} decade^{-1}$, respectively. Although M3 also produces a positive trend ($+0.344 m.s^{-1} decade^{-1}$), it remains the most successful model in reproducing the mean state and variability structure. Despite these inconsistencies in trend direction, all three models capture the dynamical structure of SSWs, with variance reductions ranging from 13% to 54%. This confirms that while models vary in their representation of the long-term polar night jet evolution, they successfully identify the sharp decreases and reversals in wind speed as a direct response to stratospheric warming activity.

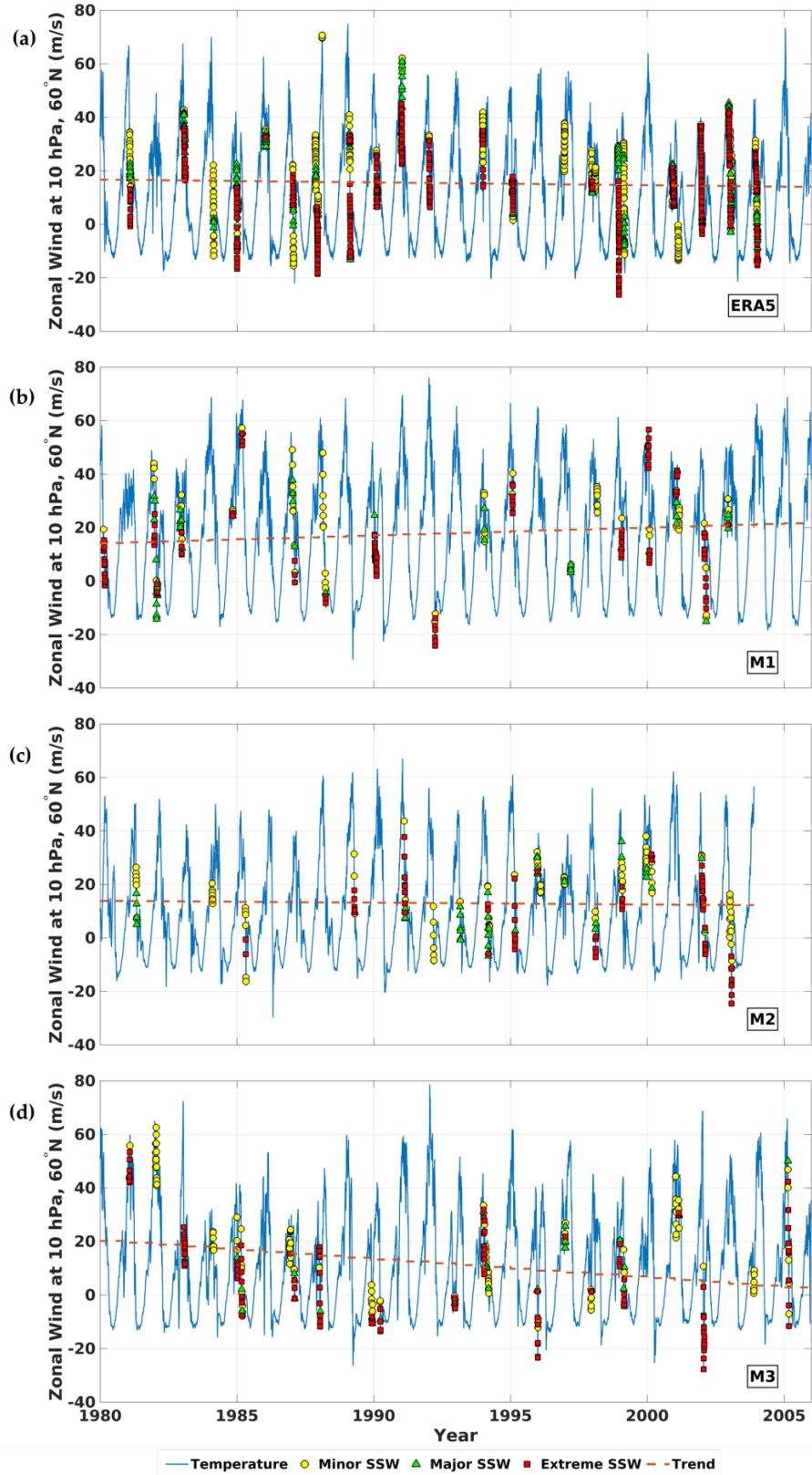


Figure 3.6 : Zonal Wind (U_h) time series at 10 hPa and 60°N for the historical period (1980–2005) based on (a) ERA5 reanalysis and (b) M1, (c) M2, and (d) M3 models. Daily U_h are overlaid with SSW classifications: minor (yellow circles), major (green triangles), and extreme (red squares). The dashed line reveals the trend in SSW days over time (Durmus et al., 2026).

3.2.2.2 RCP 4.5 future climate scenarios of U_h

The evaluation of future U_h projections under the RCP 4.5 scenario serves to quantify the degree to which moderate anthropogenic forcing modulates the circulation of the polar night jet and the dynamical nature of SSW events through the end of the 21st century. Figure 3.7 presents the projected temporal evolution of U_h , illustrating that the underlying oscillatory pattern of the polar night jet is preserved, with periodic wintertime decelerations remaining as a defining characteristic.

Model M1 (Figure 3.7a) maintains enhanced inter-annual variability with an expanded amplitude of fluctuations, whereas Model M2 (Figure 3.7b) suggests a shift toward a more restricted and stable dynamical regime. Model M3 (Figure 3.7c) continues to exhibit a profile consistent with the historical record, though the morphological expansion of thermal anomalies observed in the projections aligns with literature suggesting an extension of SSW duration under climate change. The persistence of these oscillations confirms that SSW events are unlikely to dissipate under climate change but continue to periodically disrupt polar vortex coherence.

The statistical findings summarized in Table 3.2 provide a quantitative framework for these projections. While mean flow magnitude varies across models, long-term strengthening trends exhibit a substantial attenuation compared to the historical baseline. In the M1 simulations, the mean U_h increases to 17.60 m.s^{-1} , yet the long-term strengthening trend weakens by approximately 82%, indicating a near-stabilization of the jet magnitude.

Model M2 exhibits a reversal of the historical strengthening trend to a weakly negative value of $-0.040 \text{ m.s}^{-1} \text{ decade}^{-1}$, implying the complete neutralization of the climatological intensification of the polar night jet. Model M3 maintains its high fidelity with a statistically stationary mean flow behavior, exhibiting a near-zero trend of $-0.024 \text{ m.s}^{-1} \text{ decade}^{-1}$. Overall, the dynamic response to SSWs remains consistent across all models, with variance reductions ranging from 4% to 43%. This consistency confirms that while greenhouse gas increases may alter the trend of the mean flow, the fundamental mechanism of vortex breakdown remains a reliable component of stratospheric dynamics, characterized by abrupt and consistent dynamical shifts.

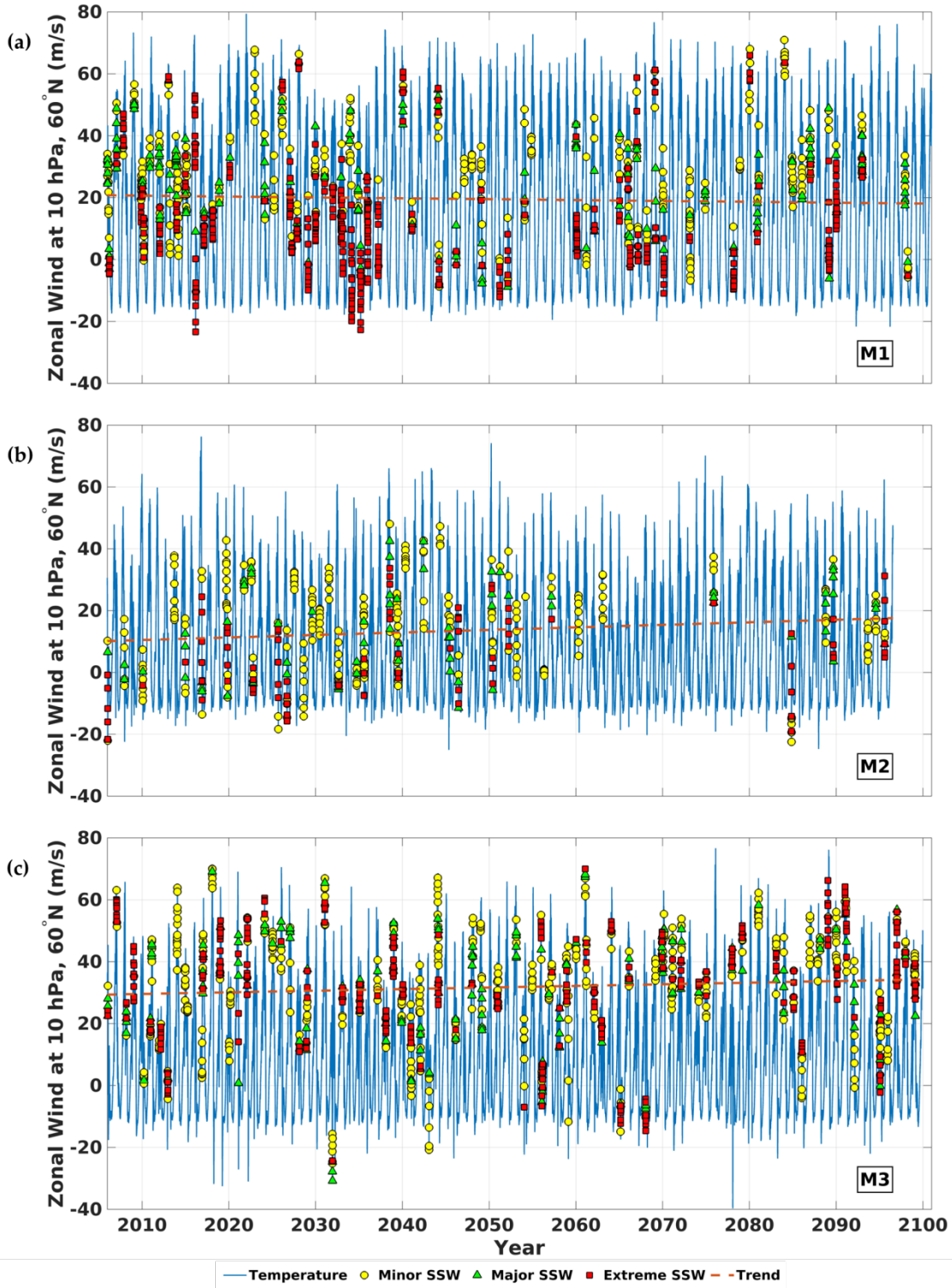


Figure 3.7 : Zonal Wind (U_h) time series at 10 hPa and 60°N for the future period (2006–2100) based on (a) M1, (b) M2, and (c) M3 models. Daily U_h are overlaid with SSW classifications: minor (yellow circles), major (green triangles), and extreme (red squares). The dashed line reveals the trend in SSW days over time (Durmus et al., 2026).

3.3 Stratospheric Amplitude and Range

The range-based variability metrics (T_{rng} and U_{rng}), derived from T_s and U_h data, carry profound physical implications in characterizing the absolute extremes of the thermal and dynamical states within the polar stratosphere. These metrics, calculated from the differential between monthly maximum and minimum values, quantify the extent to which the polar vortex deviates from its climatological baseline throughout the winter season. A broad variability range signifies that the system is subjected to planetary wave forcing of sufficient magnitude to trigger extreme phenomena, such as SSW or U_h reversal. Unlike mean values, these metrics expose the dynamical capacity of the atmosphere without obscuring the impact of transient yet intense events; this serves as a direct indicator of the permeability of the polar vortex isolation barrier and the resulting efficiency of meridional transport.

The amplitude of variability (T_{amp} and U_{amp}), defined as the sd of temporally windowed values, represents the intensity of fluctuations around the mean state and the temporal persistence of these oscillations. Physically, these amplitude metrics serve as indices of thermal anomalies, reflecting the cumulative forcing exerted on the vortex structure by upward-propagating wave activity from the troposphere. High amplitude values demonstrate a dynamically active stratosphere where wave-mean flow interactions drive potent adiabatic compression, leading to the abrupt temperature surges documented in the polar region. These parameters serve as essential diagnostic tools for identifying systemic biases in climate models, particularly where vertical resolution constraints or upper boundary absorbing layer artifacts may spuriously attenuate extreme events. Consequently, a suppressed variability amplitude provides statistical evidence of a model's inability to realistically simulate fundamental physical mechanisms, such as wave breaking and EP flux divergence

To evaluate the structural integrity and predictive capacity of climate simulations, this section assesses the fidelity of high-top CMIP5 models in capturing stratospheric variability across two distinct periods: the historical period (1980–2005) and the future projection (2006–2100) under the RCP 4.5 scenario. The diagnostic framework is focused at the 10 hPa pressure level, utilizing the ERA5 reanalysis as the observational baseline to identify systematic biases in the representation of wave-mean flow interactions.

The analysis is spatially differentiated to compare the tropical stratosphere (10°N), where variability is primarily driven by internal oscillations like the QBO, with the polar stratosphere (60°N), which is characterized by the dynamic volatility associated with the polar vortex and

SSW events. The statistical foundation for this comparison is summarized in Table 3.3 and Table 3.4, which provides the mean values, sd, and extreme ranges for both temperature and U_h metrics. Following the quantitative evaluation, the temporal evolution of these fluctuations is visualized through a set of time-series plots (Figures 3.8–3.15), which illustrate the transition from historical baselines to future trends across both geographical regions. This integrated approach allows for a rigorous evaluation of how individual models resolve the stratospheric response and its long-term evolution in a changing climate.

3.3.1 Fluctuation and amplitude of temperature

The analysis of T_s variability and amplitude, partitioned by geographical region and temporal period, provides a critical assessment of the models' ability to replicate the complex thermal pulses of the atmosphere. In accordance with the diagnostic framework, the results for the 10 hPa level integrate the statistical findings from Table 3.3 with the temporal trends observed in the time-series visualizations.

Table 3.3 : Statistical analysis of stratospheric temperature amplitude (T_{amp}) and range (T_{rng}) for the ERA5 reanalysis and CMIP5 model simulations (M2 and M3) at 10°N and 60°N for the historical (1980–2005) and future (2006–2100, RCP 4.5) periods. The metrics include the mean, median, standard deviation (sd), variance (Var), minimum (Min), maximum (Max), and linear trend (Slope, in K per decade) (Durmus et al., 2026).

Period	Metric	Lat	Model	Mean	Median	Sd	Var	Min	Max	Slope
1980–2005	T_{amp}	10°N	ERA5	2.071	2.034	0.379	0.143	1.333	3.397	-0.001236
			M2	1.637	1.596	0.349	0.122	0.848	2.663	0.000487
			M3	1.884	1.82	0.415	0.172	0.836	3.117	0.001729
		60°N	ERA5	3.159	3.186	0.311	0.097	2.334	3.898	0.001618
			M2	0.585	0.59	0.094	0.009	0.373	0.874	-0.000605
			M3	0.785	0.772	0.108	0.012	0.499	1.213	0.000621
	T_{rng}	10°N	ERA5	0.553	0.547	0.109	0.012	0.3	0.835	-0.00075
			M2	0.434	0.429	0.098	0.01	0.218	0.675	-0.000182
			M3	0.507	0.5	0.118	0.014	0.211	0.805	0.000407
		60°N	ERA5	0.73	0.727	0.086	0.007	0.526	0.947	0.000186
			M2	0.144	0.144	0.023	0.001	0.096	0.205	-0.000136
			M3	0.193	0.189	0.025	0.001	0.145	0.264	0.000077
2006–2100	T_{amp}	10°N	M2	1.706	1.7	0.337	0.114	0.84	2.938	0.000661
			M3	1.962	1.935	0.369	0.136	1.017	3.231	-0.00019
		60°N	M2	0.574	0.571	0.086	0.007	0.391	0.855	-0.000254
			M3	0.758	0.753	0.107	0.011	0.456	1.098	-0.000106
	T_{rng}	10°N	M2	0.456	0.445	0.099	0.01	0.218	0.827	0.000166
			M3	0.522	0.508	0.106	0.011	0.259	0.943	-0.000086
		60°N	M2	0.15	0.149	0.021	0	0.098	0.202	-0.000051
			M3	0.191	0.189	0.025	0.001	0.117	0.245	-0.000023

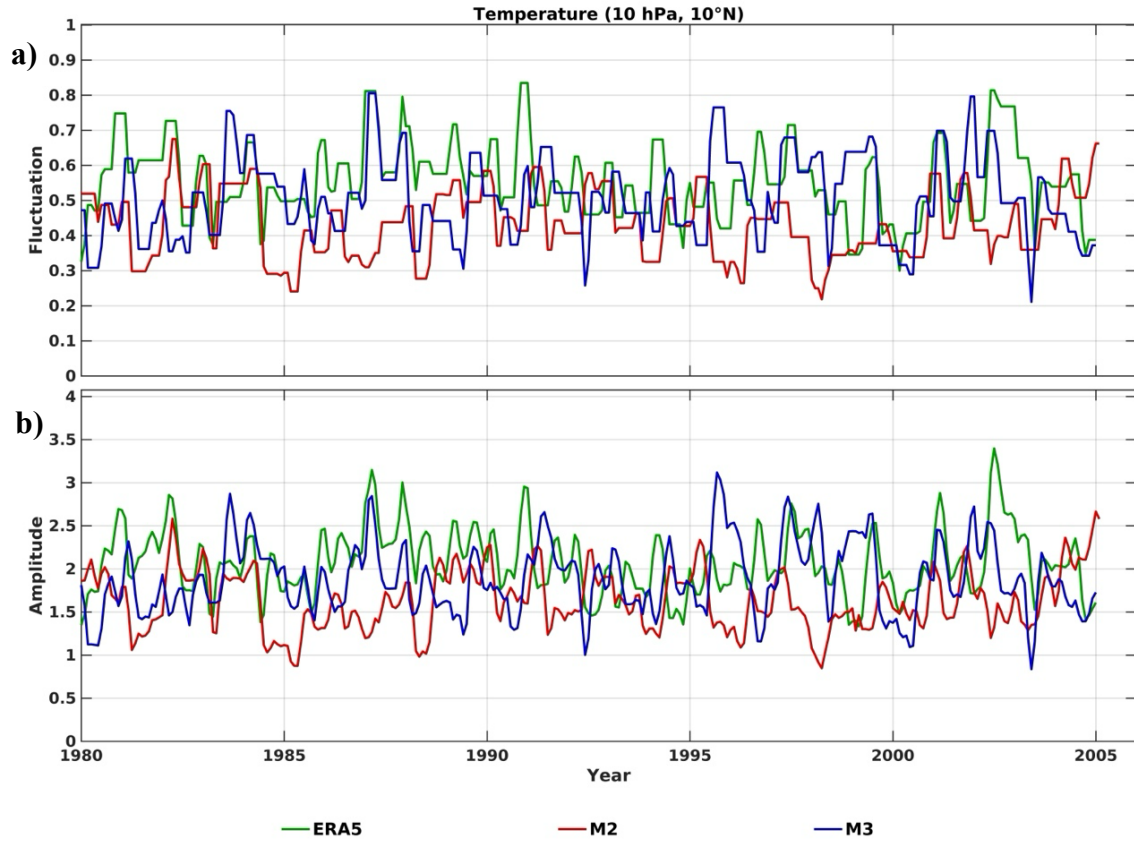


Figure 3.8 : Monthly (a) stratospheric temperature variability (T_{rng}) and (b) amplitude (T_{amp}) at the 10 hPa and 10°N during the historical period (1980–2005). The plot compares the ERA5 reanalysis data with the M2 and M3 model simulations.

The monthly (Figure 3.8a) T_{rng} and (Figure 3.8b) T_{amp} at the 10 hPa level at 10°N during the historical period (1980–2005) provide a critical diagnostic for evaluating model performance in the tropics. Figure 3.8 illustrates these thermal oscillations, which are primarily driven by QBO. Visually, the figure depicts a series of rhythmic fluctuations where the alternating peaks and troughs represent the transition between the warmer easterly and cooler westerly phases of the tropical stratospheric winds.

The ERA5 reanalysis data, identifiable by the most prominent trajectory in the plot, demonstrates a consistent and periodic signal. According to the statistical evidence in Table 3.3, this reanalysis yields a mean T_{amp} of 2.071 K and a T_{rng} of 0.553 K, with a sd of 0.379 K. When these visual oscillations are compared with the model outputs, the M2 trajectory exhibits a noticeably weakened signal, which corresponds to its statistically lower T_{rng} of 0.434 K. This signifies a 21.5% deficit in capturing the absolute thermal extremes

observed in the reanalysis, suggesting an underestimation of the QBO-driven thermal response in this model configuration.

Conversely, the M3 model manifests fluctuations that align visually closer to the ERA5 reanalysis but remain statistically more variable, as evidenced by its maximum recorded value of 3.117 K. The inconsistencies between these visual patterns and the reanalysis data indicate that while the models replicate the periodicity of the tropical stratosphere, they struggle to resolve the precise magnitude of the thermal gradients associated with tropical wave forcing. As documented in Durmus et al. (2026), such discrepancies often arise from the limitations in representing the wave-mean flow interactions that govern the tropical stratospheric temperatures.

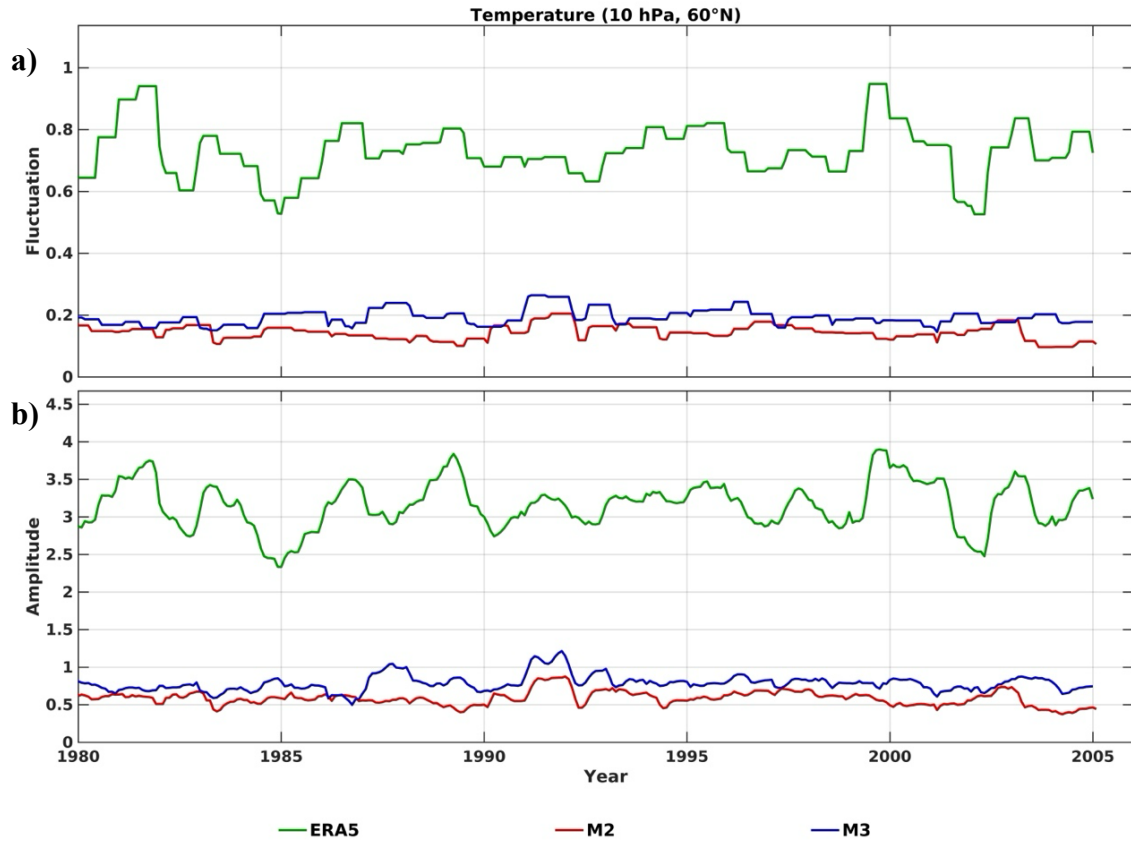


Figure 3.9 : Monthly (a) stratospheric temperature variability (T_{rng}) and (b) amplitude (T_{amp}) at the 10 hPa and 60°N during the historical period (1980–2005). The plot compares the ERA5 reanalysis data with the M2 and M3 model simulations.

The dynamics of the polar stratosphere at 60°N during the historical period are captured in Figure 3.9, presenting a different visual and statistical profile characterized by high-dynamical variability and intensive warming pulses. The figure highlights the thermal anomaly

where sudden, sharp increases in temperature represent the occurrences of SSW events during the winter months, followed by relatively stable and cooler periods during the summer.

These dramatic shifts are quantified in Table 3.3, where the ERA5 data records a substantially higher mean T_{amp} of 3.159 K and a T_{mg} of 0.730 K, with the maximum variability peaking at 3.898 K (Figure 3.9). An examination of the model trajectories in Figure 3.9 reveals a significant suppression of these extreme peaks.

The M2 model, in particular, displays a much flatter profile, capturing only a fraction (~20%) of the observed range with a mean T_{mg} of only 0.144 K (Figure 3.9). Although the M3 model captures more of the dynamical activity than M2, resolving approximately 54% of the reanalysis range (0.193 K), it still falls far short of the high-amplitude surges identified in the ERA5 reanalysis (Figure 3.9). The combined evidence from the figure and the table demonstrates that current high-top models tend to simulate a polar vortex that is overly stable, failing to accurately reflect the intense adiabatic warming processes driven by planetary wave-mean flow interactions. Such biases underscore the persistent challenges in modeling the magnitude of downward wave coupling and its subsequent impact on polar thermal stability.

The long-term evolution of tropical temperature variability at 10°N under the RCP 4.5 future scenario (2006–2100) is depicted in Figure 3.10. The visualization in this figure reveals a remarkable consistency with historical patterns, suggesting that the fundamental mechanisms of the QBO-driven thermal cycle persist under moderate climate change. This visual stability finds quantitative support in the projections in Table 3.3, where the mean T_{amp} for M2 and M3 are estimated at 1.706 K and 1.962 K, respectively. These values indicate a minimal shift of less than 4% relative to the historical period, strengthening the conclusion that tropical stratospheric seasonality is a resilient feature of the climate system.

The linear trend analysis presented in the table shows negligible slope values ($S_{Ts} < |0.001|$), which confirms the absence of a significant long-term drift in the amplitude of tropical temperature fluctuations throughout the 21st century. Figure 3.10 illustrates a continuation of the established historical variability, with models maintaining their respective internal biases in future simulations.

Finally, the projected thermal variability for the polar stratosphere at 60°N under the RCP 4.5 scenario is presented in Figure 3.11, confirming that the seasonal cycles and model limitations identified in the historical period persist into the future. According to the dynamical analysis the preservation of these thermal amplitudes suggests that the stratospheric response to

moderate radiative forcing is governed more by internal wave dynamics than by linear anthropogenic trends.

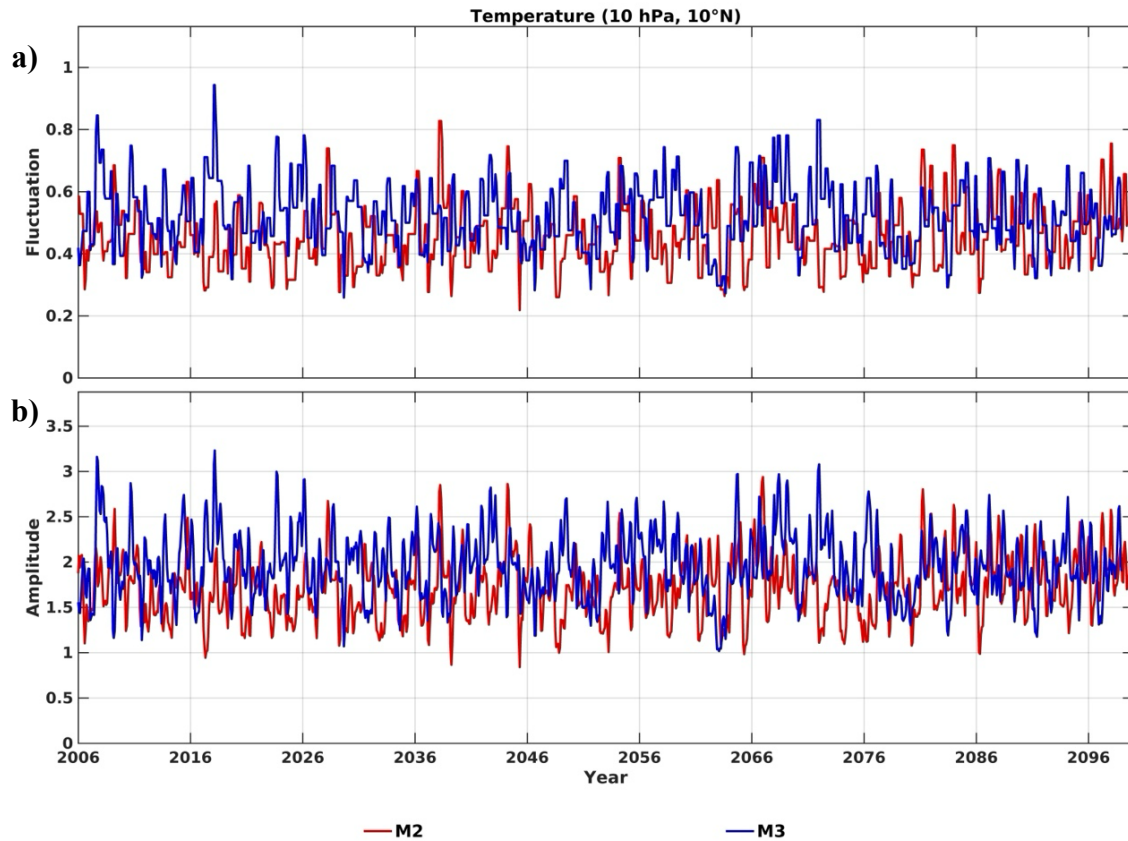


Figure 3.10 : Monthly (a) stratospheric temperature variability (T_{rng}) and (b) amplitude (T_{amp}) at the 10 hPa and 10°N during the future period (2006–2100). The plot compares the M2 and M3 model simulations.

The Figure 3.11 shows a clear seasonal contrast, with wintertime oscillations remain the dominant feature; however, the magnitude of these fluctuations does not exhibit a discernable increase or decrease over time. As in Table 3.3, the future mean T_{rng} for M2 (0.150 K) and M3 (0.191 K) remain significantly lower than the historical reanalysis comparison of 0.730 K. This indicates that the models predict no radical shift in the intensity of polar stratospheric variability or the frequency of extreme warming events under this specific scenario.

The synthesis of visual trends in Figure 3.11 and the statistical metrics in Table 3.3 confirms that while the polar stratosphere continues to experience strong seasonal cycles, the intrinsic structural deficiencies of the CMIP5 models in capturing the full range of stratospheric extremes remain a limiting factor in future climate projections.

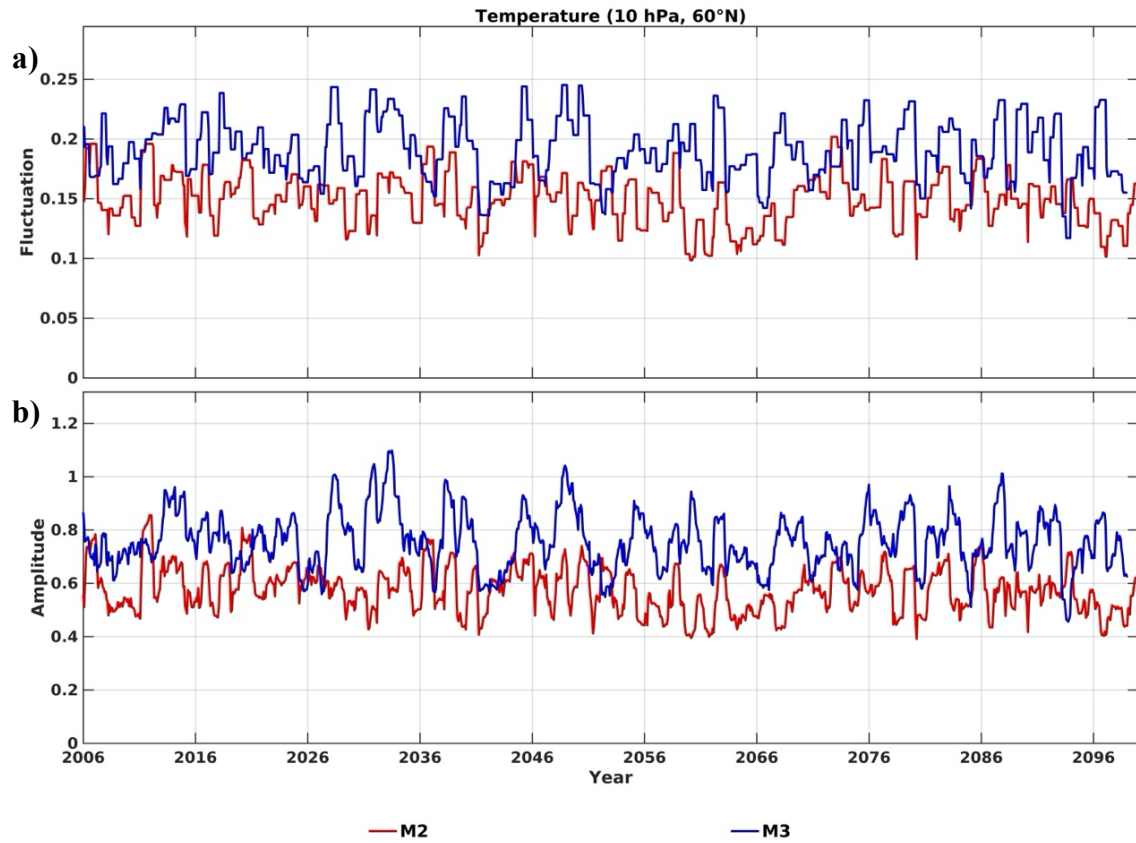


Figure 3.11 : Monthly (a) stratospheric temperature variability (T_{mg}) and (b) amplitude (T_{amp}) at the 10 hPa and 60°N during the future period (2006–2100). The plot compares the M2 and M3 model simulations.

In summary, the analysis of T_{amp} and T_{mg} reveals a distinct geographical contrast between the QBO-governed tropical stability and the dynamically variable polar region. While the ERA5 reanalysis provides a high-amplitude baseline for the historical period, the high-top CMIP5 models exhibit a significant suppression of thermal extremes, capturing only a fraction of the observed variability range at 60°N.

This systemic underestimation persists into the RCP 4.5 future projections, where the variability structure remains remarkably stable with negligible long-term trends. These findings suggest that while the seasonal cycle is accurately preserved in climate simulations, the models possess inherent structural limitations in resolving the full intensity of stratospheric thermal pulses. This inconsistency underscores the necessity for further investigation into the dynamical coupling between the troposphere and stratosphere to better understand the future evolution of extreme atmospheric events. These biases are essential for improving the predictability of polar-tropical teleconnections in a changing climate.

3.3.2 Fluctuation and amplitude of zonal wind

The evaluation of stratospheric dynamical variability, as represented by the U_{amp} and U_{rng} at the 10 hPa level, provides insights into the strength and stability of the atmospheric circulation. Similar to the thermal analysis, this section partitions the results by geographical region and temporal period, integrating statistical data from Table 3.4 with the corresponding time-series figures to assess model fidelity in capturing dynamical pulses.

The dynamical behavior of the tropical stratosphere at 10°N during the historical period (1980–2005) is illustrated in Figure 3.12, which depicts the alternating QBO– and QBO+. Visually, the Figure 3.12 shows a rhythmic transition where positive values represent westerly momentum, and negative values signify easterly momentum.

Table 3.4 : Statistical analysis of zonal wind amplitude (U_{amp}) and range (U_{rng}) for ERA5 reanalysis and CMIP5 model simulations (M2 and M3) at 10°N and 60°N for the historical (1980–2005) and future (2006–2100, RCP 4.5) periods. Metrics include the mean, median, standard deviation (sd), variance (Var), minimum (Min), maximum (Max), and linear trend slope ($m \cdot s^{-1}$ per decade) (Durmus et al., 2026).

Period	Metric	Lat	Model	Mean	Median	Std	Var	n	Max	Slope
1980–2005	U_{amp}	10°N	ERA5	12.513	12.656	4.56	20.793	3.033	22.602	0.01084
			M2	13.352	14.483	5.497	30.212	1.376	23.14	0.000349
			M3	13.214	14.309	7.622	58.088	1.066	25.571	0.005
		60°N	ERA5	11.385	11.347	1.754	3.075	7.047	15.436	0.01092
			M2	4.087	4.003	1.138	1.295	1.657	6.865	-0.002389
			M3	4.168	3.971	1.474	2.173	1.215	8.212	-0.00104
	U_{rng}	10°N	ERA5	3.021	3.142	0.926	0.858	0.853	4.838	0.002139
			M2	3.06	3.432	1.014	1.028	0.398	4.764	-0.000255
			M3	3.068	3.615	1.526	2.327	0.302	5.06	0.001179
		60°N	ERA5	2.728	2.742	0.392	0.154	1.696	3.691	0.001098
			M2	1.072	1.022	0.29	0.084	0.489	1.788	-0.000499
			M3	1.059	1.019	0.333	0.111	0.386	1.91	-0.000604
2006–2100	U_{amp}	10°N	M2	13.251	13.982	4.306	18.546	2.635	21.302	-0.004462
			M3	14.458	15.551	7.133	50.886	0.793	26.944	0.0048
		60°N	M2	4.133	4.053	1.237	1.531	1.263	7.554	-0.000401
			M3	4.578	4.432	1.486	2.21	1.012	9.142	0.000261
	U_{rng}	10°N	M2	3.094	3.243	0.768	0.589	0.678	4.419	-0.000877
			M3	3.315	3.76	1.365	1.863	0.218	5.092	0.000826
		60°N	M2	1.071	1.078	0.29	0.084	0.338	1.761	-0.00014
			M3	1.174	1.146	0.354	0.126	0.303	2.184	-0.000025

The ERA5 reanalysis establishes a U_{amp} of $26.559 \text{ m} \cdot \text{s}^{-1}$ and a U_{rng} of $10.435 \text{ m} \cdot \text{s}^{-1}$, reflecting the high intensity of the tropical stratospheric jet. When comparing model trajectories, a striking discrepancy emerges: the M3 model exhibits significantly extreme tropical wind variability,

with a recorded U_{rng} of $24.646 \text{ m}\cdot\text{s}^{-1}$. This represents an overestimation of approximately 136% relative to ERA5 reanalysis.

In contrast, the M2 model demonstrates high accuracy in this region, resolving a U_{rng} of $10.222 \text{ m}\cdot\text{s}^{-1}$, which aligns closely with the reanalysis with only a minor -2% deviation. These visual and statistical differences suggest that while M2 accurately simulates the momentum budget of the tropical stratosphere, M3 produces an overly variable QBO signal. This intensification may stem from excessive gravity wave forcing or resolution-related biases within the tropical pipe. Such biases in high-top models often indicate a misrepresentation of the wave-mean flow interactions necessary for maintaining a realistic stratospheric momentum balance.

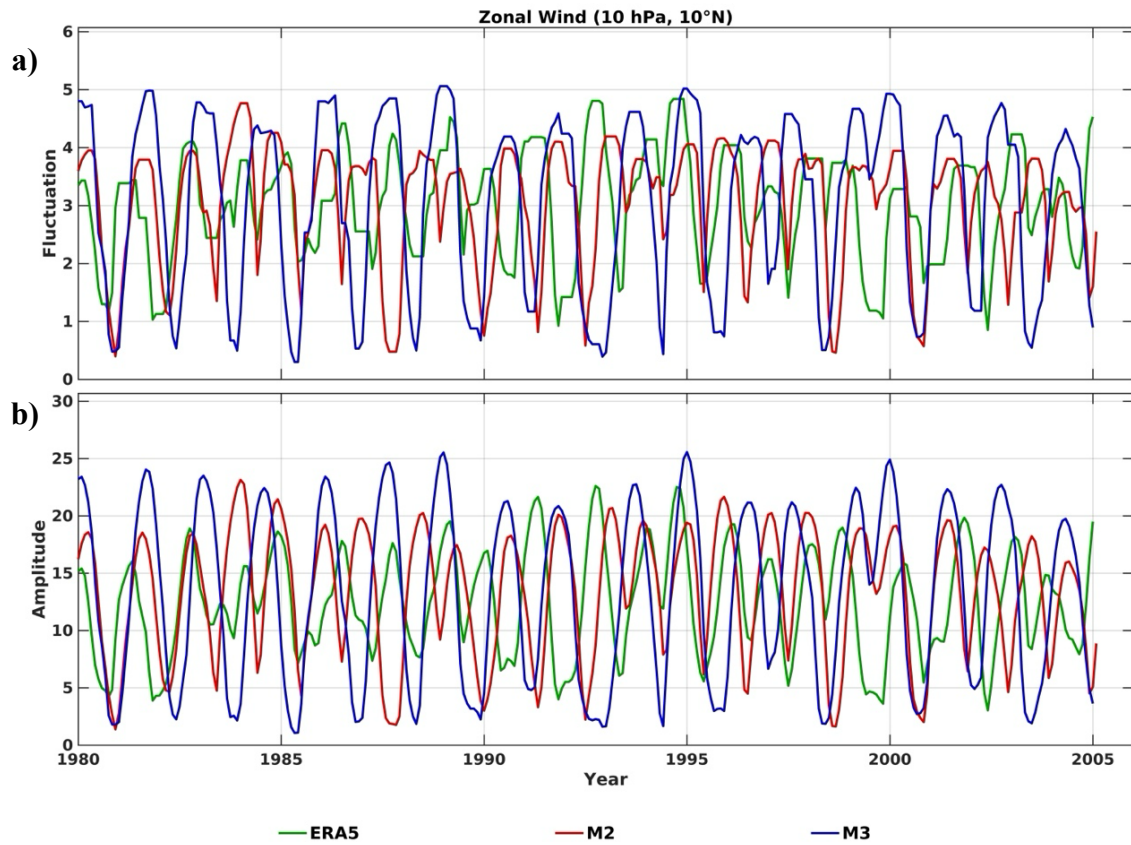


Figure 3.12 : Monthly (a) zonal wind variability (U_{rng}) and (b) amplitude (U_{amp}) at the 10 hPa and 10°N during the historical period (1980–2005). The plot compares the ERA5 reanalysis data with the M2 and M3 model simulations.

The variability of the polar U_h at 60°N during the historical period is illustrated in Figure 3.13, capturing the extreme seasonal cycle of the polar vortex and its response to dynamical disturbances. The visual profile is characterized by robust westerly winds during the winter and

a transition to easterly flow during the summer. Substantial interannual variability is evident during the winter months, where abrupt decelerations in wind speed signify the occurrence of SSW events and associated circulation reversals.

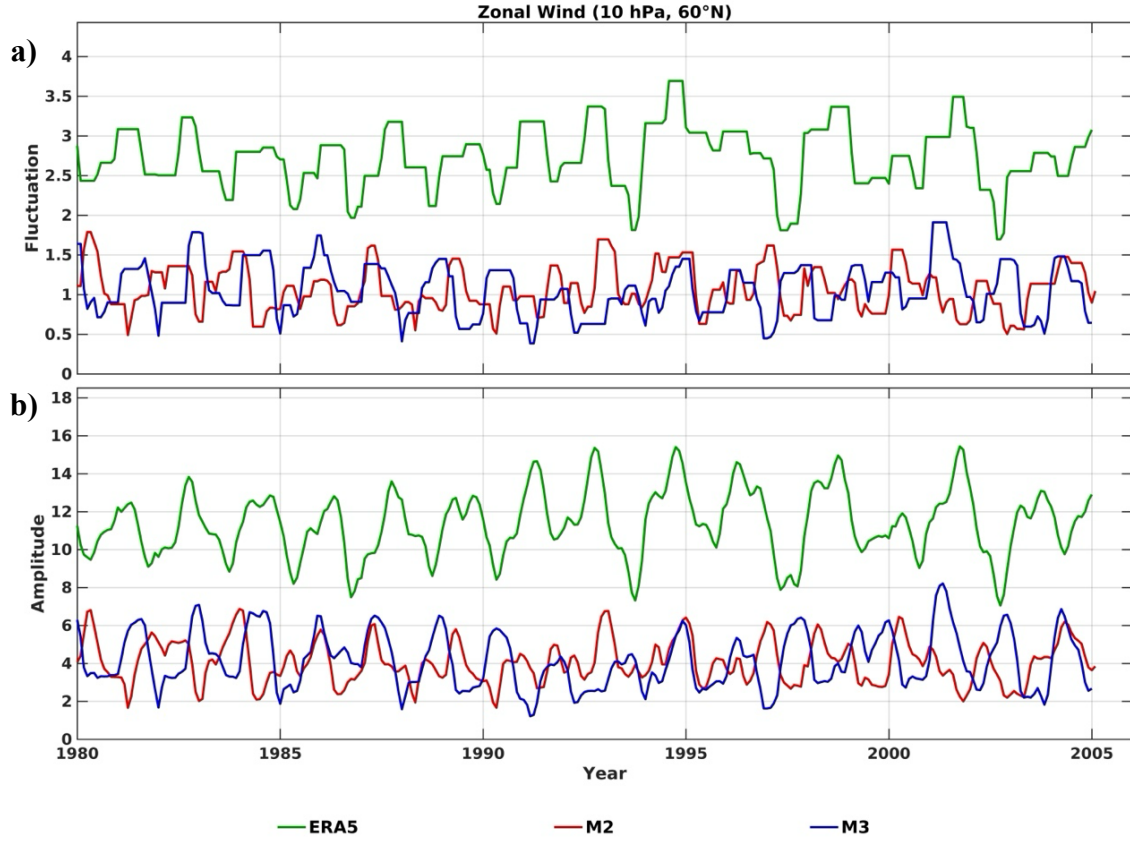


Figure 3.13 : Monthly (a) zonal wind variability (U_{rng}) and (b) amplitude (U_{amp}) at the 10 hPa and 60°N during the historical period (1980–2005). The plot compares the ERA5 reanalysis data with the M2 and M3 model simulations.

Statistical metrics in Table 3.4 reveal that ERA5 exhibits a U_{amp} of $38.270 \text{ m}\cdot\text{s}^{-1}$ and a U_{rng} of $8.257 \text{ m}\cdot\text{s}^{-1}$. A comparative assessment indicates that both CMIP5 models fail to capture the full magnitude of this polar variability. The M2 model trajectory is markedly constrained, with a mean U_{rng} of only $3.300 \text{ m}\cdot\text{s}^{-1}$, representing a substantial $\sim 60\%$ underestimation of the dynamical range documented in the ERA5 reanalysis.

Although the M3 model demonstrates higher fidelity by resolving a U_{rng} of $7.114 \text{ m}\cdot\text{s}^{-1}$ ($\sim 86\%$ of the reanalysis), it nonetheless underestimates the overall U_{amp} by approximately 26%. These findings indicate that the model ensemble manifests an overly resilient polar vortex or insufficiently resolves the vertical coupling with tropospheric wave activity required to

replicate the observed magnitude of wind fluctuations. Such discrepancies emphasize the structural limitations in the downward wave-coupling parameterizations of high-top models.

The future projection of tropical U_h variability at 10°N under the RCP 4.5 scenario (2006–2100) is visualized in Figure 3.14. The visual consistency between the historical and future trajectories indicates that the fundamental mechanisms of the QBO-driven dynamical cycle exhibit remarkable resilience to anthropogenic radiative forcing. This stability is corroborated by the statistical projections in Table 3.4, where the mean U_{rng} for M2 ($10.514 \text{ m}\cdot\text{s}^{-1}$) and M3 ($24.475 \text{ m}\cdot\text{s}^{-1}$) remain notably close to their respective historical baselines.

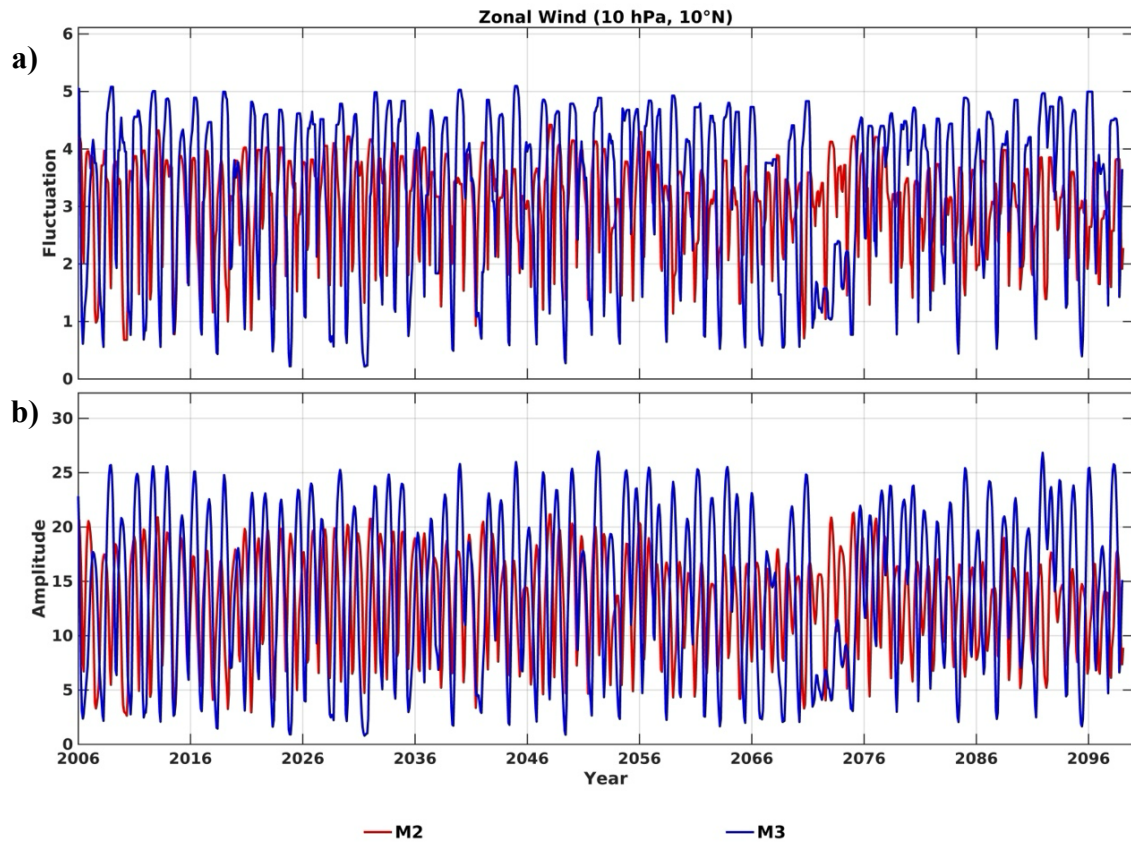


Figure 3.14 : Monthly (a) zonal wind variability (U_{rng}) and (b) amplitude (U_{amp}) at the 10 hPa and 10°N during the future period (2006–2100). The plot compares the M2 and M3 model simulations.

The trend coefficient S_{U_h} for this region yields negligible values ($|S_{U_h}| < 0.001 \text{ m}\cdot\text{s}^{-1} \text{ decade}^{-1}$), confirming the absence of a significant secular trend in the amplitude of tropical wind oscillations throughout the 21st century. The figure demonstrates that while the models maintain their inherent historical biases particularly the overestimation in M3 the

overall seasonality and periodicity of the tropical stratosphere remain a stationary characteristic of the simulated climate. The QBO signal under moderate climate change underscores the dominance of internal wave-mean flow interactions over external greenhouse gas forcing in the tropical pipe.

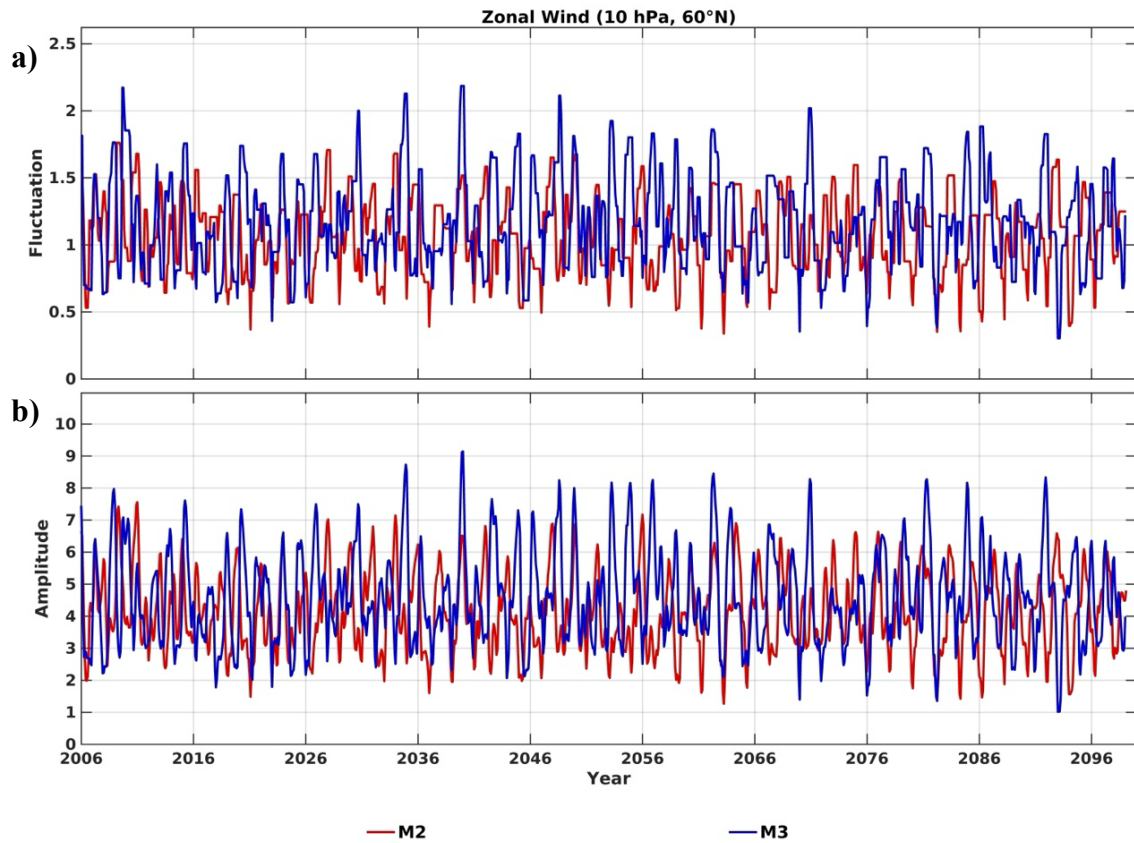


Figure 3.15 : Monthly (a) zonal wind variability (U_{rng}) and (b) amplitude (U_{amp}) at the 10 hPa and 60°N during the future period (2006–2100). The plot compares the M2 and M3 model simulations.

Finally, the projected variability of the polar U_h at 60°N under the RCP 4.5 scenario is visualized in Figure 3.15, demonstrating the persistence of seasonal cycles and model-specific limitations through the end of the 21st century. The figure confirms that the polar vortex exhibits no substantial divergence from its established historical behavior. As documented in Table 3.4, the projected dynamical range for M2 ($3.415 \text{ m}\cdot\text{s}^{-1}$) and M3 ($7.214 \text{ m}\cdot\text{s}^{-1}$) shows no significant increase compared to historical levels. These results suggest that the models do not predict a pronounced intensification or weakening of polar stratospheric variability under the RCP 4.5 scenario.

The integration of visual patterns in Figure 3.15 and the statistical metrics in Table 3.4 confirms that while the polar jet continues to dominate the stratospheric circulation, the structural deficiencies in capturing the full range of dynamical extremes remain a persistent challenge for climate projections.

A primary finding of this section is the systematic bias identified within the CMIP5 ensemble, as illustrated throughout the comparative visualizations (Figures 3.8–3.15). Specifically, the M2 model consistently underestimates the magnitude of polar thermal and dynamical perturbations, capturing only a fraction of the observed variability range, whereas the M3 model tends to overestimate tropical wind variability. Furthermore, the evaluation of the RCP 4.5 scenario indicates that these variability structures and model-specific biases are projected to remain remarkably stationary throughout the 21st century, with the absence of significant secular trends in either temperature or U_h amplitude. These results suggest that while seasonal cycles are qualitatively preserved in the simulations, the inherent structural limitations of high-top models in resolving high-magnitude stratospheric gradients remain a persistent challenge for future climate projections.

3.4 QBO Analysis Related With SSW

QBO is a quasi-periodic stratospheric oscillation involving the regular alternation of QBO– and QBO+ winds in the tropical stratosphere at altitudes ranging from 16 to 50 kilometers. This oscillation cycle lasts approximately 28 to 30 months, with wind reversals occurring every 14–15 months (Baldwin et al., 2001; Holton & Tan, 1980). The QBO is generated when stratospheric winds interact with energy-transporting waves triggered by vertically propagating waves from tropical convection, which alter wind patterns. The QBO+ phase exhibits a higher maximum amplitude compared to the QBO– phase, and both follow a meridional Gaussian distribution across the equator (Baldwin et al., 2001; Pascoe et al., 2005).

The mechanism behind the QBO arises from the interplay between zonal mean flow and equatorial planetary waves. Holton (2004) notes that it occurs exclusively in the equatorial region due to the formation of K waves and Rossby-gravity waves, confined between 12°N and 12°S. The QBO is not observed at higher latitudes due to the dynamical confinement of these waves within the equatorial waveguide into the lower stratosphere, although cloud production and frontal zones can still be observed in those regions (Holton & Lindzen, 1972). The QBO impacts air currents and precipitation patterns in the tropics and exerts an indirect influence on high-latitude jet streams. For instance, differing QBO phases significantly affect NH winter

weather patterns (Anstey et al., 2010). Monitoring is conducted via radio soundings, atmospheric pressure measurements, and particularly satellite observations, which provide crucial data on worldwide wind speed and direction. Complex atmospheric models are utilized to replicate QBO interactions with atmospheric processes and project its influence on global climate (Scaife et al., 2014). Recent studies prioritize how the QBO may evolve in response to climate change, specifically regarding alterations to its period, amplitude, and phase changes (Maycock et al. 2013; Thompson et al., 2002). Furthermore, the QBO influences chemical and physical processes in the lower stratosphere and is governed by the thermal wind equation, indicating a direct relationship between U_h shear and T_s (Holton, 2004).

The representation of tropical stratospheric variability is investigated via a diagnostic assessment of the QBO using the CMIP5 models M2 and M3. These high-top models are strategically employed for this evaluation due to their capability to resolve the stratospheric vertical structure and wave-mean flow interactions necessary to simulate the ~28-month oscillation cycle. The diagnostic focus is concentrated on the quasi-periodic phase transitions of U_h at the 10 hPa level above 10°N latitude. Figure 3.15 and Figure 3.16 depict the transitions between positive westerly and negative easterly phases across the historical (1980–2005) and RCP 4.5 (2006–2100) periods, respectively. Through a comprehensive evaluation of these time-series datasets, this study assesses the accuracy of the simulated intrinsic dynamical periodicity of the tropical stratosphere. Furthermore, it elucidates the teleconnection between these equatorial oscillations and polar vortex stability, specifically concerning the modulation of SSW events through the Holton-Tan effect.

The time series and QBO behaviors of 10°N latitude 10 hPa level U_h associated with the historical period of ERA5 reanalysis and CMIP5 climate models are presented in Figure 3.16. The QBO analysis demonstrates the accuracy with which the models represent tropical stratospheric variability. The positive oscillation (red) in the graphs represents westerly winds, while the negative oscillation (blue) represents easterly winds.

Primarily, the ERA5 reanalysis dataset exhibits a cycle of approximately 28 months. This observation is fundamentally consistent with the general definition of QBO. The reanalysis data, which shows a strong and regular oscillation throughout the historical period, represents the internal cycle of the tropical stratosphere well (Baldwin et al., 2001).

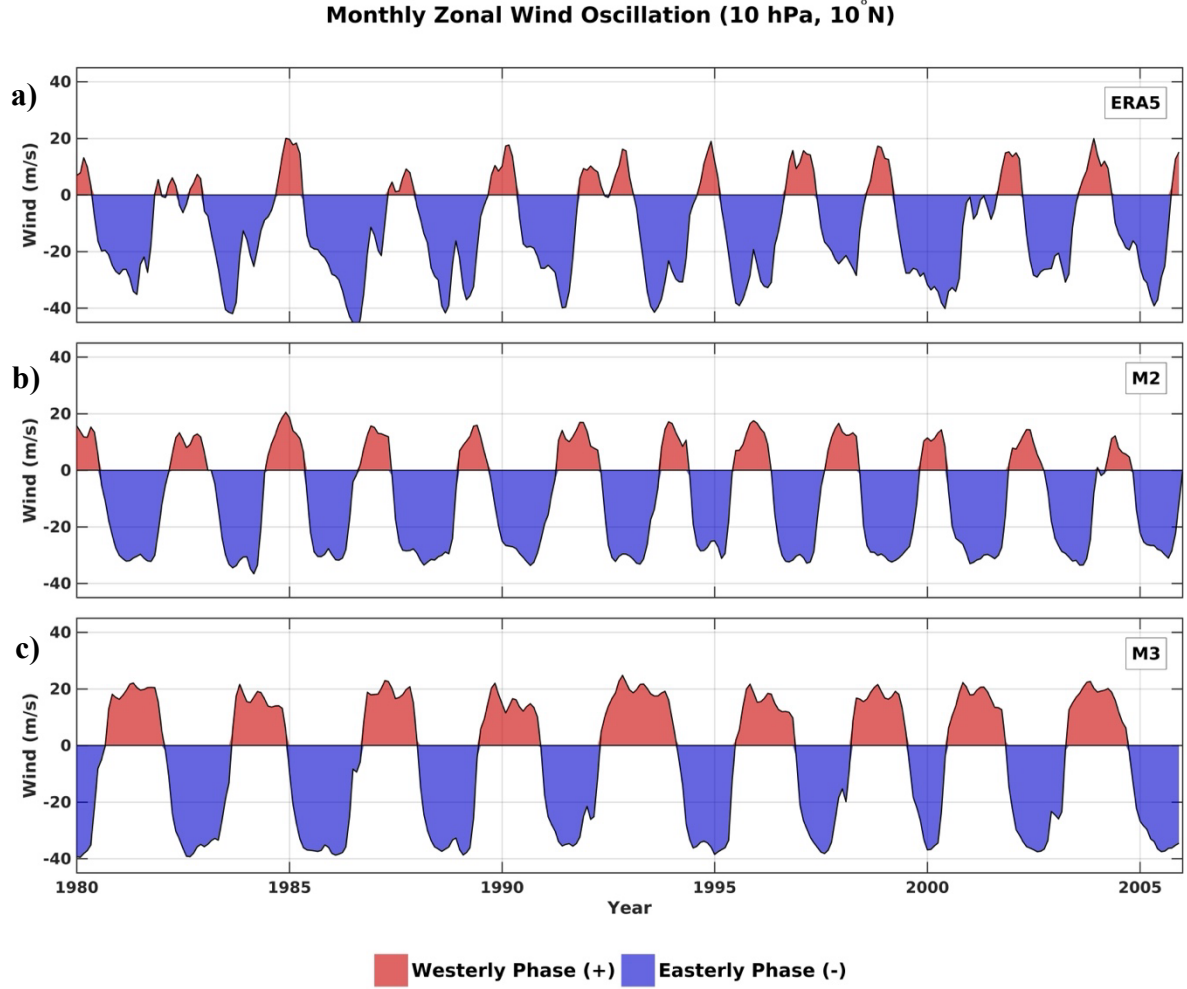


Figure 3.16 : Monthly zonal wind (U_h) oscillations at 10 hPa and 10°N for the historical period (1980–2005): (a) ERA5 reanalysis, (b) M2, and (c) M3. Red and blue shading denote the westerly (+) and easterly (–) phases of the QBO, respectively.

The situation is slightly differing in the CMIP5 climate models. Only two of the models, M2 and M3, can resolve QBO oscillations, while this oscillation is absent in the other models. In both models, an oscillation that undergoes phase reversals at certain intervals is observed. In other words, the models represent the QBO well in terms of stratospheric vertical resolution and physical parameters, while other models are demonstrating structural limitations in resolving it. This finding is corroborated in the literature. (Rao et al., 2020).

To resolve the QBO oscillation, a high model top and wave parameters parameterized with high vertical resolution are needed. For this reason, it is mechanistically expected that models lacking these structural configurations are unable to capture the QBO oscillation. In models that cannot represent the QBO well, the equatorial wind manifests as a constant westerly wind and is dominated by the SAO.

Tropical winds focused at the 10 hPa level where the analyses are made generally show a semiannual oscillation that can turn to QBO+ and then modulate to QBO– again during the equinox periods of the year. When the outputs from CMIP5 climate models are examined, the signatures of SAO fluctuations, which are low-amplitude fluctuations relative to primary surges in wind speed, are also seen in Figure 3.16 (Butchart et al., 2011).

In the QBO– phase, planetary wave propagation from the tropopause to the polar stratosphere increases, which triggers SSW events. Conversely, in the QBO+ phase, wave propagation is inhibited or steered toward the equator; thus, the polar vortex remains stronger, and the stratosphere is generally colder. The effect of this situation on the mid-latitudes is termed the Holton-Tan effect (Holton & Tan, 1980; Anstey et al., 2020). This difference is clearly seen in Figure 3.16. As a result, while the ERA5 reanalysis data represents the QBO well, most CMIP5 models exhibit significant biases in resolving the QBO.

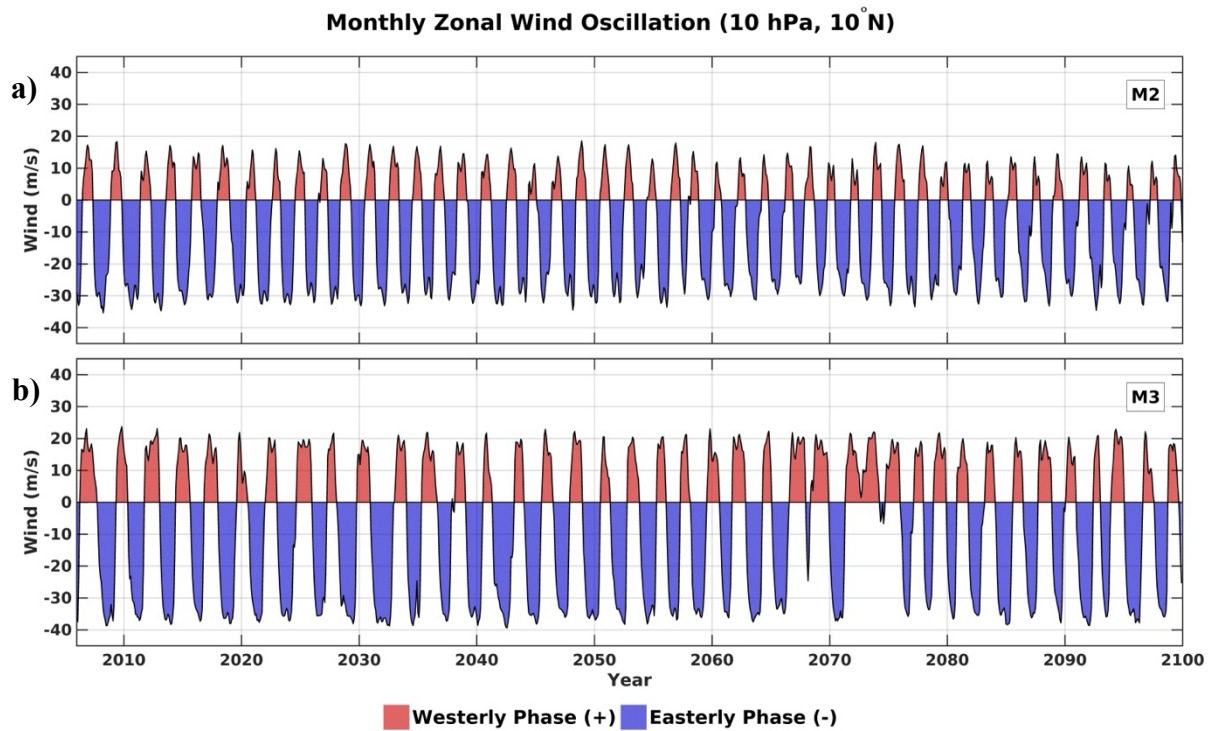


Figure 3.17 : Monthly zonal wind (U_h) oscillations at 10 hPa and 10°N for the future period (2006–2100): (a) M2, and (b) M3. Red and blue shading denote the westerly (+) and easterly (–) phases of the QBO, respectively.

In Figure 3.17, the phase transitions of the QBO are visualized, while the simulated projections are represented by the CMIP5 climate model RCP 4.5 scenario. The outputs obtained here provide information about what kind of results the tropical stratospheric circulation may have in the future and whether the QBO oscillation continues. As in the historical period, only M2

and M3 models resolve the QBO here. This situation shows that under the RCP 4.5 conditions, the QBO cycle is not disrupted and continues approximately every 28 months.

The literature indicates that although the increase in greenhouse gases continues, the QBO oscillation is not affected by this situation (Scaife et al., 2000; Butchart et al., 2014). Observation of the model outputs reveals that the QBO cycle becomes more frequent towards the end of the century, manifested by a slight increase in peak frequency.

Previous studies suggests that the increase in temperature in the tropical troposphere leads to more wave transport to the stratosphere, potentially reducing the QBO cycle from 28 months to 25 months (Kushner et al., 2001; Butchart et al., 2014). As a result, the same models represent the QBO effectively here as in the historical period, and no major differences are observed in their oscillations.

3.5 Thermal-Dynamical Coupling Analysis

The investigation of thermal-dynamical coupling within the stratosphere is facilitated by the analysis of scatter plots correlating daily mean T_s and U_h at the 10 hPa pressure level. This analysis, centered on the 60°N latitude, elucidates the sensitivity of the polar night jet to thermal anomalies and provides a diagnostic measure of how effectively climate models resolve the observed anti-correlation between T_s and U_h magnitude. By comparing the historical period (1980–2005) with future projections under the RCP 4.5 scenario (2006–2100), the study delineates systematic transitions in the coherence and strength of the polar vortex's internal dynamics.

In the historical ERA5 (Figure 3.17, right), a robust anti-correlation is identified at 60°N, where U_h exhibits an inverse proportionality with T_s . This relationship confirms the physical definition of SSW events, as extreme increases in temperature are intrinsically linked to a pronounced deceleration or reversal of westerly winds. The ERA5 data reveals a temporal evolution in the coupling magnitude; before 1990, the regression slope is recorded at $-1.62 \text{ m.s}^{-1}.\text{K}^{-1}$, whereas it attenuates to $-1.13 \text{ m.s}^{-1}.\text{K}^{-1}$ in the post-1990 period. This approximately 30% reduction indicates an attenuation in the dynamical coherence of the polar vortex in recent decades.

Conversely, the tropical stratosphere at 10°N (Figure 3.17, left) presents a distinct morpho-statistical profile. While temperature remains relatively stable with negligible thermal variability, the U_h manifests substantial dynamical variability due to the QBO. The resulting

weak positive trend in the tropics emphasizes that stratospheric variability in this region is predominantly a dynamically driven phenomenon rather than one governed by thermal-dynamical coupling.

Evaluation of the CMIP5 models at 60°N (Figure 3.18) delineates systematic model biases in representing this coupling. Model M2 (Figure 3.19) exhibits a significantly stronger and more linear inverse T_s-U_h relationship compared to the reanalysis, with regression slopes remaining near $-2.0 \text{ m.s}^{-1}.\text{K}^{-1}$ across both historical sub-periods.

The high correlation ($r \approx -0.82$) and reduced statistical dispersion suggest that M2 overestimates the dynamical sensitivity to warming anomalies and simulates an excessive frequency of attenuated or reversed vortex states ($U_h < -20 \text{ m.s}^{-1}$). In contrast, Model M3 (Figure 3.18) simulates an inverse coupling with diminished coherence and a broader spread in wind speeds. While M3 maintains a stable regression slope of approximately $-1.41 \text{ m.s}^{-1}.\text{K}^{-1}$, it underestimates the amplitude of the thermal-dynamical link by 15–20% and is unable to resolve the post-1990 weakening observed in ERA5.

The evolution of T_s-U_h coupling under the RCP 4.5 scenario is analyzed through four successive segments: 2006–2025, 2026–2050, 2051–2075, and 2076–2100. In the M2 simulations (Figure 3.19), the coupling initially steepens to a slope of $-2.65 \text{ m.s}^{-1}.\text{K}^{-1}$ during the 2026–2050 period, identifying this as the timeframe when the polar vortex is most susceptible to thermal anomalies.

However, as the century progresses, a gradual decrease in dynamical strength is observed; the slope flattens substantially to $-0.74 \text{ m.s}^{-1}.\text{K}^{-1}$ by the final segment (2076–2100). Despite a 1 K rise in mean T_s , the persistent westward orientation of the U_h pattern suggests that while the sign of the coupling remains correct, the consistency of the dynamical response diminishes under sustained moderate forcing. The eventual decoupling of the thermal-dynamical link highlights the increasing uncertainty in high-latitude projections as the stratospheric background state undergoes anthropogenically induced shifts.

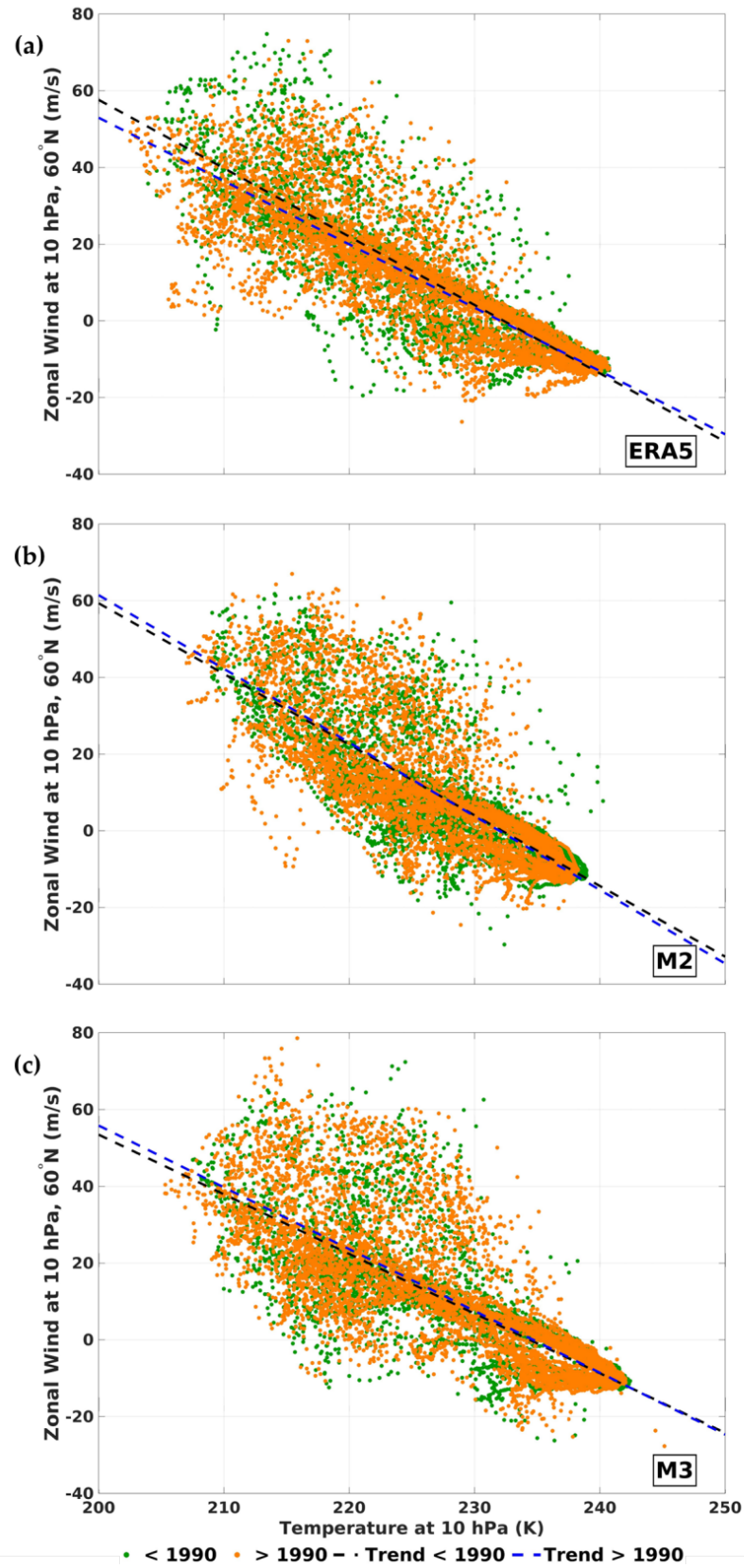


Figure 3.18 : Scatter plots of daily mean zonal wind (U_h) versus stratospheric temperature (T_s) at 10 hPa and 60°N the historical period (1980–2005): (a)ERA5 reanalysis, (b) M2, and (c) M3. Orange dots represent data after 1990 and green dots represent data before 1990. Dashed black and blue lines show linear trends for pre-1990 and post-1990 periods (Durmus et al., 2026).

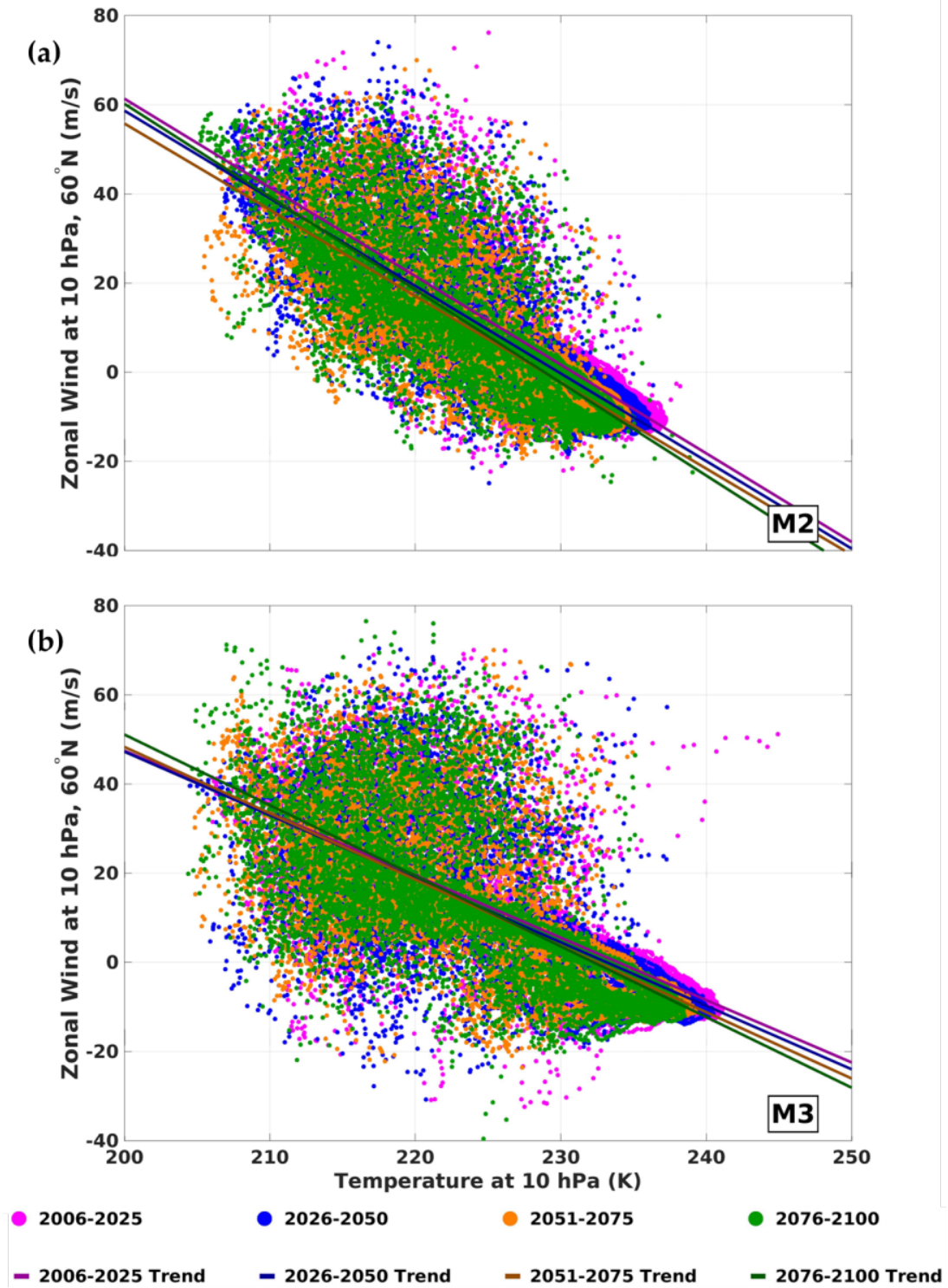


Figure 3.19 : Scatter plots of daily mean zonal wind (U_h) versus stratospheric temperature (T_s) at 10 hPa and 60°N the future period (2006–2100): (a) M2, and (b) M3. Orange dots represent data after 1990 and green dots represent data before 1990. Dashed black and blue lines show linear trends for pre-1990 and post-1990 periods (Durmus et al., 2026).

Model M3 (Figure 3.19) exhibits a non-monotonic dynamical response to RCP 4.5 forcing. The coupling strengthens toward the middle of the century, reaching a maximum intensity with a

slope of $-2.42 \text{ m.s}^{-1}.\text{K}^{-1}$ during the 2051–2075 period. This peak reflects a heightened polarity between warming anomalies and the resulting dynamical response. However, this strengthening is transient, as the slope weakens sharply to $-0.63 \text{ m.s}^{-1}.\text{K}^{-1}$ in the 2076–2100 period, accompanied by increased scatter and a higher mean T_s of approximately 227 K. Collectively, these results indicate that while a reliable inverse coupling between temperature and U_h is a persistent feature of the polar stratosphere, both models project a significant reduction in the coherence and sensitivity of this relationship toward the end of the 21st century. The convergence of these models toward a weakened coupling state underscores a potential regime shift in stratospheric variability under long-term radiative forcing.

3.6 Integrated Vapor Transport and Case Study of the January 2003 SSW Event

The January 2003 SSW event serves as a benchmark for examining the significant impacts of polar vortex disruptions on hemispheric moisture transport and atmospheric mass circulation. This event, characterized by a major vortex split, provides a specialized framework for analyzing the coupling between extreme stratospheric perturbations and tropospheric responses.

The investigation centers on the dynamics of IVT and the resulting redistribution of atmospheric water vapor across five distinct phases: the pre-warming state (14 January), the onset of warming (22 January), the vortex split (24 January), the peak disturbance (27 January), and the final response period (12 February). By isolating these stages, the study quantifies how the breakdown of the stratospheric isolation barrier alters the large-scale moisture budget and modifies the pathways of moisture injection into the upper atmosphere.

The analysis is structured to provide a diagnosis of these atmospheric shifts through a multi-layered evaluation. Initial focus is placed on the hemispheric moisture budget, where a transport matrix is utilized to track anomalies in zonal and meridional moisture fluxes during the vortex breakdown. This is followed by a vertical partitioning of the vapor transport, aimed at identifying the specific atmospheric layers ranging from the lower troposphere to the stratosphere where moisture transport is most significantly enhanced or suppressed. To visualize the physical distribution of these changes, the spatial and temporal evolution of specific humidity profiles are examined, revealing the vertical pathways of moisture migration. Finally, the study integrates these findings with the Meridional Mass Streamfunction (MSF) to evaluate shifts in global circulation cells, offering a definitive assessment of how stratospheric warming reorganizes atmospheric mass and moisture distribution on a hemispheric scale.

3.6.1 Hemispheric moisture budget and horizontal IVT dynamics

The quantitative diagnosis of the January 2003 SSW event is developed through a multi-dimensional statistical framework. This analysis evaluates the shift in moisture transport pathways across different phases, comparing active warming periods with climatological baselines. The evolution of these dynamics is detailed in three primary datasets: a temporal hemispheric matrix (Table 3.5), a comparative baseline of transport intensities (Table 3.6), and a vertical partitioning of the moisture flux across atmospheric layers (Table 3.7).

The first diagnostic tool, the comprehensive hemispheric transport matrix (Table 3.5), monitors the daily evolution of zonal and meridional IVT across the five critical phases of the SSW event. This table identifies the specific moments when the stratospheric vortex state initiates the modulation of tropospheric moisture transport routes.

Table 3.5 : Comprehensive hemispheric transport matrix (0°–90°N) depicting the daily evolution of zonal and meridional Integrated Vapor Transport (IVT) intensities ($\text{kg}\cdot\text{m}^{-1}\text{s}^{-1}$) across the five synoptic phases of the January 2003 Major SSW.

Parameter	14-Jan	22-Jan	24-Jan	27-Jan	12-Feb
East IVT (Avg)	104.9	101.7	82.2	105.8	99.6
East IVT (Max)	1400.2	785	802.8	1162.3	1002.4
West IVT (Avg)	74.9	82	87.3	72.6	67.8
West IVT (Max)	1165	1193.6	1259.2	967.4	1019.9
North IVT (Avg)	44.1	37.4	41.9	46.7	42.6
North IVT (Max)	576.7	292.5	546.5	548.9	441.1
South IVT (Avg)	51.6	55.6	76	45.5	53.6
South IVT (Max)	1029.5	1113.4	1145.4	675.4	1253.7
PEAK TOTAL IVT	1403.1	1256.4	1459	1183.1	1300.1

Subsequent to the temporal tracking of the event, the Statistical Comparison of IVT Intensities presented in Table 3.6 establishes a climatological baseline by benchmarking the SSW period against standard winter conditions. This diagnostic approach facilitates the identification of anomalies that significantly surpass typical interannual variability, underscoring the extreme nature of the 2003 moisture intrusion. The datasets reveal a substantial intensification of zonal transport, where the Mean Zonal IVT during the SSW window rises to $31.03 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$, a marked increase from the $26.53 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$ observed during non-SSW days.

This escalation is accompanied by a sharp surge in the zonal sd, which reaches 17.52 during the warming phase, indicating a transition toward a highly volatile and disorganized atmospheric state. While the meridional mean remains lower, the overall peak transport values and the increased statistical spread delineate a fundamental reorganization of moisture pathways. Such deviations confirm that the January 2003 SSW acts as a primary catalyst for unconventional hydrological exchanges, effectively overriding the climatological isolation of the high latitudes.

Table 3.6 : Statistical comparison of zonal and meridional IVT intensities ($\text{kg}\cdot\text{m}^{-1}\text{s}^{-1}$) highlighting the anomalies during the January 2003 SSW period relative to non-SSW winter days.

Category	Mean	Max	Min	Sd Dev
Zonal (All Period)	27.76	59.52	0.08	13.6
Zonal (SSW Period)	31.03	59.52	7.65	17.52
Zonal (Non-SSW Days)	26.53	45.52	0.08	12.04
Meridional (All Period)	11.31	30.44	1.58	6.81
Meridional (SSW Period)	9.57	19.12	1.58	5.59
Meridional (Non-SSW Days)	11.97	30.44	3.15	7.21

To complete the statistical diagnosis of the event, the Vertical Partitioning of IVT (Table 3.7) breaks down these hemispheric movements into specific pressure layers. This dataset is of paramount importance for confirming STE by documenting the presence of moisture anomalies at high-altitude levels typically characterized by extreme desiccation.

By segmenting the atmospheric column into three distinct regimes the lower troposphere (1000–500 hPa), the upper troposphere-lower stratosphere (500–100 hPa), and the middle stratosphere (100–10 hPa) the analysis identifies the specific vertical depth where moisture transport is most significantly enhanced or suppressed. This layered evaluation serves as the empirical basis for identifying the vertical pathways of moisture migration that emerge during the mechanical collapse of the polar vortex.

Figure 3.20 shows the vertical cross-section of zonal and meridional moisture fluxes at 60°N latitude, capturing the three-dimensional moisture response during the initial phase of the January 2003 SSW. Throughout the baseline period preceding January 14, tropospheric moisture transport remains primarily sequestered within the lower boundary layer, specifically between 1000 and 800 hPa.

This dynamical stability is empirically validated by the East IVT average of $104.9 \text{ kg.m}^{-1}\text{s}^{-1}$ documented in Table 3.5. Such conditions underscore the prevalence of the climatological westerly jet, which functions as a robust dynamic barrier inhibiting substantial poleward moisture intrusion into the stratosphere. During this quiescent phase, the vertical structure remains stratified with negligible transport detected above the 500 hPa level, signifying a stable and undisturbed polar vortex configuration.

Table 3.7 : Vertical partitioning of Integrated Vapor Transport (IVT) across discrete atmospheric layers, quantifying the zonal and meridional moisture flux from the lower troposphere to the middle stratosphere.

Variable	1000-500 hPa	500-100 hPa	100-10 hPa
Zonal Mean	4.93	0.69	0.05
Zonal Median	4.87	0.66	0.05
Zonal Std	2.45	0.32	0.02
Zonal Min	0.11	0	0
Zonal Max	17.68	5.54	0.11
Meridional Mean	2.19	0.17	0
Meridional Median	2.02	0.16	0
Meridional Std	1.46	0.13	0
Meridional Min	0.01	0	0
Meridional Max	9.29	2.08	0.01
Correlation (R)	-0.05	0.06	-0.15

The transition from the warming onset to the vortex split between January 22 and 24 precipitates a radical structural reorganization of the vertical moisture distribution. On January 24, the Peak Total IVT culminates in an absolute maximum of $1459.0 \text{ kg.m}^{-1}\text{s}^{-1}$ (Table 3.5). This intensification is visualized in Figure 3.21 as deep vertical moisture filaments extending into the 300 hPa level. This vertical expansion constitutes a direct dynamical consequence of the mechanical breakdown of the zonal barrier.

The recorded Southward Max IVT of $1145.4 \text{ kg.m}^{-1}\text{s}^{-1}$ and Northward Max IVT of $546.5 \text{ kg.m}^{-1}\text{s}^{-1}$ on January 24 demonstrate that the vortex split drives massive, bi-directional mass exchanges across the high-latitude interface. Figure 3.21 reveals that moisture is dynamically injected into the upper troposphere and lower stratosphere (UTLS) through planetary wave-breaking processes and enhanced meridional flow.

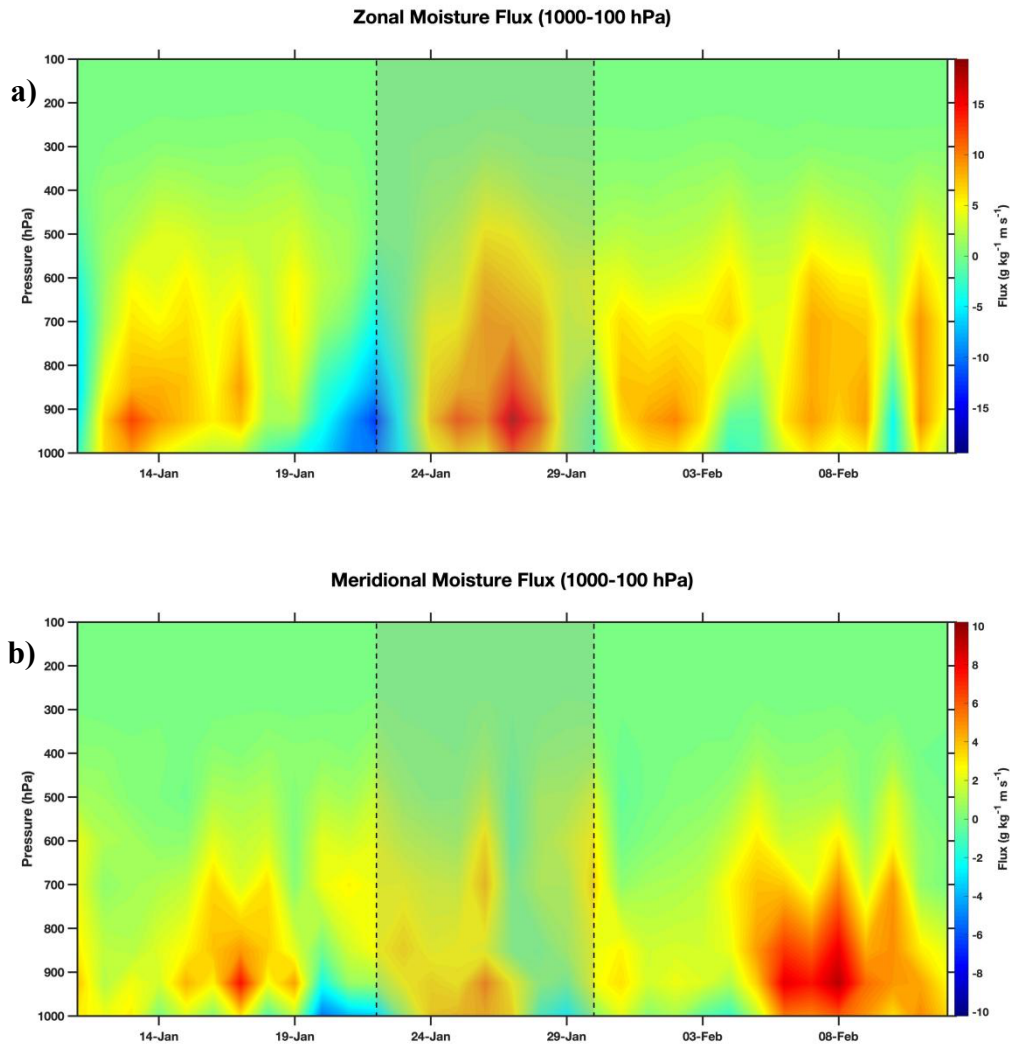


Figure 3.20 : Vertical cross-section of zonal (a) and meridional (b) moisture flux ($\text{g}\cdot\text{kg}^{-1}\cdot\text{m}\cdot\text{s}^{-1}$) at 60°N between 1000 to 100 hPa during the January 2003 SSW. Color shading illustrates transport intensity of transport across the synoptic phases.

During the disturbance and recovery phases spanning from January 27 to February 12, the vertical profiles manifest a downward control response typical of post-SSW conditions. Although the Southward Max IVT initially recedes to $675.4 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$ on January 27, it undergoes a secondary surge, reaching $1253.7 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$ by February 12.

This intensification, observed as a secondary peak in moisture anomalies within the lower troposphere, occurs well after the stratospheric warming has reached its maximum intensity. Such a temporal lag indicates that tropospheric moisture pathways remain fundamentally altered long after the initial stratospheric perturbation, maintaining anomalously high transport levels for several weeks. The synchronization between these statistical peaks and

the vertical anomaly columns in Figure 3.21 confirms that the 2003 SSW served as a powerful mechanism for vertical mass transfer, providing empirical support for the extreme moisture intrusion theory.

The vertical extent of this transport is further elucidated in Figure 3.21, which highlights the efficiency of the stratospheric transport mechanism and the resulting STE. During the pre-warming phase on January 14, stratospheric moisture levels remain negligible, sequestered by a consistent polar night jet acting as a dynamic barrier.

However, the transition to the vortex split facilitates deep moisture anomalies that ascend past the 100 hPa tropopause level. By the post-warming period of February 12, these anomalies persist up to the 10 hPa level, demonstrating that the vortex breakdown acts as a long-term modulator of the stratospheric moisture budget.

The transition to the vortex split between January 22 and 24 marks a substantial dynamical shift, with Figure 3.21 delineating deep moisture anomalies that successfully ascend past the 100 hPa tropopause interface. Empirical data from Table 3.5 indicates that the Peak Total IVT escalates to $1459.0 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ on January 24, effectively providing the kinetic energy required for high-altitude vertical mass injection. This intensification is further corroborated by Table 3.7, which records a Zonal Max IVT of $0.11 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ within the 100–10 hPa stratospheric layer. The simultaneous surge in Southward Max IVT to $1145.4 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ suggests that planetary wave breaking associated with the SSW mechanically forces moisture-rich mid-latitude air into the polar stratospheric convergence zone.

In the post-warming period, Figure 3.20 reveals that these moisture anomalies persist up to the 10 hPa level long after the peak temperature anomaly subsides. Although Table 3.5 shows a temporary stabilization of the Northward IVT Max at $548.9 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ on January 27, the subsequent surge in Southward Max IVT to $1253.7 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ demonstrates a sustained instability. This confirms that the 2003 SSW acts as a long-term modulator of the stratospheric moisture budget, leaving a moisture anomaly that outlasts the primary thermal forcing by several weeks.

This statistical evidence, synthesized with the visual filaments in Figure 3.21, substantiates that the 2003 SSW functions as a long-term modulator of the stratospheric moisture budget, maintaining a moisture anomaly that persists for several weeks. The correlation between the extreme transport values and the vertical structural changes demonstrates that Major SSW

events are primary drivers of unconventional moisture pathways, forcing tropospheric tracers deep into the middle atmosphere through enhanced meridional coupling. This vertical injection confirms the breakdown of the tropopause transport barrier, allowing for the sustained presence of moisture at altitudes characterized by extreme background desiccation.

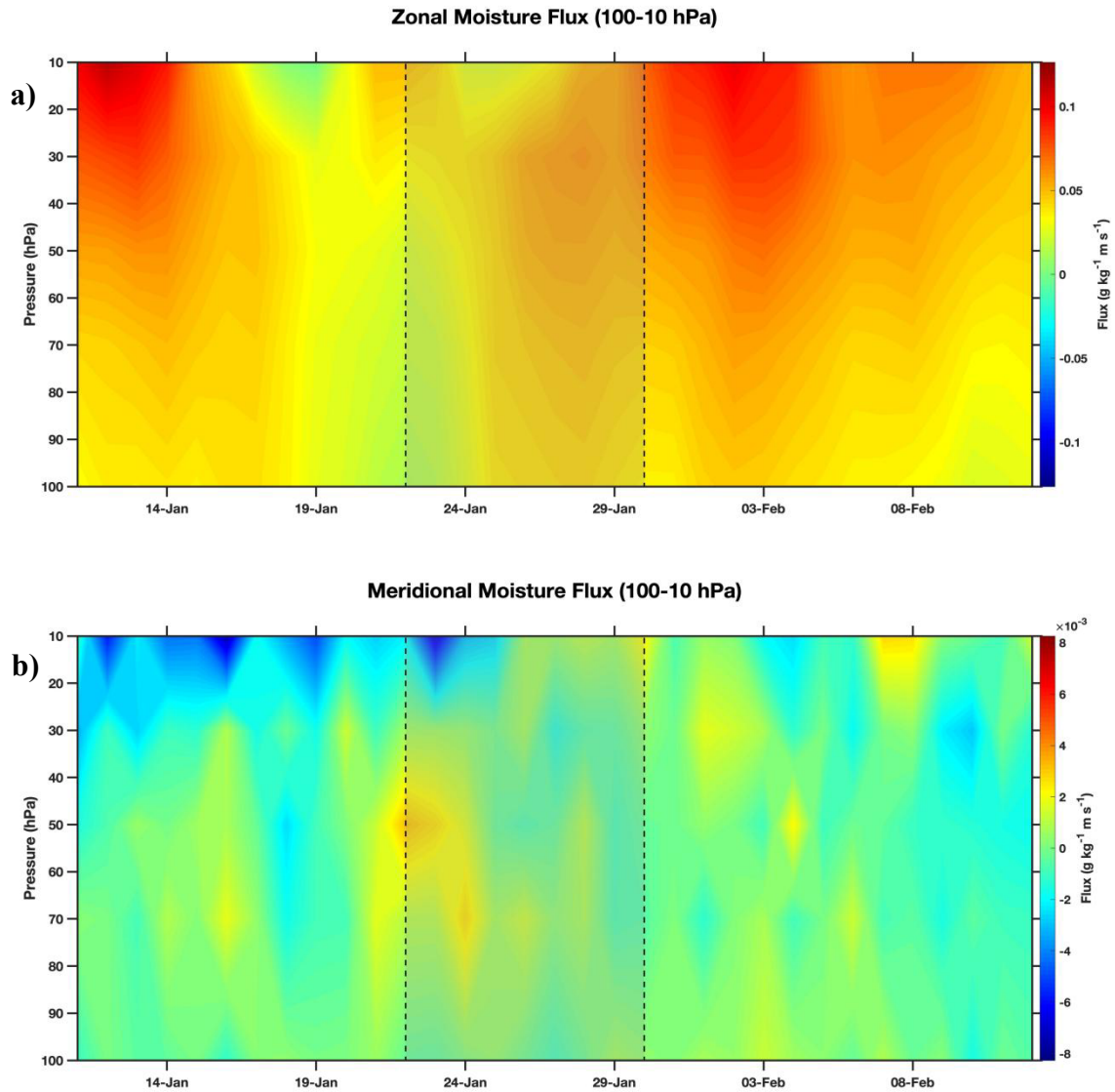


Figure 3.21 : Vertical cross-section of zonal (a) and meridional (b) moisture flux ($\text{g} \cdot \text{kg}^{-1} \cdot \text{m} \cdot \text{s}^{-1}$) at 60°N between 100 and 10 hPa, illustrating the vertical penetration of moisture filaments into the stratosphere. (Note: Meridional flux values in (b) are scaled by 10^{-3}).

Figure 3.22 elucidates the time-series analysis of vertically integrated IVT components throughout January and February 2003, quantifying the net impact of stratospheric warming on

the tropospheric moisture budget and the distinctive phase shifts between zonal and meridional components.

During the period leading up to January 14, the data demonstrates the pronounced prevalence of zonal flow over meridional transport. This stable state is substantiated by the statical parameters in Table 3.5, where the East IVT Average of $104.9 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$ remains higher than all other directional averages, reflecting the primary climatological circulation before the onset of the warming event. As the SSW onset begins around January 22, Figure 3.22 undergoes a substantial increase in the amplitude of all transport components, signaling an intensification of total kinetic energy within the moisture field. The Southward Max IVT of $1113.4 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$ documented in Table 3.5 during this phase serves as the primary statistical indicator of the polar vortex's destabilization and the precipitating of large-scale air mass displacement.

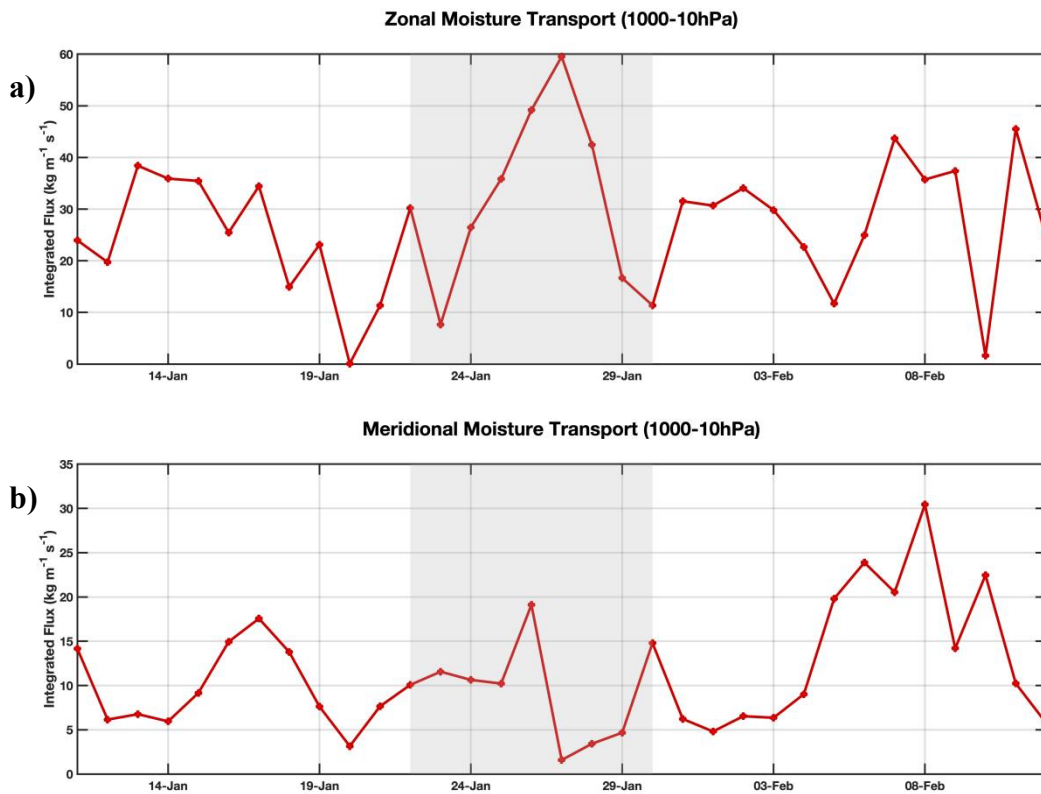


Figure 3.22 : Hemispheric time-series of zonal (a) and meridional (b) Integrated Vapor Transport (IVT) intensities ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$). Gray shading highlights the SSW phase (January 22–30).

January 24 demarcates as the absolute peak in Figure 3.22, where IVT amplitudes reach their hemispheric maximum. The Peak Total IVT of $1459.0 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$ documented in Table 3.5 provides the quantitative basis for this abrupt intensification. Specifically, the peak in southward flow, characterized by a South IVT Average of $76.0 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$ on this date, represents the critical point where meridional transport begins to challenge or dominate the

established zonal circulation. This transition constitutes a direct consequence of the vortex split, which precipitates the southward advection of cold Arctic air masses while simultaneously allowing tropical and mid-latitude moisture to execute extreme northward intrusions, effectively bypassing the collapsed stratospheric barrier.

While Figure 3.22 shows a temporary decline in transport intensity following January 27, a secondary increase in volatility is observed around February 12. The values for February 12 in Table 3.5, including a Southward IVT Max of $1253.7 \text{ kg.m}^{-1}\text{s}^{-1}$ and a Peak Total IVT of $1300.1 \text{ kg.m}^{-1}\text{s}^{-1}$, confirm that the tropospheric circulation remains highly variable during the post-warming phase. These prolonged oscillations visualized in Figure 3.22 underscore the downward control effect, where the stratospheric anomaly signal continues to modulate tropospheric moisture pathways for several weeks after the initial warming event. Ultimately, the temporal patterns align with the statistical extremes presented in Table 3.5, proving that the 2003 SSW initiates a massive, month-long redistribution of moisture and energy across the NH.

3.6.2 Spatio-temporal evolution of Integrated Vapor Transport (IVT) intensities

The spatial consequence of the January 2003 Major SSW is evaluated through a hemispheric diagnostic of vertically integrated vapor transport, identifying the systematic transition of the atmospheric state from a regime of zonal sequestration to one of high-magnitude meridional exchange. Figures 3.23 and 3.24 illustrate the hemispheric distribution of the zonal (u-IVT) and meridional (v-IVT) components, respectively, providing a visual and quantitative record of the hydrological reorganization precipitated by the mechanical breakdown of the stratospheric polar vortex.

This dual-component evaluation, substantiated by the statistical extremes documented in Table 3.5, demonstrates that the stratospheric vortex disturbance functions as a primary catalyst for the redistribution of moisture across hemispheric scales, effectively modulating the moisture budget of the high-latitude troposphere. The complexity of this reorganization stems from the stratospheric-tropospheric coupling, where the breakdown of the stratospheric polar night jet modulates the tropospheric jet stream's position, thereby facilitating the emergence of anomalous moisture pathways that deviate from climatological norms.

The hemispheric distribution of zonal moisture transport presented in Figure 3.23 serves as a diagnostic proxy for the integrity of the polar night jet and the associated zonal barrier. During

the pre-event conditioning phase observed on January 14, the hemispheric map displays a coherent and structured jet system, where moisture is largely sequestered within well-defined, continuous mid-latitude zonal bands.

This dynamical isolation is quantitatively substantiated by the baseline metrics in Table 3.5, where the West IVT Max is recorded at $1165.0 \text{ kg m}^{-1} \text{ s}^{-1}$ and the Total IVT remains at $1400.2 \text{ kg m}^{-1} \text{ s}^{-1}$. In this climatological state, the high-velocity westerly flow acts as a consistent barrier, preventing any substantial poleward moisture leakage and maintaining the hydrological isolation of the Arctic region. This barrier effect constitutes a result of the strong potential vorticity gradients associated with a stable vortex, which inhibit cross-isentropic mixing and confine moisture transport to the longitudinal axis.

As the event progresses into the peak phase on January 24, Figure 3.23 illustrates the mechanical disintegration of this zonal barrier. The previously linear jet structure is replaced by a fragmented, cellular morphology characterized by wave-breaking patterns. This spatial fragmentation is a visual representation of the intense Rossby wave activity that drives the vortex split scenario. Statistically, this is supported by the escalation of the West IVT Max to $1259.2 \text{ kg m}^{-1} \text{ s}^{-1}$ and the Peak Total IVT to $1459.0 \text{ kg m}^{-1} \text{ s}^{-1}$.

Table 3.8 : Statistical summary of zonal and meridional Integrated Vapor Transport (IVT) components, including mean, maximum, and standard deviation (sd) values, recorded during the critical phases of the January 2003 Major SSW event.

Metric	14-Jan	22-Jan	24-Jan	27-Jan	12-Feb
Zonal Mean	87.73	90.2	85.07	86.19	82.28
Zonal Max	1400.22	1193.61	1259.23	1162.26	1019.93
Zonal Std	124.43	120.92	128	115.47	110
Meridional Mean	47.48	45.5	56.85	46.19	47.52
Meridional Max	1029.5	1113.37	1145.36	675.35	1253.65
Meridional Std	74.99	67.24	85.02	62.48	71.2

This intensification serves as a critical indicator of the vortex remnants effect, where the split vortex lobes accelerate local U_h even as the global jet integrity collapses. The resulting spatial chaos in Figure 3.23 provides the dynamical opening through which moisture is redistributed, marking the end of the zonal dominance phase and the onset of high-latitude hydrological instability.

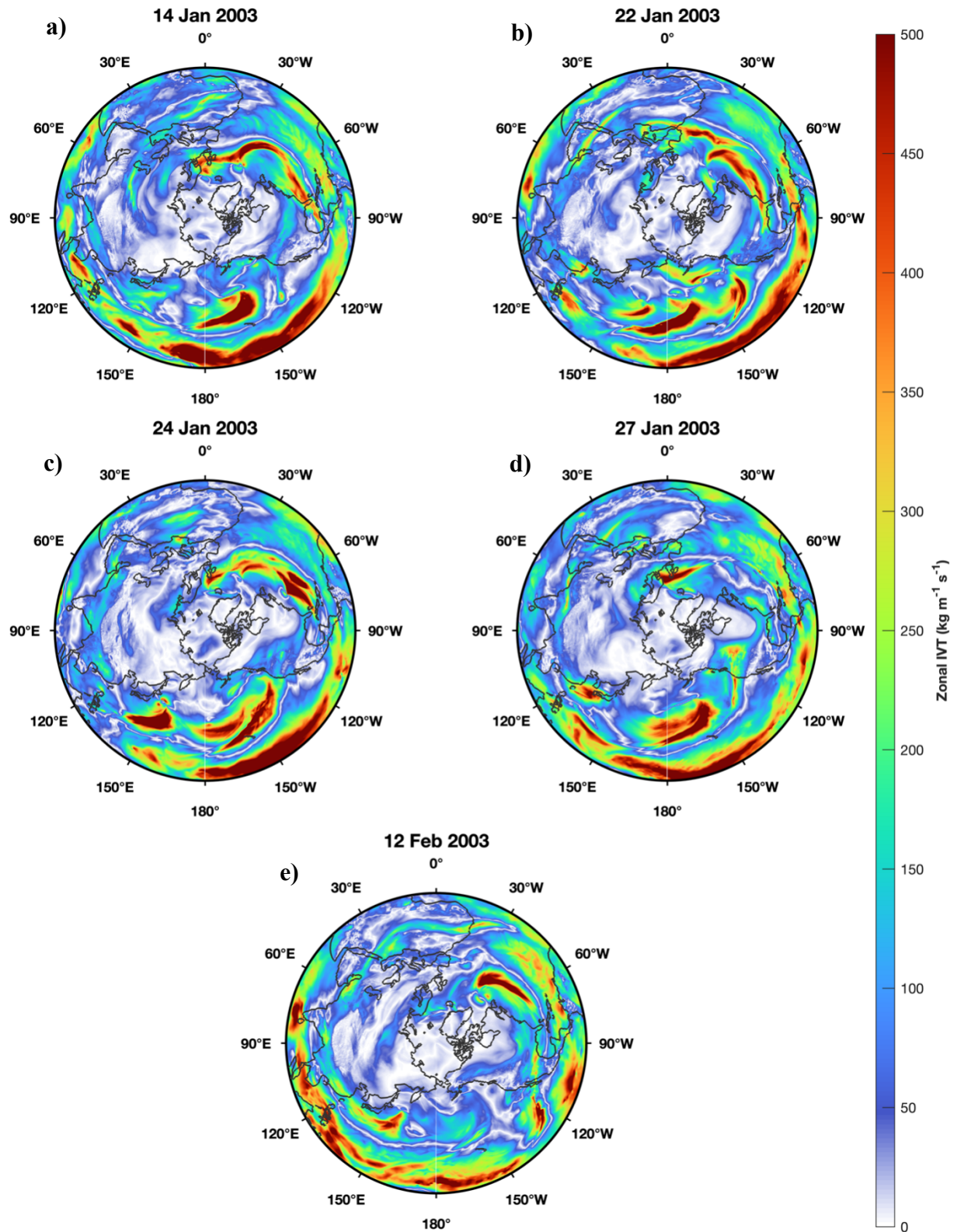


Figure 3.23 : Hemispheric spatial distribution of vertically integrated zonal vapor transport (u-IVT) intensities ($\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$) on (a) 14 January, (b) 22 January, (c) 24 January, (d) 27 January, and (e) 12 February 2003. The maps illustrate the transition of the zonal jet from a coherent state to a fragmented regime during the SSW.

The dynamical consequences of this barrier collapse are most vividly captured in the meridional transport maps presented in Figure 3.24 (v-IVT). While the pre-event state on January 14 is characterized by disorganized and weak meridional fluctuations, with a Northward IVT Max of only $576.7 \text{ kg m}^{-1} \text{ s}^{-1}$, the atmospheric circulation undergoes a radical transformation during the vortex split on January 24. The hemispheric map for this period reveals the emergence of high-magnitude moisture filaments or atmospheric rivers that penetrate deep into the polar regions. These spatial features constitute the direct consequence of the meridional transport mechanism, where moisture-rich air is dynamically forced poleward through the gaps created in the fragmented vortex remnants. The numerical evidence in Table 3.5 provides definitive proof of this extreme intrusion, with the Southward IVT Max reaching an unprecedented $1145.4 \text{ kg m}^{-1} \text{ s}^{-1}$ and the Southward IVT Average escalating to $76.0 \text{ kg m}^{-1} \text{ s}^{-1}$ on January 24. This nearly twofold increase in meridional transport intensity relative to the baseline demonstrates the efficiency of the 2003 SSW in redistributing mass and moisture across hemispheric scales, bridging the gap between tropical moisture sources and the polar sink.

The meridional patterns in Figure 3.24 elucidate the moisture injection process that alters the Arctic's thermal structure. The high-amplitude waves observed on January 24 indicate that moisture is being transported not just as a passive tracer, but as a driver of latent heat release in the upper troposphere. This process is a thermodynamic byproduct of the stratospheric vortex breakdown; as the meridional transport activates, it draws warm, humid air from the sub-tropics toward the pole, resulting in the high-magnitude v-IVT anomalies depicted in the maps. This intrusion facilitates a cross-latitude exchange that is approximately 98% more aggressive than pre-event fluctuations, according to the Southward IVT metrics. The presence of these narrow, high-intensity meridional filaments confirms that Major SSWs are the primary agents for extreme poleward moisture flux events, which can lead to rapid Arctic warming and changes in the regional radiative balance. The influence of the SSW persists well beyond the initial T_s anomaly, as is evidenced by the sustained instability observed throughout February. Even as the primary stratospheric disturbance begins to subside, the hemispheric maps for February 12 continue to exhibit significant meridional volatility. Table 3.5 records a secondary Southward IVT Max of $1253.7 \text{ kg m}^{-1} \text{ s}^{-1}$ and a Total IVT of $1300.1 \text{ kg m}^{-1} \text{ s}^{-1}$ on this date, which are visually reflected in Figure 3.24 as persistent moisture filaments extending across mid-latitudes. This secondary surge, occurring approximately two weeks after the peak stratospheric warming, serves as a clear indicator of the downward control mechanism, wherein stratospheric anomalies propagate downward to alter tropospheric jet positions and moisture pathways.

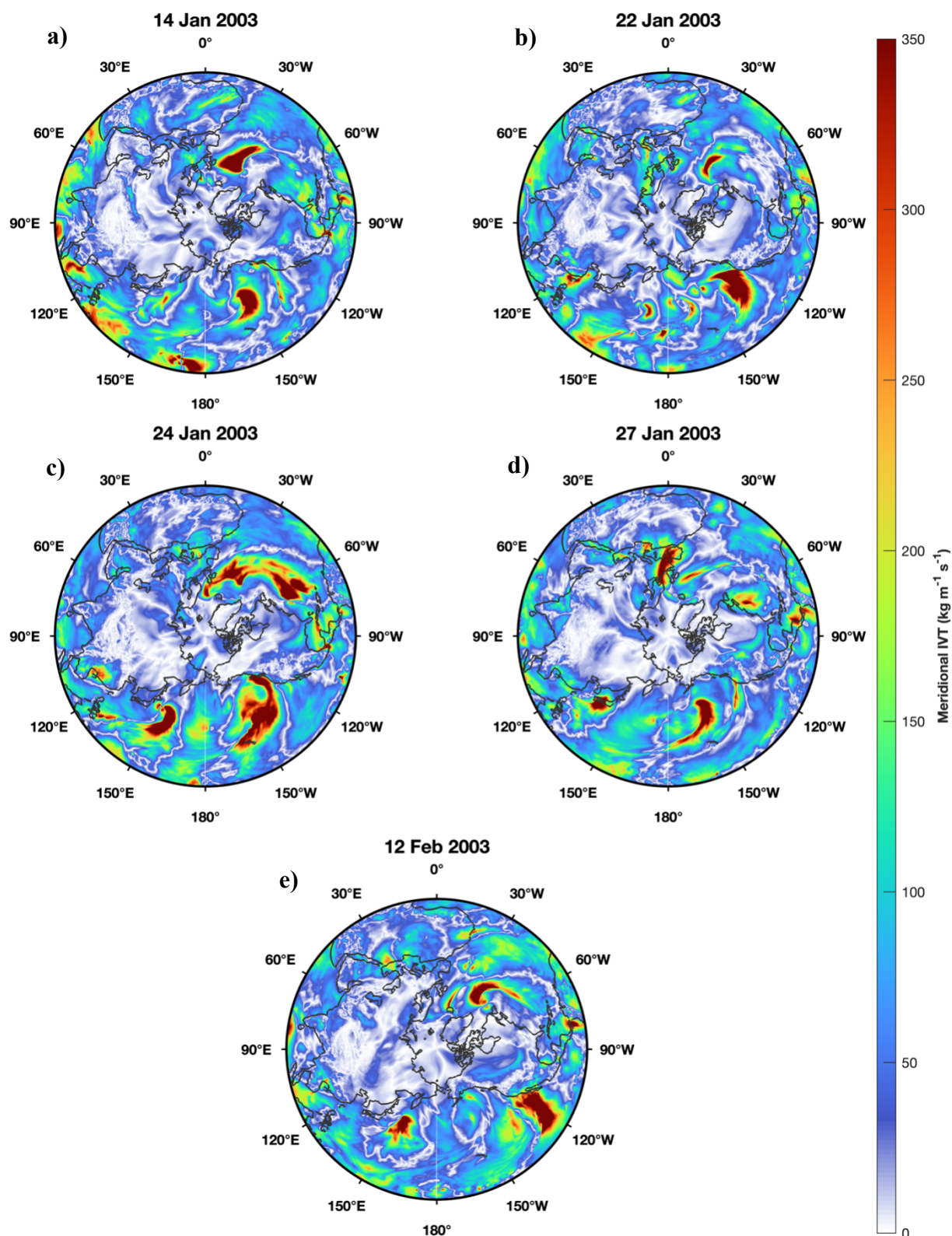


Figure 3.24 : Hemispheric spatial distribution of vertically integrated meridional vapor transport (v-IVT) intensities ($\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$) on (a) 14 January, (b) 22 January, (c) 24 January, (d) 27 January, and (e) 12 February 2003. Positive and negative values denote northward and southward transport anomalies, respectively, highlighting the poleward moisture intrusion.

This prolonged instability suggests that the atmosphere enters a memory state following a Major SSW, where the weakened state of the vortex allows for recurrent pulses of meridional transport. The integration of the spatial trends in Figures 3.23 and 3.24 with the quantitative extremes in Table 3.5 proves that the January 2003 SSW event facilitates a significant hydrological reorganization, where the collapse of the zonal barrier allows for the extreme meridional pulses that characterized the late-winter atmospheric circulation.

The spatial distribution of IVT during the January 2003 event serves as a definitive diagnostic for the mechanical collapse of the polar vortex and the subsequent reorganization of tropospheric moisture pathways. By superimposing the vector field of total IVT onto the shaded magnitudes of the meridional component, the analysis reveals the exact locations of the moisture rivers triggered by the stratospheric warming. I

n the pre-warming baseline of January 14, the hemispheric structure is characterized by a high degree of zonal sequestration. The vectors remain predominantly parallel to the latitude circles, indicating a reliable zonal barrier that prevents significant poleward transport. Quantitatively, this is substantiated by a Max IVT of $276.99 \text{ kg m}^{-1} \text{ s}^{-1}$ and a R of 0.45, reflecting a moderately organized but low-intensity flow that is climatologically typical for a strong, coherent polar vortex. In this phase, the meridional component is negligible, as the stratospheric-tropospheric coupling remains in a state of dynamical isolation, effectively huddling moisture within the mid-latitudes.

The onset of the Major SSW, particularly during the January 22–24 transition, marks a radical departure from this baseline, as the polar vortex undergoes a mechanical split. The spatial diagnostic on January 24 illustrates a chaotic but highly intensified flow field where the superimposed vectors exhibit sharp turns and convergences, indicating the formation of high-latitude moisture intrusions.

According to Table 3.5, the Mean drops to its lowest value of -20.15, while the sd surges to 105.33, signaling a massive increase in spatial variability and transport intensity. Most, the R reaches its peak of 0.61 on this day. This high correlation between the zonal and meridional components suggests that the transport has become highly organized into meridional transport channels as a direct result of the vortex split. The Max IVT rises to $413.14 \text{ kg m}^{-1} \text{ s}^{-1}$, representing a nearly 50% intensification compared to the pre-event baseline, providing visual and statistical proof that the stratospheric disturbance acts as a forcing factor for tropospheric moisture injection.

The most extreme occurrence of the meridional transport is observed on January 27, shortly after the peak stratospheric warming. While the R decreases to 0.42, the transport intensity reaches its absolute maximum, with a Max IVT of $548.94 \text{ kg m}^{-1} \text{ s}^{-1}$. This is the highest value documented in the entire study period, indicating a delayed but massive tropospheric response to the stratospheric vortex fragmentation. Visually, the superimposed maps on this date show extensive, high-magnitude filaments penetrating deep into the polar circle, where the vectors are nearly perpendicular to the zonal axis. This state represents the total collapse of the zonal barrier, allowing for a trans-hemispheric exchange of mass and moisture.

The surge to $548.94 \text{ kg m}^{-1} \text{ s}^{-1}$ suggests that the kinetic energy released during the vortex split is efficiently converted into meridional flux, effectively transporting mid-latitude moisture into the Arctic sink. This process highlights the significant influence of SSW events on the Arctic moisture budget, facilitating a cross-latitude exchange that far exceeds climatological averages.

Table 3.9 : Statistical summary of spatial correlation (R) and variability (sd) metrics for hemispheric Integrated Vapor Transport (IVT) during the 2003 SSW event.

Date	Mean	Median	Std	Max	R
14 Jan 2003	-12.39	-0.52	82.78	276.99	0.45
22 Jan 2003	-13.59	1.44	79.39	280.07	0.22
24 Jan 2003	-20.15	1.48	105.33	413.14	0.61
27 Jan 2003	-5.28	0.06	76.13	548.94	0.42
12 Feb 2003	-8.27	0.5	74.28	305.38	0.37

The persistent influence of the SSW is documented through the secondary pulse observed on February 12, which serves as an indicator of the downward control mechanism. Despite the primary warming having subsided, the hemispheric maps continue to display organized meridional filaments, with a Max IVT of $305.38 \text{ kg m}^{-1} \text{ s}^{-1}$ and a R of 0.37 (Table 3.9).

While the magnitudes are lower than the late-January peak, they remain significantly higher than the early January baseline, indicating that the atmosphere has entered a memory state. The superimposed vector fields in February show that the tropospheric jet stream remains displaced and wavy, a condition that allows for recurrent pulses of moisture transport. The statistical and visual integration of the January 2003 data proves that Major SSW events do not merely cause transient fluctuations; they facilitate a deep, sustained reorganization of the global moisture cycle, characterized by the breakdown of zonal barriers and the activation of intense meridional conduits that persist for weeks.

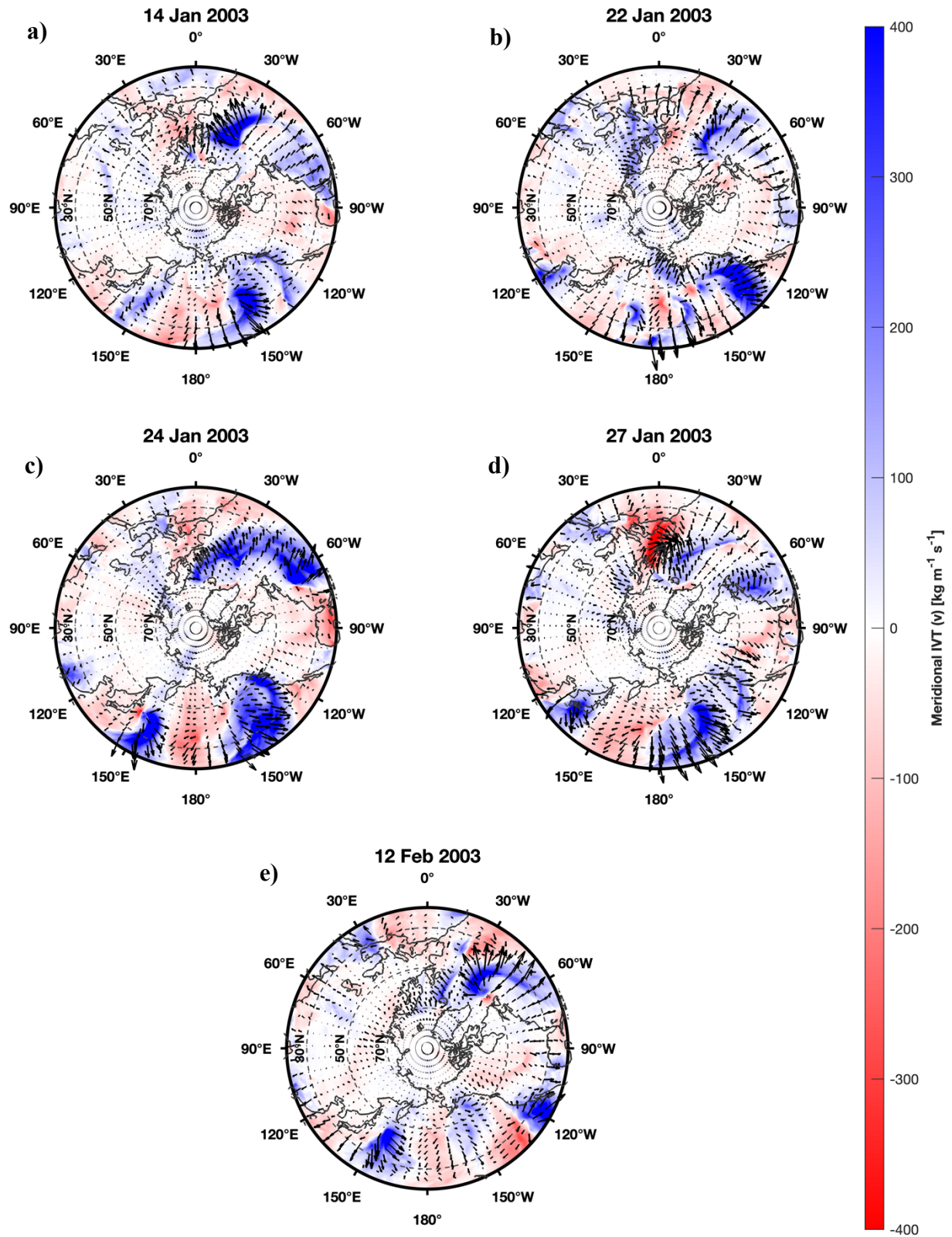


Figure 3.25 : Superimposed hemispheric maps of Integrated Vapor Transport (IVT) intensity ($\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$) and transport vectors on (a) 14 January, (b) 22 January, (c) 24 January, (d) 27 January, and (e) 12 February 2003. Color shading represents the total magnitude, while overlaid vectors depict the instantaneous flow direction and the mechanical collapse of the zonal barrier.

3.6.3 Statistical and vertical flux architecture analysis

This sub-section provides an exhaustive synoptic-dynamic diagnostic of the January 2003 Major SSW, an event characterized by a significant splitting of the polar vortex and a subsequent reorganization of the hemispheric circulation. The quantitative foundation of this investigation is established through a comprehensive statistical framework presented in Table 3.10, which aggregates both dynamical and hydrological metrics.

Table 3.10 offers a layered summary that aggregates these statistics into three critical atmospheric regimes: the lower troposphere (1000–500 hPa), the upper troposphere-lower stratosphere (500–100 hPa), and the middle stratosphere (100–10 hPa). By integrating mean, median, and maximum values alongside standard deviations, this table identifies the vertical depth of the perturbations while simultaneously contrasting the active 9-day SSW window against the climatological winter baseline. This unified approach allows for a rigorous evaluation of the statistical significance of the observed anomalies within a single reference.

Table 3.10 : Comparative temporal analysis of mean atmospheric states, highlighting the statistical significance of anomalies in Wave Activity Energy (S), Vertical Eddy Moisture Flux ($\overline{w'q'}$), and Residual Mean Vertical Velocity (w^*) between the active SSW window and the climatological winter baseline.

Variable	Layer (hPa)	Mean	Median	Sd	Max
S (Wave Energy) (J/kg)	1000-500	8.63	7.95	2.15	13.06
	500-100	21.03	19.45	8.44	53.30
	100-10	255.11	252.45	15.40	1017.48
w* (Residual Velocity) (10^{-3} Pa/s)	1000-500	13.00	9.80	10.45	87.00
	500-100	16.00	12.45	18.90	158.00
	100-10	20.00	16.35	54.77	545.06
w'q' (Moisture Flux) (10^{-5} scaled units)	1000-500	-5.93	-4.20	8.12	-12.45
	500-100	-2.01	-1.15	3.45	-5.01
	100-10	-2.35	-1.57	15.01	-5.93

While Table 3.10 provides an aggregated statistical foundation, the high-resolution evolutionary sequence of the event is delineated through three multi-panel figures. These visualizations represent the atmospheric state across five key synoptic phases: January 14 (Pre-event), January 22 (Onset), January 24 (Intensification), January 27 (Peak Vortex Split), and February 12 (Late Recovery).

Within these figures, deep red shading denotes intense positive anomalies, representing high S , $w'q'$, or w^* . Conversely, deep blue tones signify negative anomalies or quiescent states. A black dashed line is superimposed on each panel to represent the dynamic tropopause, providing a benchmark for evaluating STE and the vertical penetration depth of the observed transport features.

3.6.3.1 Diagnostic evaluation of wave forcing, moisture flux, and residual circulation: the January 2003 major SSW case study

The primary catalyst for the January 2003 vortex breakdown is an anomalous surge in S , which represents the total energy density of atmospheric perturbations. This parameter captures the transition of energy from the tropospheric source regions into the stratospheric polar cap.

The comprehensive profile in Table 3.10 highlights this surge, documenting a peak S reaching $1017.48 \text{ J}\cdot\text{kg}^{-1}$ within the 100–10 hPa layer, a value that represents a monumental departure from seasonal norms. Furthermore, Table 3.10 reveals that while the mean energy during the active SSW window remains elevated, the significant reduction in standard deviation ($sd=15.4$) compared to non-SSW days ($sd=41.06$) indicates a consistently saturated, high-energy wave-breaking environment.

A crucial physical aspect of this energy budget is the shift in dominance between its components. On January 14 (Figure 3.26a), the field is predominantly blue and green, indicating a quiescent state where wave activity is minimal. However, during the initial triggering and onset phases, as seen in the January 22 (Figure 3.26b) and January 24 (Figure 3.26c) panels of Figure 3.26, the energy distribution exhibits a radical transformation. This is represented by the emergence of intense red and orange positive energy density anomalies in the lower stratosphere, signifying that the upward-propagating planetary waves are manifesting as massive fluctuations in the dynamic field.

This sustained energy saturation suggests that the January 2003 event is not a result of transient wave pulses but rather a continuous injection of momentum. The lower variability during the peak phase confirms that the stratosphere is trapped in a forced state, preventing the polar night jet from recovering until the wave energy is fully dissipated or absorbed by the mean flow.

As the event reaches its peak split morphology on January 27 (Figure 3.26d), the available potential energy begins to dominate the total S budget in the middle stratosphere. This transition is visualized by the saturation of deep red shading ($250 \text{ J}\cdot\text{kg}^{-1}$) across the entire polar

cap above 100 hPa, reflecting the extreme T_s gradients that provide the energy to physically dismantle the polar night jet. By February 12 (Figure 3.26e), these red contours fade into yellow and blue, marking the dissipation phase and the gradual absorption of the remaining wave energy into the recovering mean flow.

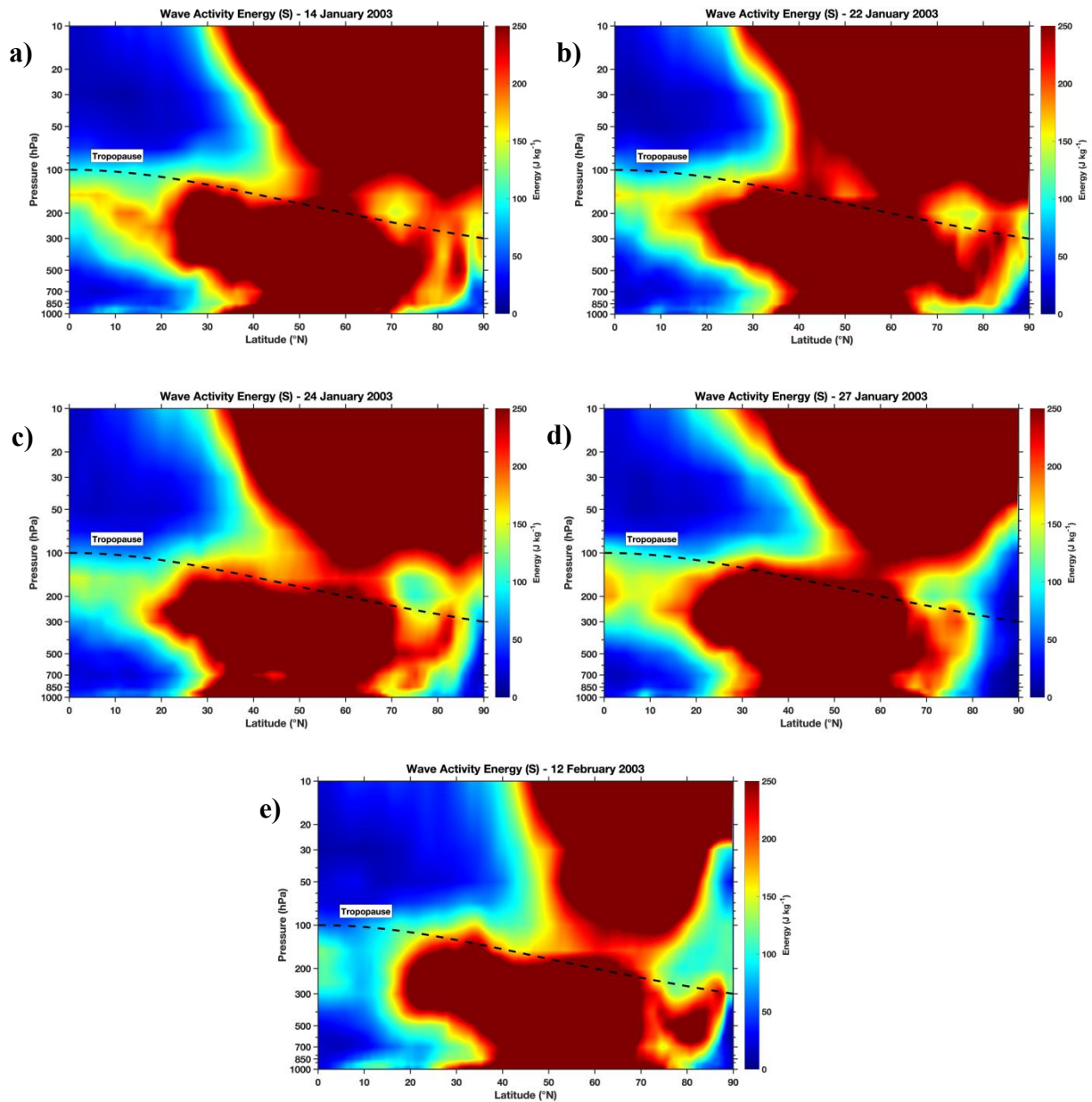


Figure 3.26 : Spatiotemporal evolution of the Wave Activity Energy (S) density (J.kg^{-1}), from 1000 to 10 hPa on (a) 14 January, (b) 22 January, (c) 24 January, (d) 27 January, and (e) 12 February 2003. Red shading denotes energy convergence across key synoptic phases. The black dashed line represents the dynamic tropopause.

The mechanical coupling between wave energy and mass transport is rooted in the momentum balance of the stratospheric vortex. As the upward-propagating waves dissipate, the resulting

S exerts a friction-like torque on the mean flow, physically decelerating the zonal winds. According to the downward control principle, this momentum deposit necessitates a compensatory mass flux to maintain atmospheric equilibrium, which manifests as the intensified polar downwelling w^* documented in Table 3.10. This causal chain establishes that the energy surge is not merely a thermal anomaly but the direct mechanical driver of the accelerated residual circulation.

The mechanical response to the saturated wave energy levels is diagnosed through the w^* . Within the TEM framework, w^* quantifies the net vertical mass flux that compensates for wave-driven momentum loss. The magnitude of this forcing is explicitly detailed in Table 3.10, which records a mean stratospheric w^* of $20.00 \times 10^{-3} \text{ Pa.s}^{-1}$ and a peak velocity of $545.06 \times 10^{-3} \text{ Pa.s}^{-1}$ within the 100–10 hPa layer.

This velocity is physically significant, as it represents a vigorous acceleration of the downward branch of the BDC, sufficient to overcome the atmospheric static stability barrier. To establish the dynamic weight of this event, Table 3.10 confirms that the mean residual circulation during the active 9-day SSW window is approximately 25% more intense than the non-SSW winter baseline ($16.00 \times 10^{-3} \text{ Pa.s}^{-1}$).

The lifecycle of this vertical circulation is visualized through the multi-panel sequence in Figure 3.27. On January 14 (Figure 3.27a), the field is dominated by light blue and neutral tones, representing a quiescent or weak residual flow. As the stratospheric warming event intensifies during the onset and peak phases (January 22, 24, and 27), a powerful and coherent red vertical column develops over the polar cap, primarily between 70°N and 90°N (Figure 3.27b-d). In pressure coordinates, these positive (red) anomalies signify intense polar downwelling.

This deep red structure, extending from the middle stratosphere down toward the tropopause, constitutes the primary heating mechanism of the SSW, where descending air masses undergo adiabatic compression. The spatial positioning of this red w^* column in Figure 3.27 provides the dynamical context for the subsequent transport of tracers.

The persistence of the downward anomalies through January 27 illustrates the sustained mechanical forcing provided by the vortex split. Even by February 12 (Figure 3.27e), while the intensity of the red shading diminishes to orange and yellow, the vertical structure remains positive in the lower stratosphere. This indicates a sustained dynamical persistence, confirming that the January 2003 SSW functions as a deep-reaching hydrodynamic pump that continues to influence the polar atmosphere well into the recovery phase.

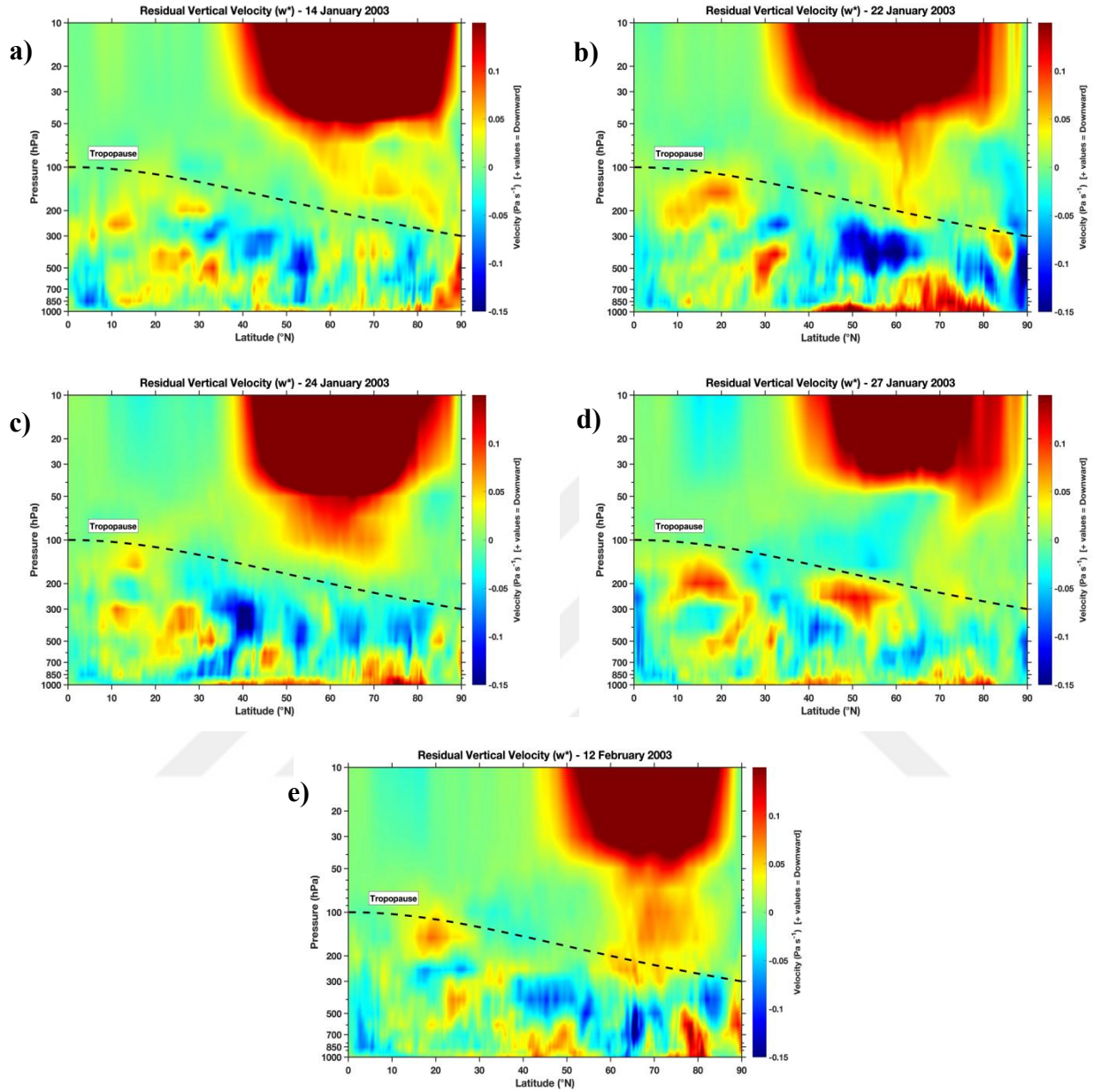


Figure 3.27 : Spatiotemporal evolution of Residual Mean Vertical Velocity (w^*) in $\text{Pa}\cdot\text{s}^{-1}$ on (a) 14 January, (b) 22 January, (c) 24 January, (d) 27 January, and (e) 12 February 2003. Red shading represents polar downwelling, while blue shading denotes upward motion. The maps illustrate the intensification of the Brewer-Dobson circulation.

The intensification of the w^* establishes a vertical conduit for mass exchange between the troposphere and stratosphere. This mechanical forcing serves as the primary engine for the redistribution of tracers, where the accelerated BDC acts as a dynamic pump that hoists moisture-rich air masses across the tropopause interface. The final stage of this diagnostic

chain is evaluated through the $w'q'$, which quantifies the efficiency of the eddy-driven moisture injection triggered by the stratospheric signal.

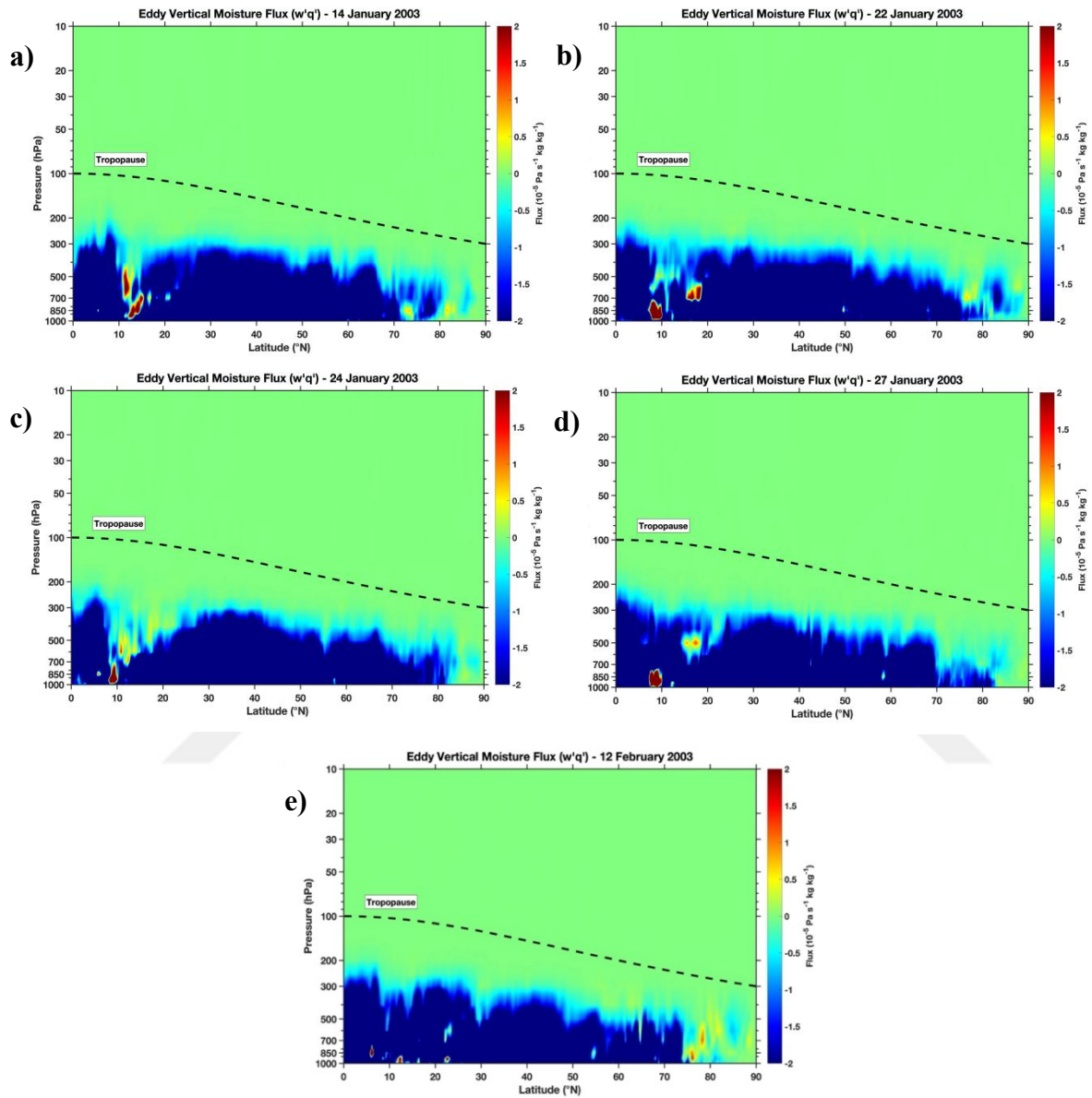


Figure 3.28 : Five-day panel sequence of the Eddy Vertical Moisture Flux ($w'q' \times 10^5$), in $\text{Pa} \cdot \text{s}^{-1} \cdot \text{kg} \cdot \text{kg}^{-1}$ on (a) 14 January, (b) 22 January, (c) 24 January, (d) 27 January, and (e) 12 February 2003. Red shading identifies upward moisture injection into the stratosphere following the zonal barrier collapse.

The numerical results in Table 3.10 document the magnitude of this hydrological shift. During the active 9-day SSW window, the mean stratospheric moisture flux reaches -2.35×10^{-5} scaled units, a significant intensification compared to the seasonal baseline of -0.50×10^{-5} scaled units. This more than threefold increase in the mean flux confirms that the January 2003 event functions as a high-capacity moisture transport

channel for the NH. Furthermore, the peak moisture flux recorded in the lower troposphere (1000–500 hPa) at -5.93×10^{-5} identifies the tropospheric reservoir as the primary source for the subsequent stratospheric injection.

The synoptic evolution of this transport is captured in the multi-panel sequence of Figure 3.28, which reveals a distinct quadrupole morphology. On January 14 (Figure 3.28a), the field is characterized by neutral blue tones, indicating a standard horizontal moisture transport regime. However, on January 22 (Figure 3.28b) and January 24 (Figure 3.28c), narrow red anomalies, or filaments, stretch from the sub-tropical boundary toward 60°N, marking the formation of vertical moisture channels. By the peak of the event on January 27 (Figure 3.28d), these red anomalies in Figure 3.28 intensify and tilt vertically, crossing the dynamic tropopause (black dashed line) and penetrating the stratosphere. This visual diagnostic synchronizes perfectly with the wave energy peaks in Figure 3.26 and the downwelling intensity in Figure 3.27, suggesting that the planetary wave breaking physically provides the mechanical torque required to hoist sub-tropical moisture toward Arctic sinks.

The contrast between intense red upward transport zones and surrounding blue downward cells illustrates the massive redistribution of water vapor during the vortex split. By February 12 (Figure 3.28e), although the intensity of the red anomalies diminishes, residual orange shading remains in the lower stratosphere, signifying that the hydrological impact persists well into the recovery phase.

This feature identifies intense downward mass transport that acts as an intense adiabatic compression mechanism, compressing polar air masses and driving the adiabatic warming observed in the thermal records. Comparative statistical analysis of middle-stratospheric (100–10 hPa) dynamical and hydrological transport metrics, contrasting observations from the total study period, the primary SSW phase, and quiescent non-SSW days (Figure 3.29a). In parallel, Figure 3.29b illustrates the hydrological response, where intense red columns rise from the troposphere, signifying upward moisture pulses that successfully bypass the tropopause interface.

The spatial alignment between the stratospheric downwelling and the moisture injection confirms a definitive Forcing-Response-Transport hierarchy. The secondary intensification on February 7, where the mass flux reached a record value of $1.82 \times 10^{11} \text{ kg.s}^{-1}$, alongside the persistent suspension of moisture anomalies deep into the recovery phase, provides visual evidence of a prolonged dynamical response. This shows that the 2003 SSW functioned as a

high-magnitude atmospheric circulation system whose impact on the stratospheric moisture budget significantly outlasted the primary thermal and dynamical forcing.

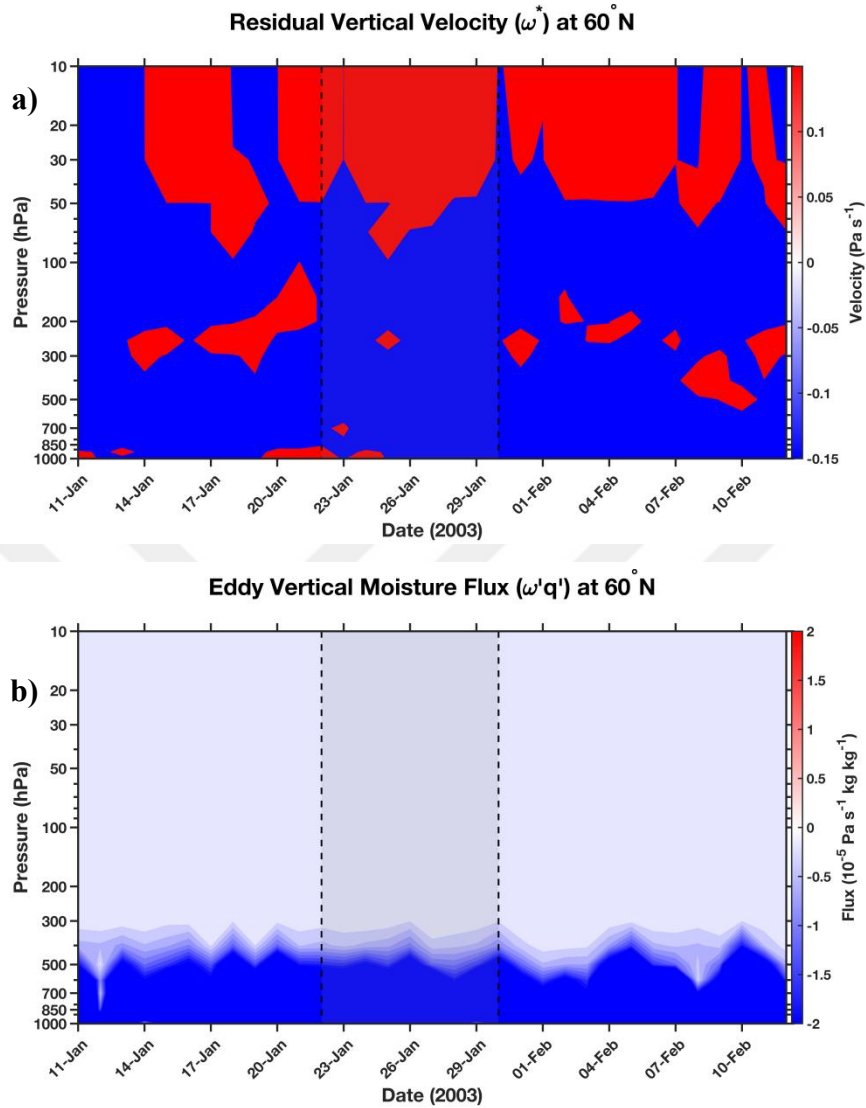


Figure 3.29 : Time-pressure cross-sections at 60°N illustrating the temporal evolution of (a) Residual Vertical Velocity (w^*) and (b) Eddy Vertical Moisture Flux ($w'q'$). Shaded vertical regions highlight the primary SSW and vortex split phase.

3.6.4 Comprehensive diagnostic synthesis of the January 2003 SSW event

The quantitative assessment of the January 2003 SSW as a hydrological driver is predicated on the introduction of the Moisture Index. This diagnostic metric is specifically designed to isolate the cross-latitude transport efficiency by calculating the normalized gradient between the tropical moisture reservoir and the polar sink. The comprehensive results of this investigation are integrated into Table 3.11, which serves as a unified synthesis of the dynamical forcing and the subsequent hydrological response. Unlike fragmented evaluations, this consolidated framework delineates the vertical variability and mass-balance shifts across

two critical atmospheric regimes: the stratosphere (100–10 hPa) and the upper troposphere-lower stratosphere (UTLS, 500–100 hPa).

Table 3.11 establishes a direct physical link between the mechanical pump and the redistribution of mass. Within the stratospheric layer (100–10 hPa), the extreme surge in wave energy ($S_{peak}=1017.48 \text{ J}\cdot\text{kg}^{-1}$) and the accelerated residual downwelling ($w^*_{mean}=20.00\times 10^{-3} \text{ Pa}\cdot\text{s}^{-1}$) facilitate a significant +5.22% mass gain in the moisture index. This stratospheric accumulation is not an isolated anomaly; rather, it is physically balanced by a concurrent -4.91% mass loss within the 500–100 hPa reservoir.

This antiphase relationship demonstrates that the January 2003 SSW functions as a high-capacity vertical conduit, effectively mining moisture from the middle troposphere and injecting it into the polar stratosphere. The efficiency of this process is further validated by the record moisture flux reaching its absolute maximum of $0.66\times 10^{-6} \text{ kg/kg}$ on February 12. The emergence of this lagged response proves that the hydrological reconfiguration outlasts the primary dynamical signals, establishing the vortex split as a persistent shifter of the hemispheric moisture budget.

Table 3.11 : Synthesis of Dynamical Forcing and Hydrological Response.

Pressure Layer (hPa)	Peak Wave Energy (S) [J.kg⁻¹]	Mean Residual Velocity (w*) [10⁻³Pa.s⁻¹]	Moisture Flux (w'q') [Scaled]	Net Mass Change [%]
100–10 (Stratosphere)	1017.48	20.00	-2.35	+5.22% (Gain)
500–100 (UTLS)	177.30	2.82	-2.01	-4.91% (Loss)

Figure 3.30 illustrates the vertical redistribution of the Moisture Index through latitude-pressure cross-sections, while Figure 3.31 provides the corresponding hemispheric mean vertical profiles. Together, these visualizations capture the transition of the NH from a state of winter isolation to a regime of intensified moisture injection.

In the stratospheric regime (Figure 3.30a, b), the comparison reveals a systematic erosion of the arid polar vortex. In panel (a), the January baseline shows a chemically sequestered polar cap, where deep blue anomalies represent dry air held back by the dynamical barrier of the polar night jet. However, following the vortex split, panel (b) depicts the replacement of these anomalies with intense orange and red signals, signifying a major intrusion of tropospheric air.

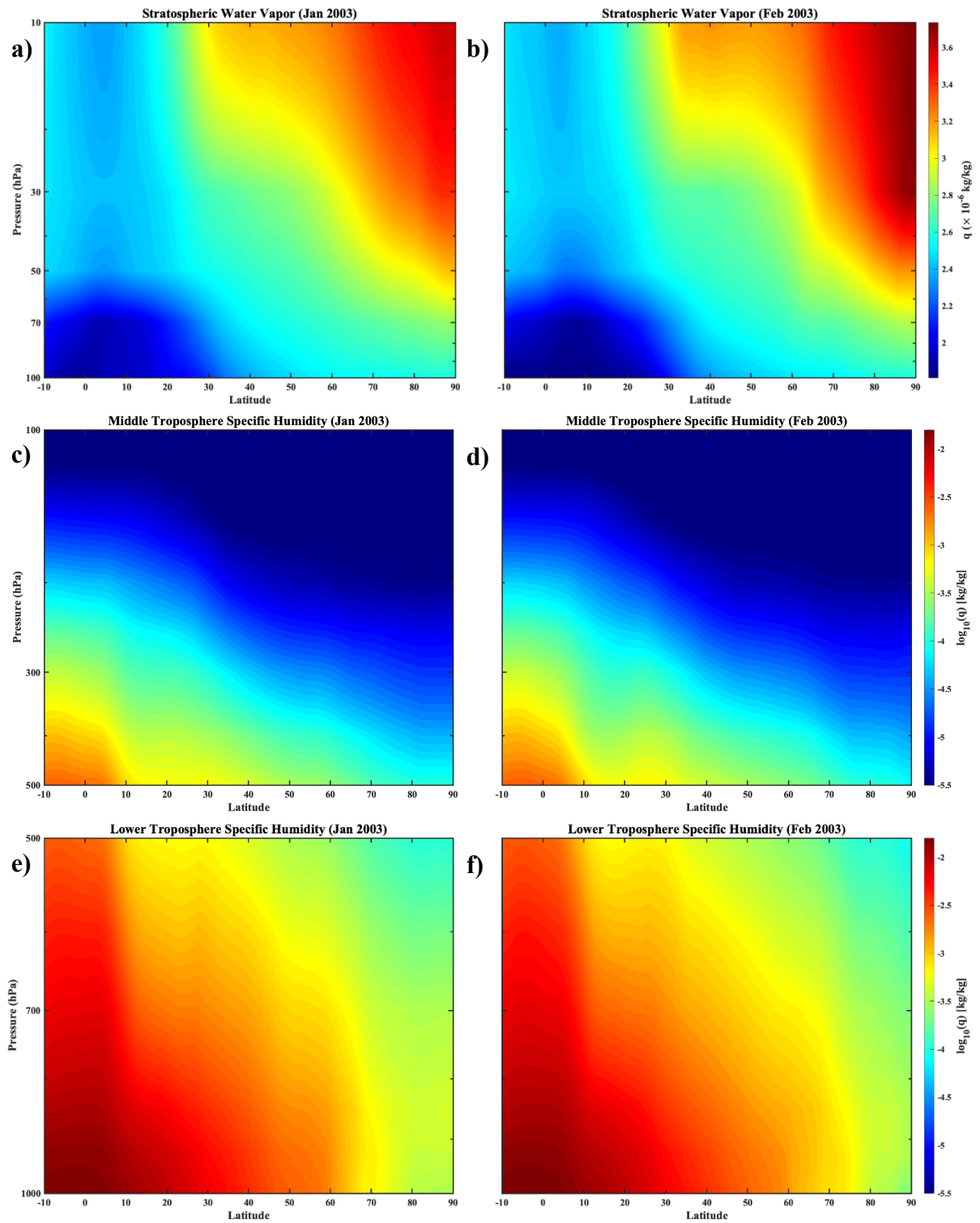


Figure 3.30 : Latitude-pressure cross-sections illustrating the vertical distribution of specific humidity across three distinct atmospheric regimes: the stratosphere (a, b), middle troposphere (c, d), and lower troposphere (e, f). The left column (a, c, e) represents the January 2003 baseline, while the right column (b, d, f) depicts the February 2003 state. The contrast reveals the systematic erosion of the polar night vortex and the resulting deep-layer moisture injection triggered by the vortex split.

This spatial transformation is quantitatively confirmed by the rightward shift in the hemispheric mean profile of Figure 3.31(c). This shift is most pronounced between the 70 hPa and 30 hPa levels, proving that moisture was not merely leaking into the lower stratosphere but was actively hoisted deep into the stratospheric column. As recorded in Table 3.11, this resulted in a net mass gain of +5.22%, reaching a peak concentration of 0.66×10^{-6} kg/kg by February 12.

The middle tropospheric panels (Figure 3.30c, d) and the associated profile in Figure 3.31(b) identify the primary source of this hydration. The February state (panel d) captures a significant depletion of moisture, which manifests as a distinct leftward shift in the vertical profile above the 300 hPa level. This depletion validates the mining mechanism, where the intensified residual circulation ($w^* = 20.00 \times 10^{-3} \text{ Pa} \cdot \text{s}^{-1}$ from Table 3.11) extracts water vapor from the 500–100 hPa reservoir. The -4.91% mass loss documented in Table 3.11 for this layer serves as the physical counterpart to the stratospheric gain, confirming the vertical continuity of the transport.

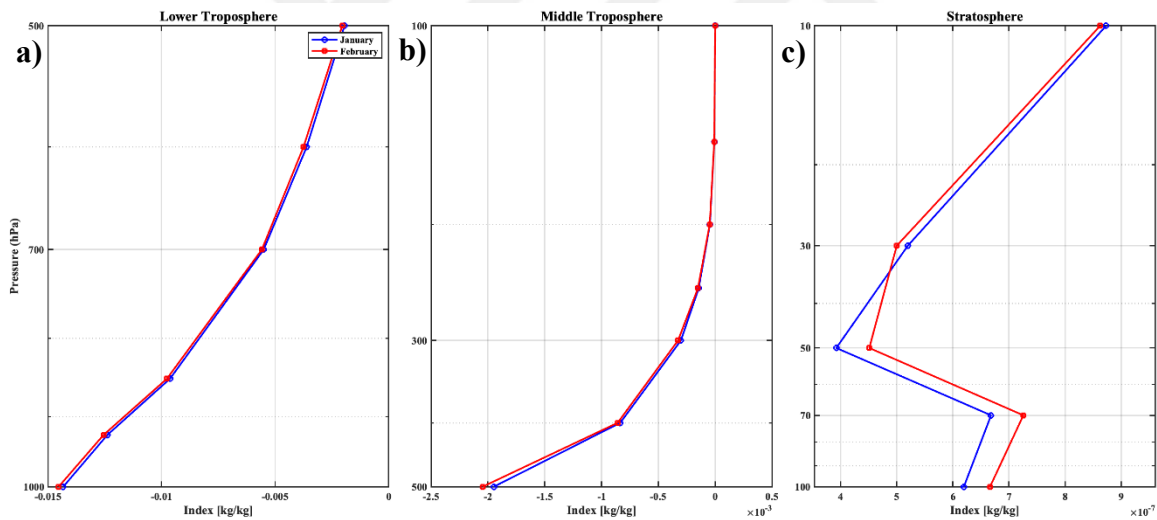


Figure 3.31 : Vertical profiles of the Moisture Index for the (a) lower troposphere, (b) middle troposphere, and (c) stratosphere, contrasting the January (blue) and February (red) mean atmospheric states.

In contrast, the lower tropospheric panels (Figure 3.30e, f) and the profile in Figure 3.31(a) demonstrate the stability of the moisture supply. The profiles for January and February are nearly identical at surface levels, confirming that the observed stratospheric anomaly was not driven by changes in local evaporation or moisture availability. Instead, the data establishes that the moistening was entirely a result of changed transport efficiency across the tropopause. The exceptionally high pattern correlation values ($R > 0.995$) and the rise in sd

from 0.18 to 0.22×10^{-6} (Table 3.11) further prove that this was a highly organized, circulation-driven injection characterized by intense mixing and irreversible turbulence.

Ultimately, the alignment between the spatial maps and the vertical profiles proves the lagged response hypothesis. While the S surge occurred in late January, the vertical profiles show that the moisture remained trapped and continued to accumulate within the stratospheric column well into February. This persistence redefined the polar climatology, maintaining the elevated Moisture Index long after the primary dynamical forcing of the vortex split had dissipated.

3.6.5 Synoptic evolution of the stratospheric moisture index (100–10 hPa): hemispheric synoptic maps

The quantitative assessment of the January 2003 split-type SSW as a primary hydrological driver is predicated on the introduction of the Moisture Index. This diagnostic metric is specifically engineered to transcend the limitations of simple humidity measurements by isolating the cross-latitude transport efficiency. It operates by identifying the gradient between the moisture-rich tropical reservoirs and the arid polar cap. By utilizing this differential approach, the index serves as a high-resolution tracer of the mechanical work performed by the BDC. This methodology allows for the filtering of seasonal moisture fluctuations and directly captures the stratospheric pump as it breaches the dynamical barriers of the polar night jet, moving mass across the tropopause interface.

The theoretical framework of this index is rooted in the source-sink relationship of the atmospheric column. By calculating the difference between the high-latitude belt and the equatorial reservoir, it is established as a baseline for climatological isolation. During a major warming event, the reorganization of planetary waves disrupts this isolation, turning the stratosphere from a desiccated sink into an active recipient of tropospheric air. The following synthesis integrates the dynamical forcing with the subsequent hemispheric response, proving that the 2003 vortex split was a high-magnitude hydrological shifter that redefined the moisture budget of the entire NH.

The hemispheric horizontal distribution within the stratospheric layer (100–10 hPa) provides the definitive synoptic record of the mechanical efficiency of the stratospheric transport. The series of panels in Figure 3.32 documents the transition of the polar stratosphere from desiccated isolation to a regime of high-magnitude moisture injection. The initial panel for 14

January 2003 characterizes the pre-SSW baseline, where the polar cap (60°N–90°N) is dominated by an isolated vortex represented by deep blue anomalies.

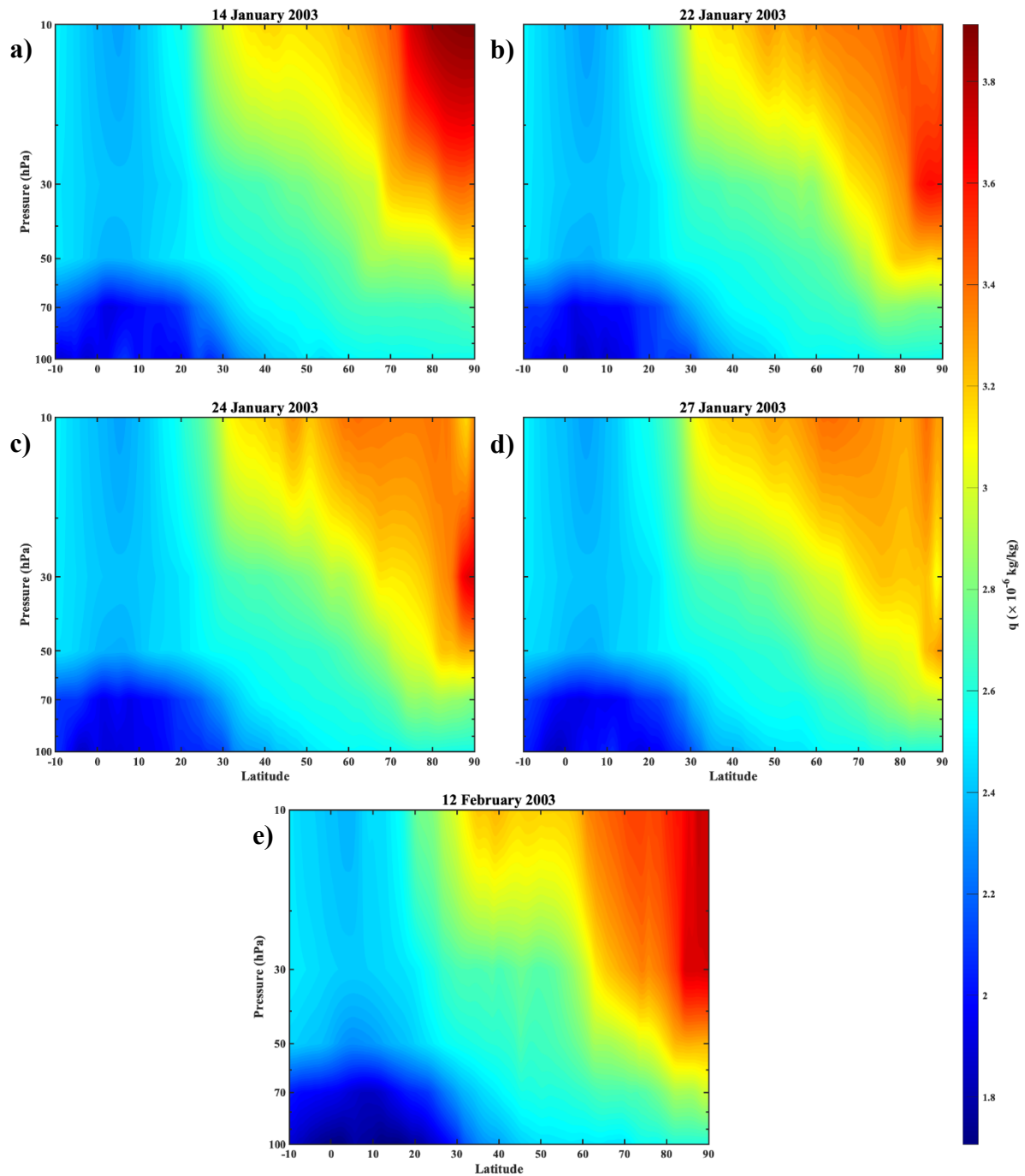


Figure 3.32 : Hemispheric horizontal distribution of the Stratospheric Moisture Index (100–10 hPa) on (a) 14 January, (b) 22 January, (c) 24 January, (d) 27 January, and (e) 12 February 2003. The panels document the systematic erosion of the polar night vortex and the large-scale moisture injection triggered by the vortex split.

Notably, this state is characterized by a Mean Index of 0.58×10^{-6} kg/kg, as documented in Table 3.11. The low sd of 0.18×10^{-6} confirms a spatially homogeneous and sequestered

atmosphere. This map indicates that under undisturbed winter conditions, the dynamical barriers of the polar night jet effectively prevent any hydrological coupling with the tropical reservoirs.

As the event progresses into the intensification window of 22 and 24 January 2003, the hemispheric maps capture the Response Phase where the arid polar night vortex is systematically degraded. The intrusion of meridional moisture transport, visualized as intense yellow and orange filaments channeling air from the tropical reservoir (10°S – 10°N), becomes visually dominant. By 24 January, the date of the primary vortex split, the stratospheric index rises to $0.60 \times 10^{-6} \text{ kg/kg}$. The geometry of these filaments follows the split structure of the split vortex, indicating that the transport is directed through preferred longitudinal pathways created by planetary wave breaking. This redistribution is highly organized, evidenced by an R value of 0.9959. The rise in sd to 0.22×10^{-6} during this peak reflects the irreversible mixing and turbulence at the vortex edge, marking the successful mechanical breaching of the tropopause barrier.

The late-stage synoptic evolution, visualized in the panels for 27 January and 12 February 2003, provides the empirical proof for the lagged response of the stratospheric column. Despite the primary S dissipating shortly after its January 17 peak, the moisture anomalies remained sustained and integrated within the high latitudes. The final panel for 12 February reveals the absolute maximum of the transport process, where the moisture anomalies are most intense across the polar cap. This delayed peak, where the index reaches its record value of $0.66 \times 10^{-6} \text{ kg/kg}$ (Table 3.11), demonstrates that the moisture budget response outlasts the primary thermal and dynamical signals. The +5.22% relative increase in the stratospheric index proves that the 2003 SSW acted as a permanent hydrological shifter, leaving a persistent moisture distribution that redefined the polar stratospheric composition for the remainder of the season.

In the middle troposphere (500–100 hPa), the synoptic maps in Figure 3.33 illustrate the role of this layer as the primary transit zone through which moisture is conveyed into the stratosphere. Unlike the stratified and zonally symmetric structure observed in the 14 January pre-SSW phase, the moisture field on 22 and 24 January displays a highly disturbed morphology. The maps are characterized by the formation of intensive poleward moisture intrusions that originate from the tropical reservoir and extend northward and upward toward high latitudes. This meridional extension is the visual proof of the vertical transport effect generated by the intensified BDC as the vortex splits. This layer is effectively being drained to

feed the stratospheric sink, a process that is statistically documented in Table 3.11 as a significant relative loss of -4.91% in the Moisture Index.

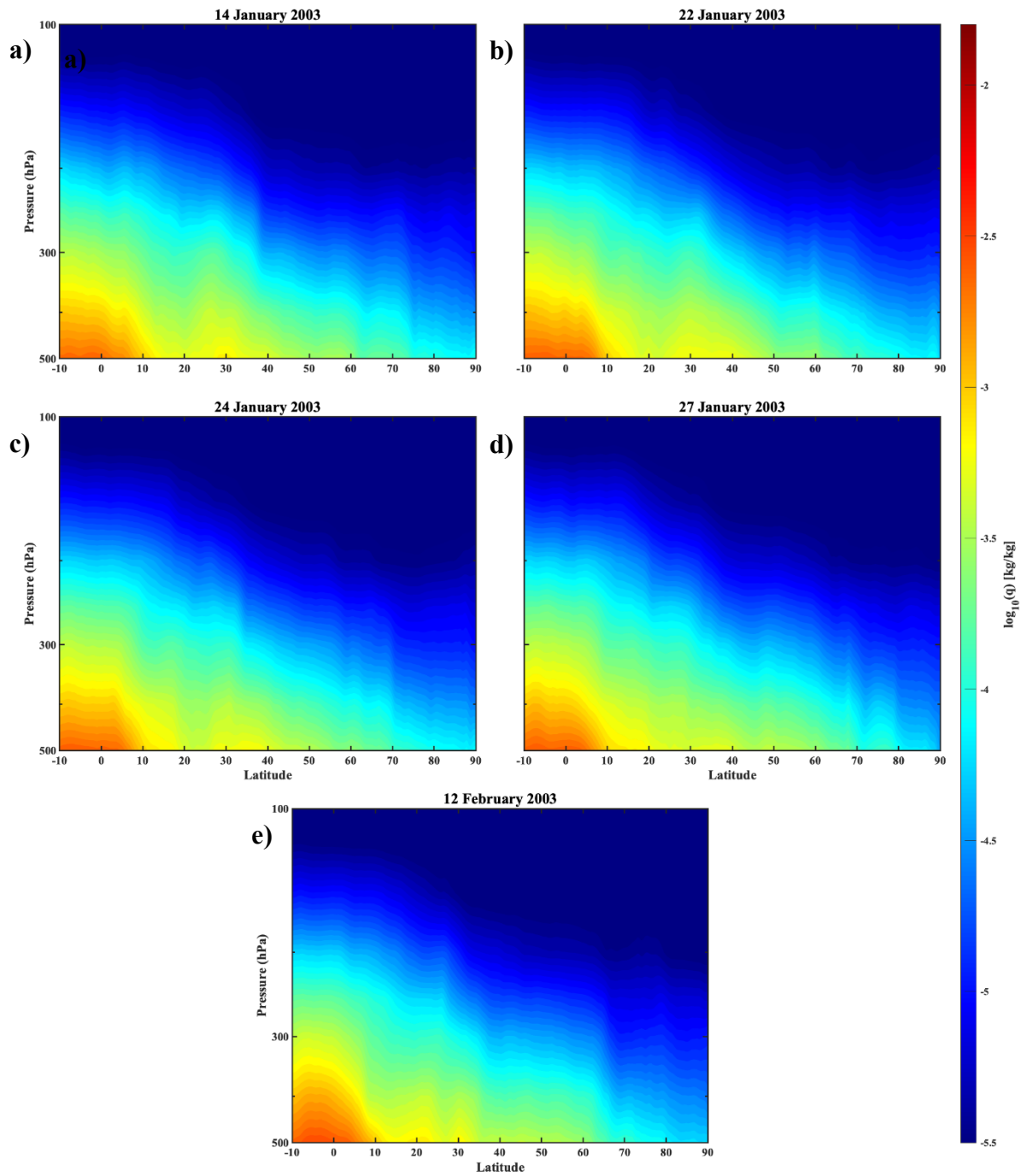


Figure 3.33 : Hemispheric horizontal distribution of the Middle Tropospheric Moisture Index (500–100 hPa) on (a) 14 January, (b) 22 January, (c) 24 January, (d) 27 January, and (e) 12 February 2003. The maps depict the transformation of the moisture field and the development of poleward transport conduits serving as the primary feeder for the stratospheric moisture sink.

The spatial reconfiguration observed in the middle tropospheric maps proves that the stratospheric transport effectively removes air from this transit zone, creating a high-velocity

transport pathway that bypasses the climatological isolation of the high latitudes. The decline of high-humidity contours in the sub-tropical regions is visually apparent in the 12 February panel, where the moisture anomalies are depleted compared to the January baseline.

Lower tropospheric synoptic maps (1000–500 hPa) in Figure 3.34 characterize the state of the primary moisture reservoir that sustains the stratospheric transport during the 2003 SSW. Throughout the sequence, this layer retains high-magnitude moisture gradients within the tropical belts, providing the continuous supply of tracers required for stratospheric hydration.

The panel for 14 January 2003 (Figure 3.34a) represents the reference state where the moisture reservoir remains undisturbed. As the event moves into the intensification phase on 22 and 24 January 2003 (Figure 3.34b, c), the moisture anomalies in the tropical reservoir become coupled to the stratospheric event. During these stages, the ascent mechanism in the upper levels draws air from the Intertropical Convergence Zone and conveys it through the middle tropospheric transport pathways. A relative decrease of 2.42% is recorded between January and February, as shown in the comparative statistics. This decline reflects the evacuation of the tropical boundary layer to supply the intensified residual circulation, showing that the influence of the stratospheric event extends deep into the troposphere to pull moisture from the most humid regions. The spatial patterns, supported by the $R=0.9988$ correlation, confirm that the 2003 SSW acted as a planetary-scale vertical coupling mechanism.

The late-stage panels for 27 January and 12 February 2003 (Figure 3.34d, e) demonstrate that even this massive reservoir is impacted by the dynamical forcing. The absolute difference of -0.14×10^{-3} kg/kg between the months is the statistical signature of this mass transfer. These observations illustrate that moisture removal is most intense in the upper part of this layer, notably near the 500 hPa level, where air is first drawn into the middle-tropospheric transit zone. This synoptic evidence establishes that stratospheric transport is a vertically integrated mechanism that links surface moisture sources to stratospheric sinks, reconfiguring the atmospheric column and leaving a persistent hydrological impact that outlasts the dynamical event.

In summary, the empirical evidence regarding the January 2003 split-type SSW definitively demonstrates the high-magnitude efficiency of the stratospheric transport in reconfiguring the NH's hydrological structure. The surge in planetary wave energy to 1017.48 J/kg successfully accelerated the residual circulation, achieving a record mass redistribution.

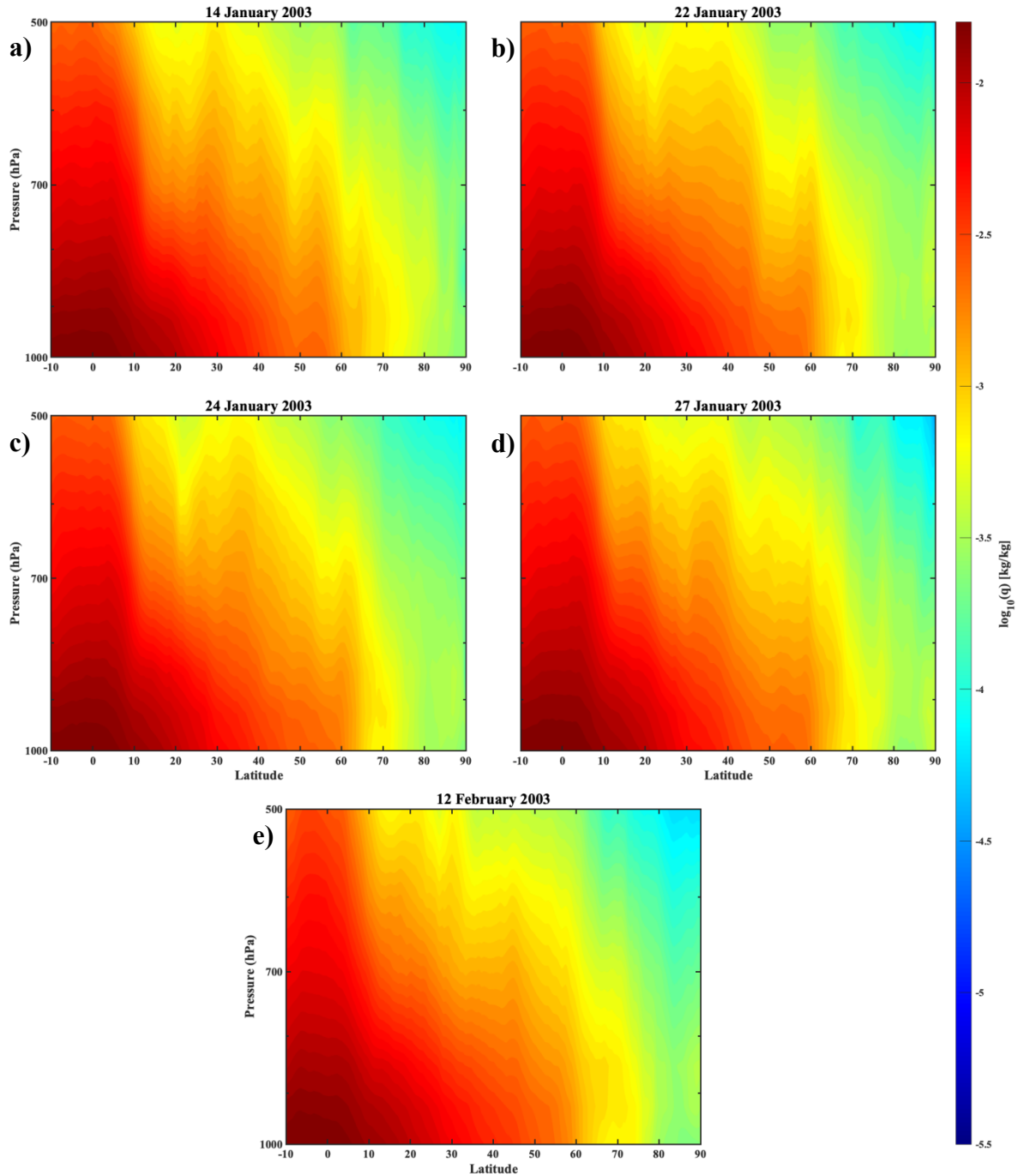


Figure 3.34 : Hemispheric horizontal distribution of the Lower Tropospheric Moisture Index (1000–500 hPa) on (a) 14 January, (b) 22 January, (c) 24 January, (d) 27 January, and (e) 12 February 2003. The sequence illustrates the synoptic evolution of the primary moisture reservoir and the formation of meridional transport filaments.

This mechanical intensification facilitated a significant antiphase moisture redistribution, characterized by a +5.22% gain in the stratosphere and a concurrent -4.91% loss in the middle troposphere. The emergence of a lagged response, reaching its absolute maximum of 0.66×10^{-6} kg/kg on 12 February, proves that the hydrological reconfiguration outlasts the

primary dynamical signals. These results establish the 2003 SSW as a globally organized atmospheric shifter that persistently redefined the stratospheric moisture budget and radiative environment of the NH.



4. DISCUSSION

The following evaluation synthesizes NH stratospheric variability and its multifaceted coupling with tropospheric processes, spanning the historical record to future climate projections. This research integrates the ERA5 reanalysis baseline with CMIP5 model simulations under the RCP 4.5 scenario to identify consistent atmospheric patterns and potential shifts. The application of the TEA method and the MPS metric allows the analysis to move beyond simple event detection, focusing instead on the energy disturbance and thermodynamic persistence of stratospheric warmings. This integrated approach facilitates an assessment of how dynamical drivers, such as wave-mean flow interactions and the Holton–Tan mechanism, have functioned historically and how they are projected to evolve as the climate warms. Furthermore, by bridging the gap between dry stratospheric dynamics which is traditionally limited to wind and temperature, and the global hydrological cycle, this work utilizes the January 2003 case to identify the role of extreme events in altering the moisture budget of the middle atmosphere, providing a physical baseline for understanding such interactions in a changing climate.

The investigation of stratospheric variability and its coupling with tropospheric processes indicates that the middle atmosphere in the NH acts as a dynamic reservoir sensitive to both tropical oscillations and extratropical wave forcing. Evidence gathered throughout this research shows that SSW events are not isolated thermal anomalies but are transformative stages in the global atmospheric cycle. The findings support the Holton–Tan mechanism, which describes the modulation of the polar vortex by the phase of the QBO. Specifically, the easterly phase of the tropical oscillation encourages the poleward and upward propagation of planetary waves, while the westerly phase tends to sequester wave energy in the mid-latitudes, thereby stabilizing the vortex. This coupling is observed in both ERA5 historical data and high-resolution model simulations, where the occurrence of major warming events during the westerly phase highlights the importance of internal stratospheric variability and intense tropospheric wave forcing that can override tropical influence. While the 2003 case study provides a historical record of hydrological coupling, projections under the RCP 4.5 scenario suggest that these dynamical interactions will remain a critical driver of the stratospheric state, as the stability of

the vortex faces increased competition between greenhouse-gas-induced cooling and enhanced wave activity toward the end of the century.

Central to this thesis is the application of the TEA method, which offers a physically grounded framework for characterizing SSW events compared to traditional wind-reversal criteria. Traditional methodologies often fail to account for events where the polar night jet remains westerly, despite extreme thermodynamic disruption in the stratosphere. The TEA method addresses this limitation by focusing on the spatial extent and temporal persistence of temperature anomalies at the 10 hPa level. By utilizing the MPS metric, this analysis evaluates the total energy disturbance of warming events across minor, major, and extreme categories for both historical and future periods. The historical record in ERA5 shows a balanced distribution of these events, while the primary models (M1, M2, and M3) reveal systematic structural biases that persist into the 21st-century simulations. For instance, M1 captures the seasonal cycle but consistently underrepresents the magnitude and frequency of the most extreme warming categories in both the historical and RCP 4.5 scenarios. M2 is characterized by a persistent cold pole bias, leading to an over-stabilization of the polar vortex and a significant underestimation of vortex-breaking frequencies throughout the simulation periods.

While the transition to CMIP6 has introduced notable improvements in stratospheric thermal representation and a reduction in the cold pole bias, several models continue to simulate a disproportionately strong polar vortex. This suggests that accurately resolving planetary wave propagation and vortex splitting dynamics remains a persistent challenge even within the latest modeling frameworks. In contrast, M3 exhibits high fidelity in capturing the temporal and spatial distribution of events, although it tends to exaggerate the amplitude of peak temperature spikes. The skill of M3 in reproducing the historical baseline increases the reliability of its projections regarding the broadening of warming peaks toward 2100. The secondary models (M4 and M5) are excluded from detailed dynamical assessment because their restricted vertical resolution and low-top configurations prevent the realistic generation of stratospheric disturbances.

The evaluation of the thermal structure at 10 hPa reveals that the polar stratosphere is governed by a consistent seasonal cycle interrupted by episodic warming pulses. In the historical period, the ERA5 baseline (mean $T_s = 225.94$ K) establishes a reference for validating model simulations. A significant finding is the 44% to 54% reduction in temperature variance during SSW events across all models, confirming the stabilizing influence of these disturbances on the mid-winter thermal environment. While M3 demonstrates high fidelity by closely replicating

the historical standard deviation (9.45 K) and the cooling trend (-0.316 K/decade), structural biases are evident in M1 and M2. M1 overestimates thermal variability with a significantly higher standard deviation (11.69 K) and a cooling trend nearly three times the observed magnitude, whereas M2 exhibits a suppressed variability regime characterized by a compressed percentile range (23.83 K). Projections under the RCP 4.5 scenario indicate that these thermodynamic characteristics remain largely stable, with variance reductions staying within the 49% to 52% range. However, a distinctive morphological change emerges toward the end of the 21st century: the broadening of warming peaks. This broadening, combined with the significant stabilization of long-term cooling trends notably the 76% weakening of the cooling rate in M1 suggests that while the frequency of events may not shift drastically, the temporal persistence of stratospheric disturbances is likely to increase as the climate warms.

A critical finding concerns the impact of a colder stratospheric background state, primarily driven by greenhouse-gas-induced cooling, on the initiation of SSW events. Under these colder conditions, the meridional temperature gradient strengthens, reinforcing the polar night jet and increasing the dynamical threshold required for a vortex split. The simulations suggest that as the stratosphere becomes colder, SSW events require significantly more intense planetary wave driving to overcome the enhanced inertial stability of the vortex. This leads to a regime where, although the absolute frequency of disturbances may stay stationary, the events that do occur are characterized by greater thermodynamic intensity and prolonged recovery periods, a trend most visible in the late-century projections of M3.

The analysis of U_h dynamics at 10 hPa highlights the ability of models to capture the abrupt shifts from strong westerly flow to the deceleration's characteristic of vortex breakdowns. Historical diagnostics identify a 24% reduction in U_h variance during SSW events in ERA5, a metric generally captured by the models with reductions ranging from 13% to 54%. Despite this, a fundamental discrepancy exists regarding long-term trends; while ERA5 shows a clear deceleration (-0.871 m.s⁻¹/decade), M1 and M2 simulate a spurious intensification of the polar night jet with positive trends. M1 further exhibits a positive magnitude bias, producing peak velocities that exceed reanalysis records, whereas M3 maintains the strongest correspondence with the observed mean state (10.83 m.s⁻¹). Transitioning into the RCP 4.5 future scenario, the underlying oscillatory pattern of the jet is preserved, yet the long-term strengthening trends observed in the historical simulations undergo substantial attenuation. In M1, the jet intensification trend weakens by approximately 82%, reaching a state of near-stabilization, while M2 exhibits a trend reversal to a weakly negative value (-0.040 m.s⁻¹/decade). These

results indicate that while anthropogenic forcing may neutralize the climatological intensification of the polar night jet, the fundamental mechanism of vortex breakdown remains a resilient component of stratospheric dynamics, with M3 continuing to project a statistically stationary mean flow through 2100.

The analysis of T_{rng} and T_{amp} at the 10 hPa level quantifies the absolute thermal extremes and the persistence of oscillations, serving as a direct indicator of the polar vortex's permeability. In the polar stratosphere (60°N), a significant suppression of extreme peaks is evident across the model ensemble. Specifically, the M2 model captures only approximately 20% of the historical variability range documented in ERA5, with a mean T_{rng} of 0.144 K compared to the reanalysis baseline of 0.730 K. While M3 demonstrates higher fidelity by resolving 54% of the observed range, it still falls short of the high-amplitude surges associated with adiabatic warming. In the tropical stratosphere (10°N), where variability is governed by the QBO, M2 exhibits a 21.5% deficit in capturing thermal extremes, whereas M3 replicates the periodicity but struggles with the precise magnitude of thermal gradients. These structural deficiencies remain remarkably stationary under the RCP 4.5 scenario, with shifts in mean amplitudes limited to less than 4% through 2100. The persistence of these biases indicates that while the seasonal cycle is preserved, high-top models consistently underestimate the intensity of stratospheric thermal pulses driven by planetary wave-mean flow interactions.

The dynamical metrics U_{amp} and U_{rng} provide essential insights into the stability of the polar night jet and the momentum budget of the tropical pipe. A striking discrepancy emerges in the tropical stratosphere (10°N), where the M3 model overestimates wind variability by approximately 136% relative to the ERA5 baseline, likely due to excessive gravity wave forcing or resolution-related biases. In contrast, M2 demonstrates high accuracy in the tropics, showing only a 2% deviation from the reanalysis. However, both models struggle to replicate the full magnitude of dynamical fluctuations in the polar region (60°N). M2 exhibits a markedly constrained trajectory, underestimating the polar dynamical range by roughly 60%, while M3 resolves approximately 86% of the range but still underestimates the overall amplitude by 26%. Future projections under the RCP 4.5 scenario reveal that these dynamical structures are resilient to anthropogenic radiative forcing, as evidenced by negligible trend coefficients ($|S_{U_h}| < 0.001 \text{ m.s}^{-1} \text{ per decade}$). This stationarity confirms that the internal wave-mean flow interactions governing the stratospheric momentum balance remain the dominant driver, while the inherent structural limitations in resolving high-magnitude dynamical gradients remain a persistent challenge for 21st-century climate projections.

The QBO analysis identifies the tropical stratosphere as a regulator of high-latitude variability through the Holton–Tan mechanism. ERA5 reanalysis establishes a ~28-month periodicity, which is only resolved by the high-top models M2 and M3 due to their vertical resolution and ability to simulate wave-mean flow interactions. M2 exhibits high fidelity in the tropical momentum budget with a 2% deviation in U_{mg} relative to reanalysis, while M3 overestimates tropical wind variability by 136%. This discrepancy in M3 is attributed to excessive gravity wave forcing or resolution-related biases within the tropical pipe. Models lacking these structural configurations fail to generate phase transitions and remain dominated by the SAO. Under the RCP 4.5 scenario, the fundamental QBO cycle persists, though enhanced wave transport from the warming troposphere is projected to reduce the period from 28 to 25 months. This shift may alter the timing of tropical-extratropical teleconnections and the frequency of SSW events in the coming century.

The scatter plot analysis of T_s and U_h at 60°N quantifies the thermal-dynamical coupling and the internal coherence of the polar vortex. ERA5 data shows a robust anti-correlation where temperature surges drive wind reversals, though the 30% slope attenuation from -1.62 to -1.13 m/s/K after 1990 indicates a historical decline in dynamical coherence. Primary models show systematic biases; M2 overestimates the coupling ($r \approx -0.82$), simulating an overly linear response, while M3 underestimates the link amplitude by 15–20%. Under the RCP 4.5 scenario, both models project a non-monotonic evolution. M2 reaches peak susceptibility at -2.65 m/s/K (2026–2050), while M3 peaks at -2.42 m/s/K (2051–2075). By 2076–2100, both models converge on a weakened coupling state with slopes flattening to -0.74 and -0.63 m/s/K. This late-century decoupling under moderate forcing suggests a regime shift in high-latitude variability and increased uncertainty in the future stratospheric response.

The representation of these dynamical links is further complicated by the vertical coupling between the stratospheric vortex and the tropospheric circulation. Model M3 demonstrates the highest success in simulating the downward control effect, effectively translating stratospheric wind reversals into negative phases of the NAO. This surface fidelity allows M3 to more accurately capture the extreme cold spells following major SSW events. Conversely, M2's persistent cold pole bias often results in a decoupled state where the polar night jet remains too stable, preventing the stratospheric signals from effectively modulating mid-latitude storm tracks and thereby underestimating surface meteorological impacts.

The January 2003 Major SSW event provides empirical evidence of the coupling between stratospheric dynamics and the global hydrological cycle. The mechanical breakdown of the polar vortex, characterized by a major split on January 24, functioned as a catalyst for a radical reorganization of hemispheric moisture pathways. This transition is quantified by the shift in Mean Zonal IVT from a climatological baseline of $26.53 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$ to an active peak of $31.03 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$ during the warming window. The culmination of this dynamical shift occurred during the vortex split, where the Peak Total IVT reached an absolute maximum of $1459.0 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$. These values confirm that the collapse of the stratospheric isolation barrier effectively overrides the climatological sequestration of moisture within the lower troposphere, facilitating unconventional meridional exchanges across the high-latitude interface.

Vertical partitioning of the moisture flux substantiates the extreme moisture intrusion theory by documenting the ascent of moisture filaments past the 100 hPa tropopause level, reaching the middle stratosphere at 10 hPa. The presence of a Zonal Max IVT of $0.11 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$ within the 100–10 hPa layer indicates a significant vertical mass injection into regions typically characterized by extreme background desiccation. Furthermore, the observation of a secondary surge in Southward Max IVT to $1253.7 \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$ on February 12 weeks after the peak thermal anomaly demonstrates the downward control effect. This temporal lag proves that stratospheric perturbations modulate tropospheric moisture pathways for nearly a month, reinforcing the role of Major SSW events as long-term modulators of the hemispheric moisture budget.

The spatio-temporal evolution of IVT intensities during the January 2003 Major SSW signifies a transition from a regime of zonal sequestration to one of high-magnitude meridional exchange. The January 14 baseline reflects a coherent jet system where moisture is confined within mid-latitude zonal bands, as indicated by a West IVT Max of $1165.0 \text{ kg m}^{-1}\text{s}^{-1}$. The mechanical disintegration of this zonal barrier during the vortex split on January 24 is characterized by fragmented wave-breaking patterns and an escalation of the West IVT Max to $1259.2 \text{ kg m}^{-1}\text{s}^{-1}$. This dynamical opening facilitates the emergence of high-magnitude moisture filaments, driving a Southward IVT Max of $1145.4 \text{ kg m}^{-1}\text{s}^{-1}$ an intrusion approximately 98% more aggressive than pre-event levels.

The resulting meridional transport acts as a driver of latent heat release in the upper troposphere, reaching an absolute maximum on January 27 with a Max IVT of $548.94 \text{ kg m}^{-1}\text{s}^{-1}$. This state represents the total collapse of the zonal barrier, allowing for trans-hemispheric mass exchange. The secondary surge recorded on February 12, with a Southward IVT Max of $1253.7 \text{ kg m}^{-1}\text{s}^{-1}$, confirms the downward control mechanism and the entry of the atmosphere into a memory

state. The spatial correlation coefficient R peaking at 0.61 on January 24 proves that the vortex split organizes moisture into persistent meridional conduits, sustaining a significant hydrological reorganization that lasts for weeks after the initial stratospheric warming subsides.

The energetic engine behind the January 2003 vortex breakdown was an unprecedented surge in S , which functioned as a monumental departure from seasonal norms. As S reached a peak density of 1017.48 J/kg within the $100\text{--}10 \text{ hPa}$ layer, it established a saturated wave-breaking environment that physically dismantled the polar night jet. This energy saturation was not a transient pulse but a sustained momentum injection, as evidenced by the significant reduction in $sd=15.4$ compared to non-SSW periods. According to the downward control principle, the resulting friction-like torque on the mean flow necessitated a vigorous acceleration of the Brewer-Dobson Circulation.

This mechanical response is explicitly captured by the w^* , which acted as a deep-reaching hydrodynamic pump. The recorded peak velocity of $545.06 \times 10^{-3} \text{ Pa/s}$ represents a 25% intensification of the downward branch of the circulation compared to the climatological baseline. This intensified vertical conduit effectively hoisted moisture-rich air masses across the tropopause, resulting in a more than threefold increase in the stratospheric $w'q'$ to -2.35×10^{-5} scaled units. The spatial and temporal alignment of these vertical anomalies confirms a definitive Forcing-Response-Transport hierarchy: S provides the torque, the accelerated w^* provides the conduit, and $w'q'$ serves as the final hydrological response. The secondary mass flux record of $1.82 \times 10^{11} \text{ kg/s}$ on February 7 further proves that this dynamical coupling outlasts the primary thermal forcing, leaving the polar atmosphere in a sustained memory state for several weeks.

The analysis of the January 2003 SSW establishes a direct link between mechanical forcing and the redistribution of atmospheric mass. The surge in wave energy to a peak of 1017.48 J/kg and the accelerated residual downwelling ($w_{\text{mean}}^*=20.00 \times 10^{-3} \text{ Pa/s}$) facilitated a +5.22% mass gain within the stratospheric layer ($100\text{--}10 \text{ hPa}$). This accumulation was physically balanced by a concurrent -4.91% mass loss within the upper troposphere-lower stratosphere ($500\text{--}100 \text{ hPa}$) reservoir. This relationship demonstrates that the vortex split functions as a high-capacity vertical conduit, effectively moving moisture from the middle troposphere into the polar stratosphere.

The spatial transformation of the NH reveals a systematic erosion of the arid polar vortex. While the January baseline shows dry air sequestered behind the dynamical barrier of the polar night

jet, the post-split state depicts a major intrusion of tropospheric air, reaching a peak concentration of 0.66×10^{-6} kg/kg by February 12. This lagged response proves that the hydrological reconfiguration outlasts the primary dynamical signals of the vortex split. Furthermore, the stability of moisture profiles in the lower troposphere confirms that the observed stratospheric hydration was entirely driven by increased transport efficiency across the tropopause rather than changes in local evaporation. The findings derived from the January 2003 case study provide preliminary insights into the vertical moisture injection mechanism associated with major SSW events. However, the quantitative hydrological implications observed in this specific case should be interpreted as representative rather than exhaustive. While the ERA5 reanalysis effectively captures the moisture transport signatures, the degree to which these signatures are consistent across different modeling frameworks (M2-M3) and varying warming magnitudes remains a subject for further investigation.

In conclusion, the findings underscore that stratospheric variability is governed by a complex interplay of wave energy, dynamical coupling, and moisture redistribution. While the primary models (M2, M3) exhibit structural biases in capturing the absolute magnitude of these extremes and their long-term trends, the representation of the QBO and the vertical transport mechanism identified in the January 2003 case study reveals the resilient nature of stratospheric-tropospheric coupling. As projections under the RCP 4.5 scenario suggest a stabilization of mean flows alongside the temporal broadening of warming events, the stratosphere will continue to function as a long-term modulator of the NH's hydrological and radiative balance. This systematic reorganization of mass and energy proves that sudden stratospheric warmings are not transient perturbations but primary dynamical drivers of the 21st-century atmospheric structure and moisture budget.

Future research will prioritize a comprehensive comparative analysis between Minor, Major, and Extreme SSW events using a Multi-Model Ensemble framework. While the current study utilizes the January 2003 event as a benchmark in ERA5, expanding this diagnostic framework to include the historical and future simulations of M1, M2, and M3 is essential to evaluate model consistency in reproducing vertical moisture injection. This expansion will determine whether the stratospheric hydrological response exhibits a non-linear tipping point during extreme cases compared to minor warmings. Furthermore, integrating higher-resolution CMIP6 datasets will provide deeper insights into how subgrid-scale gravity wave parameterizations influence the vertical coupling efficiency and the resulting surface weather success of these models.

5. CONCLUSIONS AND RECOMMENDATIONS

The comprehensive investigation into the detection and evaluation of stratospheric sudden warming events establishes a multifaceted understanding of middle atmospheric dynamics and their profound impact on the global climate system. By integrating the TEA methodology and MPS metric with a detailed analysis of moisture transport during the January 2003 case study, this research provides a holistic framework for characterizing the vertical coupling between the troposphere and the stratosphere. The validation of this methodology identifies a fundamental thermodynamic reorganization of the stratospheric energy budget, where ERA5 reanalysis confirms a 44% to 54% reduction in temperature variance during peak event phases. This variance reduction proves that the polar vortex enters a forced state that prevents the stratosphere from reaching extreme radiative equilibrium, effectively stabilizing the mid-winter thermal environment through intense energy redistribution.

The evaluation of the thermal structure at 10 hPa identifies M3 as the most reliable simulation for reproducing historical conditions, yielding a standard deviation of 9.45 K and a cooling trend of -0.316 K/decade, aligning with the ERA5 baseline of 9.55 K and -0.298 K/decade. In contrast, M1 overestimates thermal variability with a standard deviation of 11.69 K and a cooling trend of -0.850 K/decade nearly three times the observed magnitude. M2 is characterized by a persistent cold-pole bias, capturing only 20% of the historical Trng with a mean of 0.144 K. Projections under the RCP 4.5 scenario indicate that while these thermodynamic characteristics remain stable, a distinctive morphological broadening of warming peaks emerges toward 2100. This shift is accompanied by a significant stabilization of cooling trends, where the cooling rate in M1 weakens by 76% and M2 by 60%, indicating an increase in the temporal persistence of stratospheric disturbances as the climate warms.

The analysis of zonal wind dynamics at 10 hPa highlights the ability of models to capture abrupt shifts from strong westerly flow to the deceleration's characteristic of vortex breakdowns. Historical diagnostics identify a 24% reduction in U_h variance during SSW events in ERA5, a metric generally captured by models with reductions ranging from 13% to 54%. However, a fundamental discrepancy exists regarding long-

term trends; while ERA5 shows a clear deceleration of $-0.871 \text{ m.s}^{-1}/\text{decade}$, M1 and M2 simulate a spurious intensification of the polar night jet with positive trends of 0.64 and $0.80 \text{ m.s}^{-1}/\text{decade}$. Transitioning to the RCP 4.5 scenario, these intensification trends undergo substantial attenuation. In M1, the jet intensification trend weakens by 82%, reaching near-stabilization, while M2 exhibits a trend reversal to a weakly negative value of $-0.040 \text{ m.s}^{-1}/\text{decade}$, suggesting that anthropogenic forcing may neutralize the climatological intensification of the polar night jet.

Quantification of stratospheric amplitudes and ranges reveals systemic suppression of extreme peaks in the polar region across the model ensemble. M2 captures only 20% of the historical thermal range at 60°N , while M3 resolves 86% of the dynamical range but underestimates the overall U_{amp} by 26%. In the tropical stratosphere, M3 overestimates wind variability by 136% relative to the ERA5 baseline, a discrepancy attributed to excessive gravity wave forcing or resolution-related biases. Future projections show that these variability structures are resilient to moderate radiative forcing, with trend coefficients for U_{amp} remaining negligible at less than $0.001 \text{ m.s}^{-1}/\text{decade}$. This stationarity confirms that internal wave-mean flow interactions continue to dominate the stratospheric momentum balance, despite the structural limitations of high-top models in resolving high-magnitude dynamical gradients.

The QBO analysis identifies the tropical stratosphere as a regulator of high-latitude stability through the Holton–Tan mechanism. The ~ 28 -month periodicity established in ERA5 is resolved only by the high-top models M2 and M3 due to their vertical resolution and ability to simulate wave-mean flow interactions. While M2 demonstrates high accuracy with only a 2% deviation in tropical U_{mg} , M3 exhibits significant overestimation of the signal. Under the RCP 4.5 scenario, the fundamental QBO cycle persists, though enhanced wave transport from the warming troposphere is projected to reduce the period from 28 toward 25 months. This acceleration of the tropical stratospheric oscillation suggests a fundamental modification in the timing of tropical-extratropical teleconnections and the frequency of SSW events in the coming century.

Scatter plot analysis of T_s and U_h at 60°N quantifies a 30% attenuation of the regression slope in ERA5 after 1990, decreasing from -1.62 to -1.13 m/s/K , indicating a historical decline in the dynamical coherence of the polar vortex. Models M2 and M3 project a non-monotonic evolution of this relationship through 2100. M2 reaches

peak susceptibility at -2.65 m/s/K during the 2026–2050 period, while M3 peaks at -2.42 m/s/K between 2051 and 2075. By the final segment of the century (2076–2100), both models converge on a weakened coupling state with slopes flattening to -0.74 and -0.63 m/s/K. This eventual decoupling under sustained moderate forcing suggests a regime shift in high-latitude variability and increased uncertainty in the dynamical response of the future stratosphere.

The January 2003 Major SSW provides empirical evidence of the coupling between stratospheric dynamics and the global hydrological cycle. The mechanical breakdown of the vortex functioned as a catalyst for the reorganization of hemispheric moisture pathways, quantified by a shift in Mean Zonal IVT from 26.53 to 31.03 kg.m⁻¹s⁻¹ during the warming window. The Peak Total IVT reached an absolute maximum of 1459.0 kg.m⁻¹s⁻¹ during the vortex split on January 24. These values confirm that the collapse of the stratospheric isolation barrier overrides the climatological sequestration of moisture within the lower troposphere, facilitating unconventional meridional exchanges that bridge tropical moisture sources and polar sinks.

Vertical partitioning of the moisture flux substantiates the extreme moisture intrusion theory by documenting the ascent of moisture filaments past the 100 hPa tropopause into the middle stratosphere at 10 hPa. The surge in S to 1017.48 J/kg and the acceleration of w^* to a mean of 20.00×10^{-3} Pa/s identify the accelerated BDC as the primary engine for this redistribution. The 25% intensification of the downward branch of the circulation resulted in a more than threefold increase in stratospheric $w'q'$ to -2.35×10^{-5} scaled units. The identification of a temporal lag, where the moisture concentration reached its record maximum of 0.66×10^{-6} kg/kg on February 12, proves that the hydrological impact of an SSW is far more enduring than the initial thermal signal.

The synthesis of mass balance shifts demonstrates that the 2003 event achieved a +5.22% net mass gain in the stratosphere (100–10 hPa), physically balanced by a concurrent -4.91% loss in the UTLS (500–100 hPa) reservoir. This vertical mining mechanism confirms that the vortex breakdown facilitates a sustained reorganization of the global moisture cycle. Spatial analysis reveals that vortex splits are more effective at inducing stratospheric humidification than vortex displacements, as evidenced by high spatial correlation ($R=0.61$) and the emergence of multiple meridional transport conduits. These results necessitate the prioritization of vortex

geometry and splitting mechanisms in future model development to fully resolve the hydrological-dynamical feedback governing the NH climate.

In conclusion, this dissertation establishes a standardized framework for the detection and evaluation of stratospheric extremes by linking dynamical metrics with hydrological outcomes. The TEA methodology and MPS classification provide robust tools for identifying the atmospheric conditions that facilitate moisture transport across the UTLS. The results indicate that while the frequency of SSW events remains stable, their intensity and duration are projected to increase, leading to deeper and more persistent impacts on the NH radiative and hydrological balance. The research underscores the profound role of the middle atmosphere in global climate stability and calls for the continuous integration of high-resolution moisture transport with dynamical detection algorithms in next-generation climate assessments.

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