Tidal variability and aliasing effects from contemporaneous satellite, model, and reanalysis data in the Stratosphere

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A brief Introduction to Tides

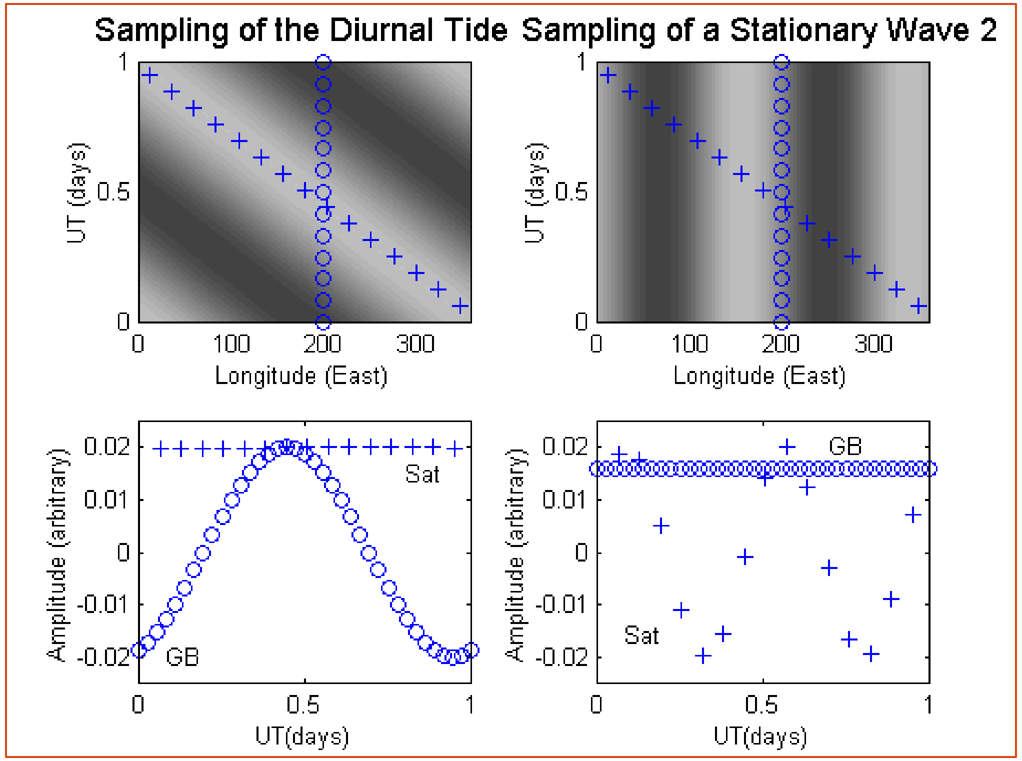
- Global scale periodic oscillations of the atmosphere.
- Classical tidal theory- Treats tides as linear perturbations on a background atmosphere dependent on latitude and altitude.
- Atmospheric tides are eigenmodes of the atmosphere described by Hough functions
- Amplitudes grow exponentially with height
- Excitation Mechanisms:
  - Thermal Forcing
    - Water vapor absorption in troposphere
    - Ozone absorption in stratosphere
  - Latent Heat Release in the troposphere
  - Ocean & Land differences
  - **Non-linear interactions** (migrating tides & stationary planetary waves)

Various Tides are

- Diurnal (24 hr), Semi-Diurnal (12 hr) and Terdiurnal (8 hr) tides
- Migrating Tides - Phase speed is equal to linear rotation speed of Earth
- Non-migrating Tides – Phase speed is different (either slow or fast) from linear rotation speed of Earth.

Objectives

- To deduce short term tidal variability
- To address aliasing problems in the spectral analysis of satellite data - Mean variability aliases into DW1 & SPW1 aliases into DS0 and DW2
- To investigate the role of non-linear interactions in the generation of non-migrating tides, specifically DS0 and DW2 produced by SPW1 and DW1

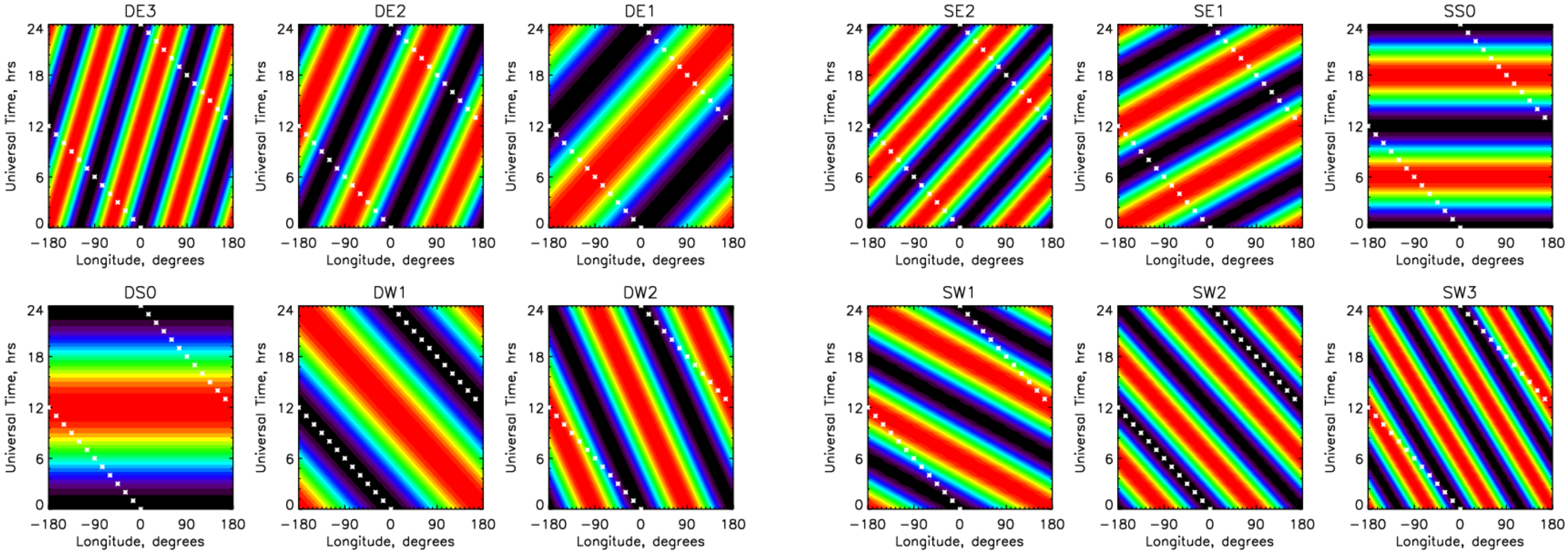


Satellite vs. Ground Based Measurements

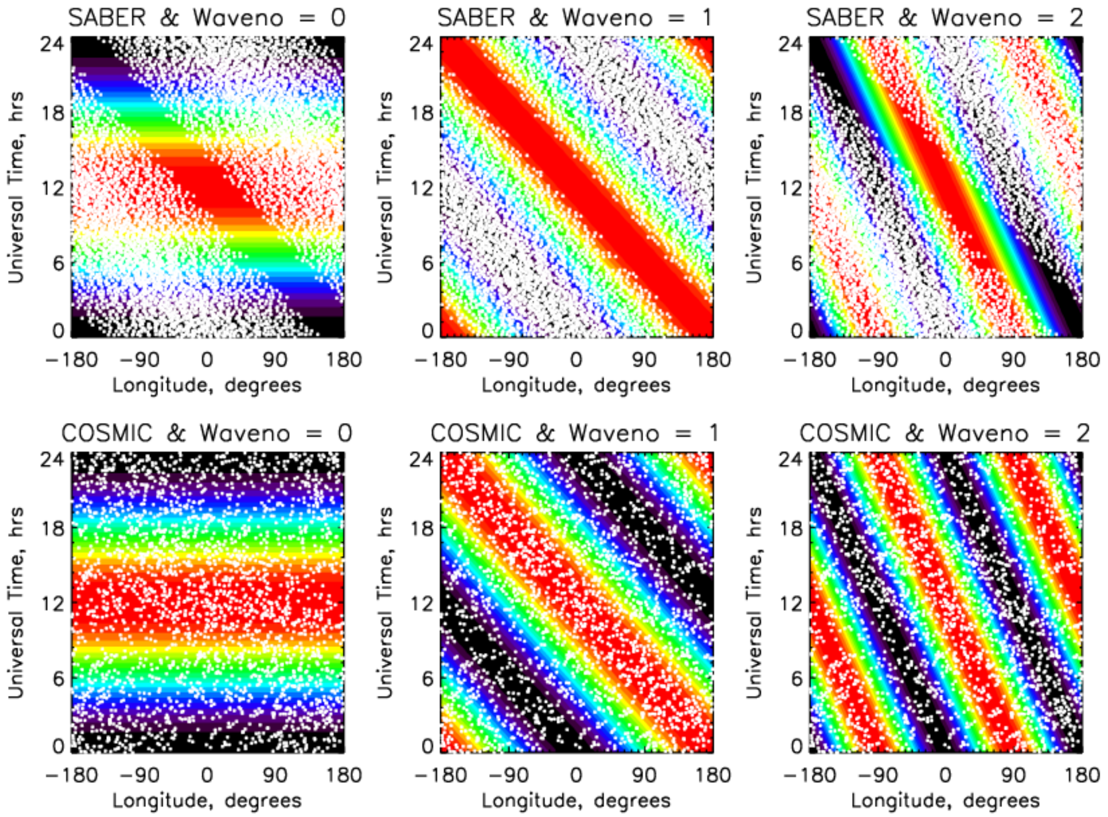
Our datasets are from

- SABER
  - An instrument onboard the TIMED satellite
  - Measures CO_2 emissions in 10 infrared bands
  - Temperatures are retrieved from these measurements
  - Data available from 2002- present
- COSMIC
  - Constellation of six satellites (FORMOSAT-3)
  - Works on the principle of GPS RO
  - Temperature in the lower atmosphere and electron density in the upper atmosphere are simultaneously retrieved.
  - Data available from 2007 to present

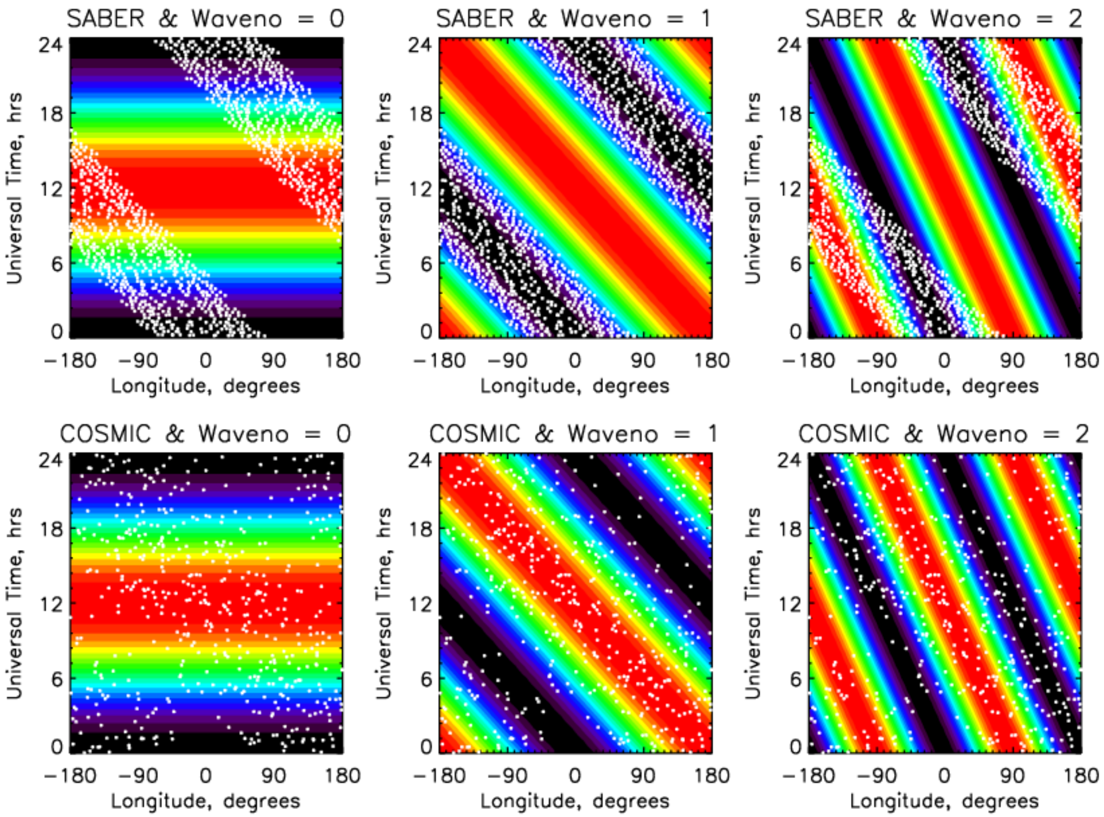
- CMAM30
  - Canadian Middle Atmosphere Model
  - A retrospective estimate of the chemical and dynamical evolution of the atmosphere over the period 1981-2010
  - Temperature and wind used in the present study.
- ERA-Interim
  - ERA-Interim is a global atmospheric reanalysis
  - Data was available from surface to 1 hPa and from 1 January 1979 to 31 August 2019 (Now, it is followed by the latest ERA-5)
  - Temperature and wind used in the present study.


DE3
DE2
DE1
SE2
SE1
SS0
DS0
DW1
DW2
SW1
SW2
SW3
Universal Time, hrs
0
6
12
18
24
Longitude, degrees
−180
−90
0
90
180

Tidal Analysis from Satellite Data – SABER/TIMED and COSMIC



60 days data



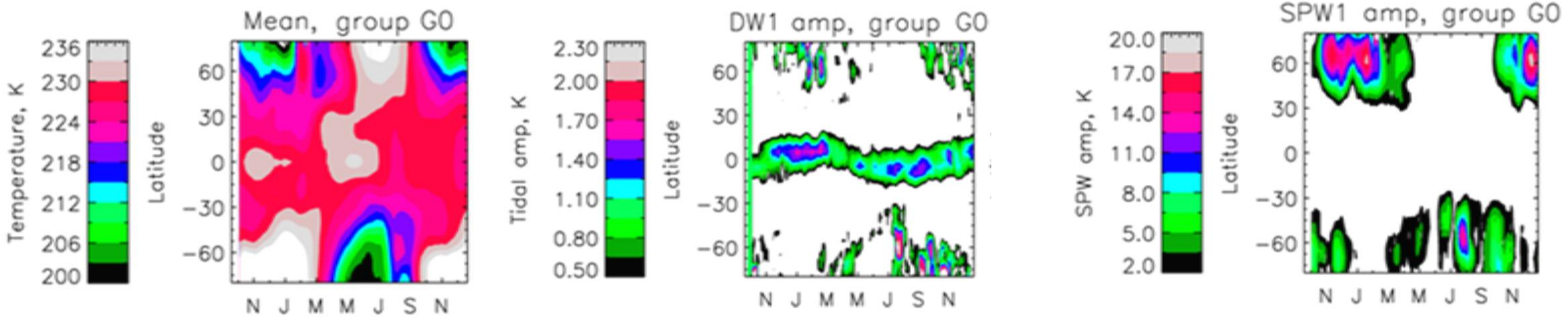
11 days data

Simultaneous Retrieval of SPW and Tidal Parameters

$$T(t,\lambda) = T_0 + \sum_{i=1}^{3}\sum_{j=-4}^{4} T_{ij}\cos(2\pi f_i t + 2\pi s_j\lambda - \varphi_{ij}) + \sum_{k=1}^{3} T_k \cos(2\pi s_k\lambda - \varphi_k)$$

- Data $T(t,\lambda)$, where t and λ are time (in hours) and longitude (in degrees), are fit to the above function using **least squares fitting method**.
- T_0 is the zonal mean
- T_k and ϕ_k are amplitudes and phases of stationary planetary waves for wavenumbers k from 1 to 3 and
- T_{ij} and ϕ_{ij} are amplitudes and phases of tides for periods i from 1 to 3 (diurnal, semi-diurnal and ter-diurnal tides) and wavenumbers j from -4 to 4.

Variability in COSMIC temperature



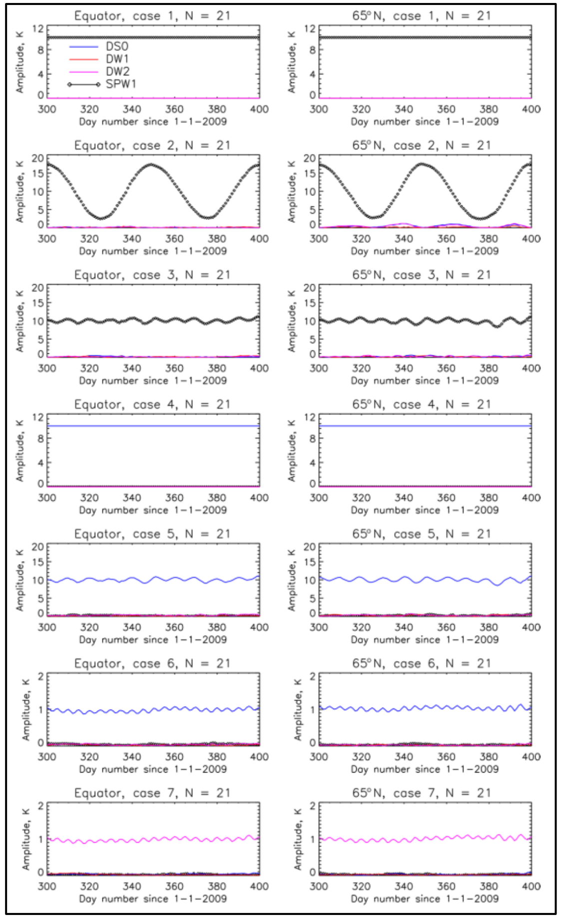
Mean, amplitude of DW1 and amplitude of SPW1 from COSMIC during 2009-2010 using a window of 21 days.

Numerical Experiments:

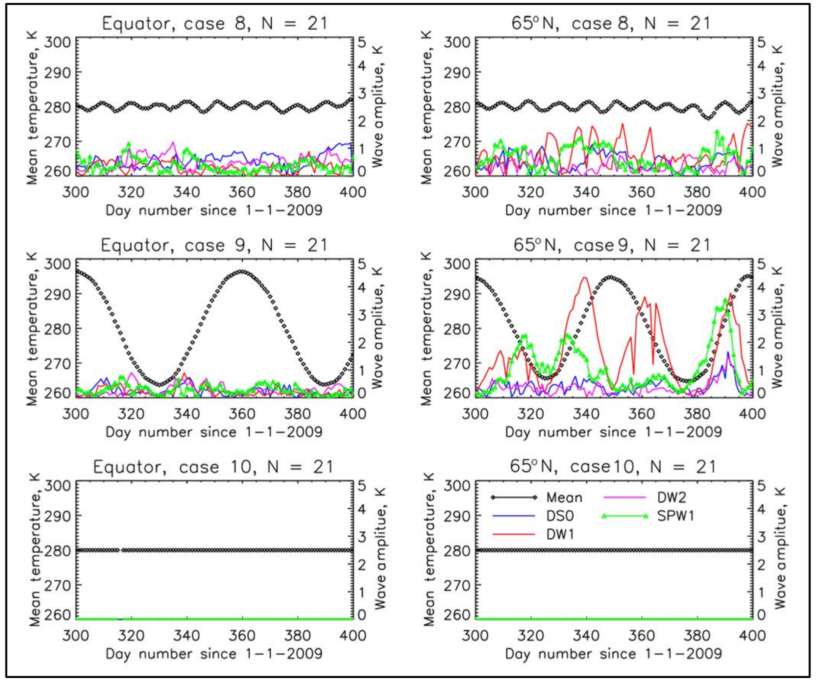
1. Assume an atmosphere consisting of only a specific wave and perform the same analysis.
2. Spectral Analysis of this atmosphere shows that significant aliasing occurs from SPW1 into DS0 and DW2

Table 1. Numerical experiments to investigate the aliasing of energy from one component into another over the Equator and 65° N as seen in Figs. 9 and 10. T is temperature, λ is longitude, t is day number and time and h is hour of day.

S.No	Atmosphere	Equation	Results
1	Constant SPW1 amplitude	$T = 10 \times \cos(2\pi\lambda/360)$	SPW1 amplitude is extracted with no errors over either latitude.
2	Slowly varying SPW1 amplitude (period = 50 d)	$T = 10 + [10 \times \cos(2\pi t/50) \times \cos(2\pi\lambda/360)]$	Maximum amplitude is underestimated and minimum amplitude is overestimated. No aliasing is observed over the Equator; however, over 65° N, DS0 and DW2 components show equal and uniform aliasing of 1 K amplitudes. This happens at times of the maximum gradient in SPW1 amplitude.
3	Fast varying SPW1 amplitude (period = 10 d)	$T = 10 + [10 \times \cos(2\pi t/10) \times \cos(2\pi\lambda/360)]$	Average SPW1 amplitude is extracted. The periodic variation of 10 d is lost in the analysis. However, no DS0 and DW2 components are observed over either latitude.
4	Constant DS0 amplitude	$T = 10 \times \cos(2\pi h/24)$	Constant DS0 component extracted successfully. No aliasing into any other component is observed over either latitude.
5	Varying and large DS0 amplitude (period = 10 d)	$T = 10 + [10 \times \cos(2\pi t/10) \times \cos(2\pi h/24)]$	Average DS0 component is extracted. No aliasing into other components is seen over either latitude.
6	Varying and small DS0 amplitude (period = 5 d)	$T = 1 + [1 \times \cos(2\pi t/5) \times \cos(2\pi h/24)]$	Average DS0 component is extracted. No aliasing into other components is seen over either latitude.
7	Varying and small DW2 amplitude (period = 5 d)	$T = 1 + [1 \times \cos(2\pi t/5) \times \cos(2\pi h/24 + 2\pi\lambda/180)]$	Average DW2 component is extracted. No aliasing into other components is seen over either latitude.
8	Fast varying mean temperature (period = 10 d)	$T = 280 + 10 \times \cos(2\pi t/10)$	Average mean variation is extracted. Aliasing is observed in DW1, SPW1, DS0 and DW2, all showing amplitudes up to 1 K over the Equator and larger at 65° N. The large peaks observed in DW1 and SPW1 at 65° N indicate significant aliasing.
9	Slowly varying mean temperature (period = 50 d)	$T = 280 + 10 \times \cos(2\pi t/50)$	Mean variation is extracted reasonably (in the range 273 to 287 K), with maximum amplitudes underestimated by 3 K and minimum values overestimated by 3 K. Aliasing is observed in DW1, SPW1, DS0 and DW2, all showing amplitudes up to 1 K over the Equator and much larger at 65° N. Large peaks of 5 K are observed in DW1, and peaks of 3 K are observed in SPW1 at 65° N. Interestingly, the peaks in DW1 occur at times of the maximum gradient in mean temperature.
10	Constant mean temperature	$T = 280$	Mean temperature is extracted and absolutely no aliasing is observed over either latitude.

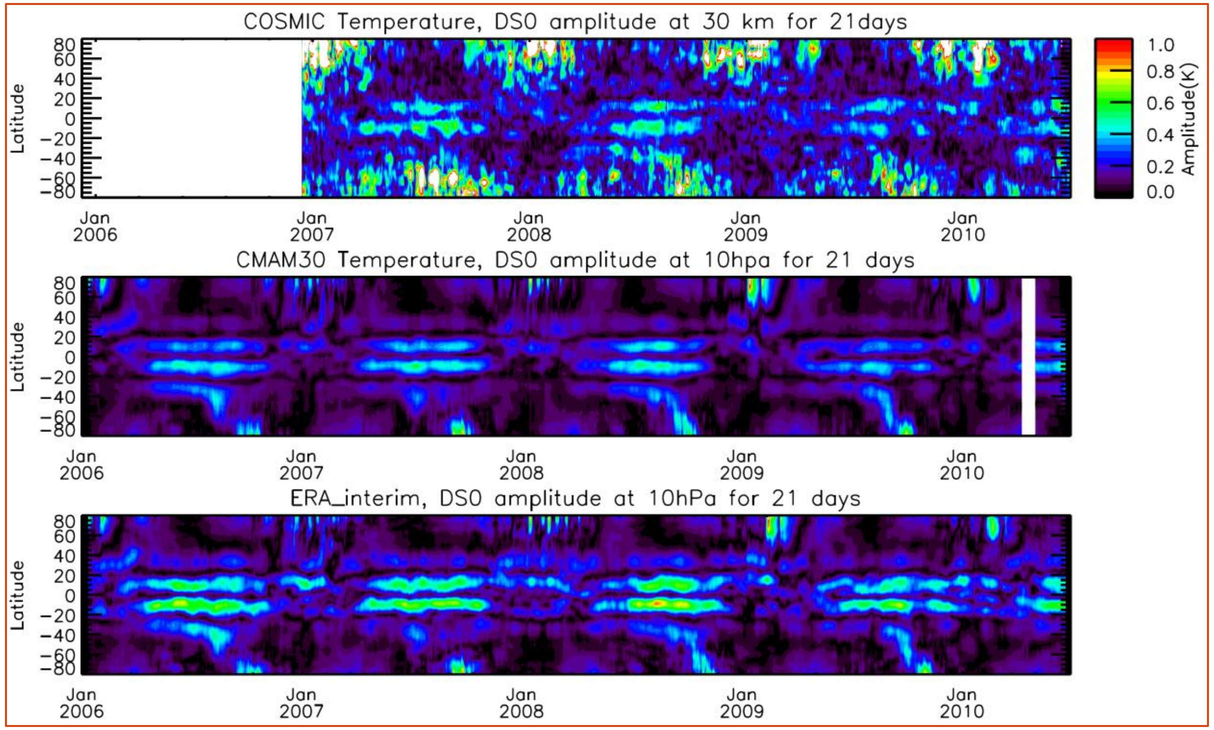


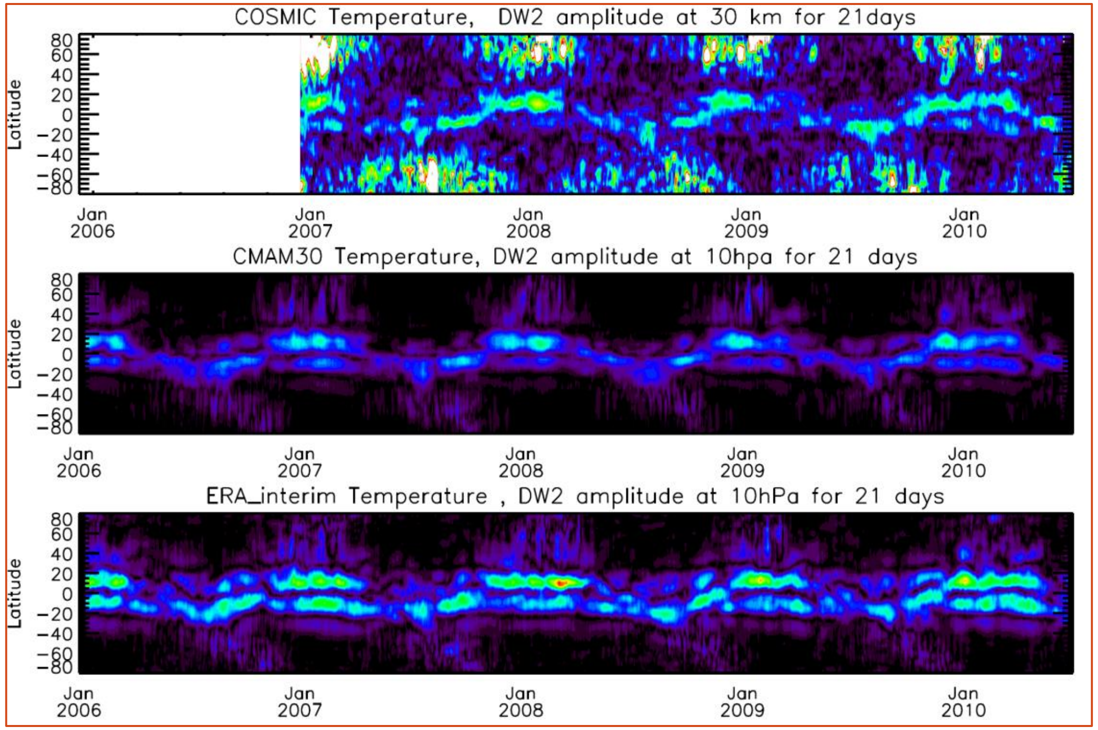
Results of numerical experiments from cases 1 to 7 (Table 1) for atmospheres considered to have only one variability among SPW1, DS0 and DW2.



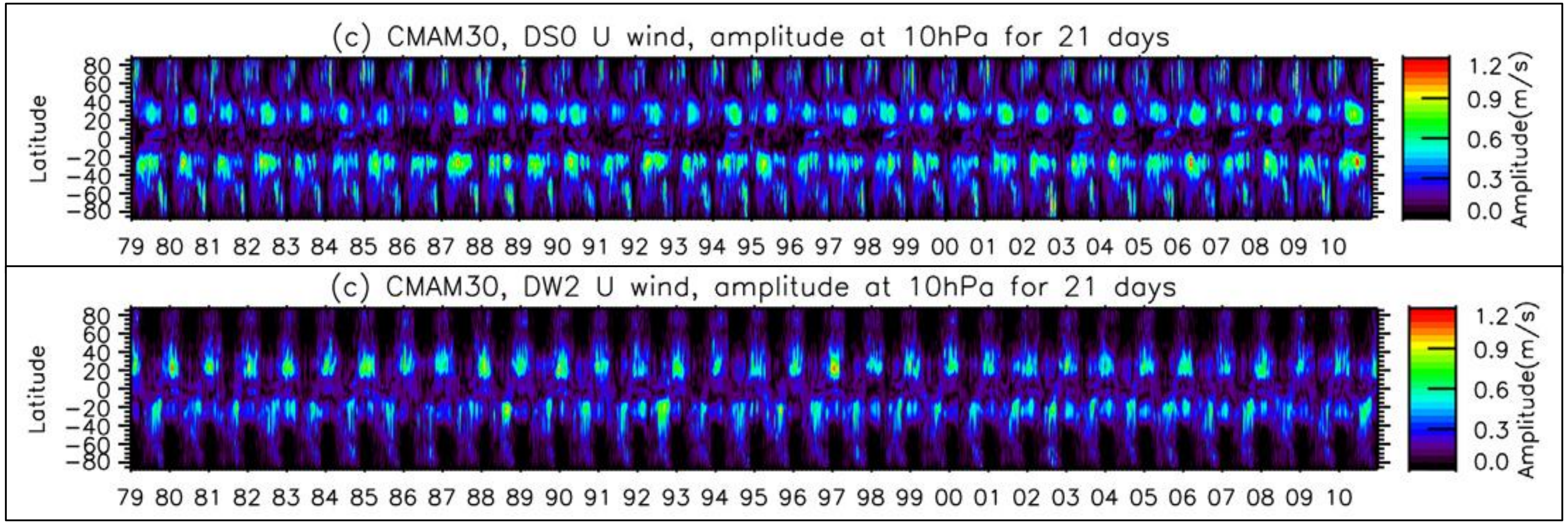
Results of numerical experiments from cases 8 to 10 (Table 1) for atmospheres considered to have only a mean temperature variation.

Das et al 2020, Annales Geophysicae





Debnath and Das et al., 2023, Atmosphere.



Das et al., 2024, Adv Space Res.

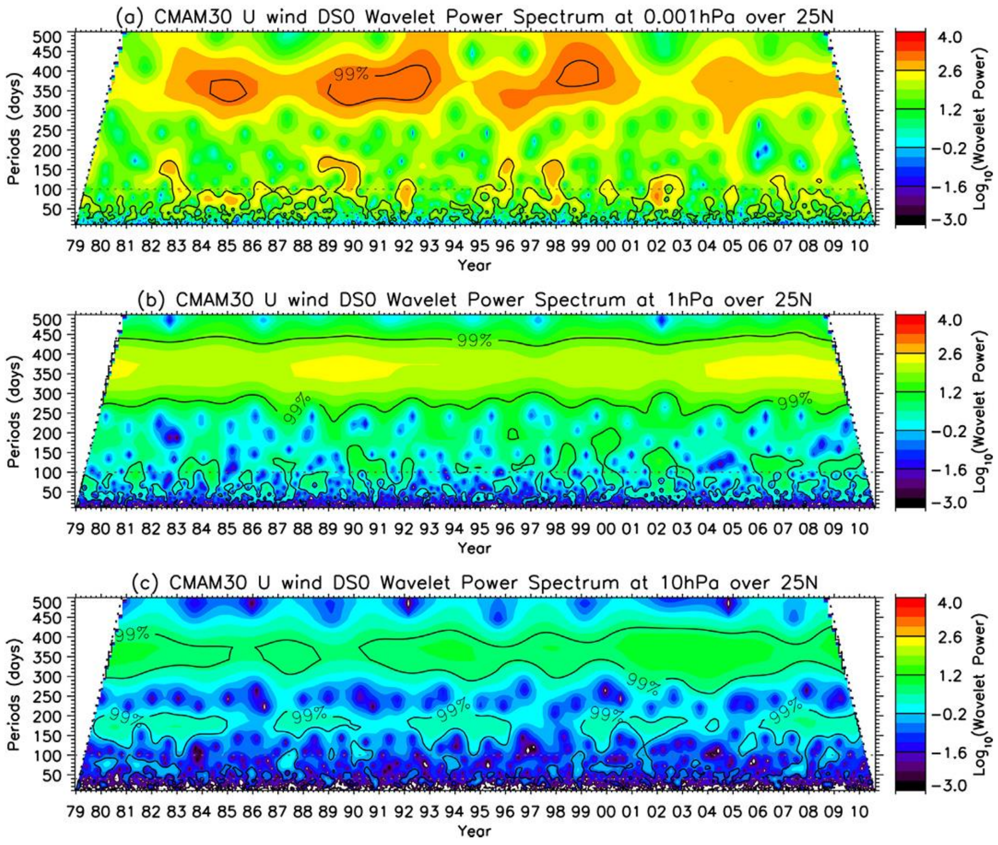


Fig. 5. Wavelet spectrograms of DS0 amplitude at 0.001 hPa, 1 hPa and 10 hPa over 25°N from CMAM30 zonal (U) wind data.

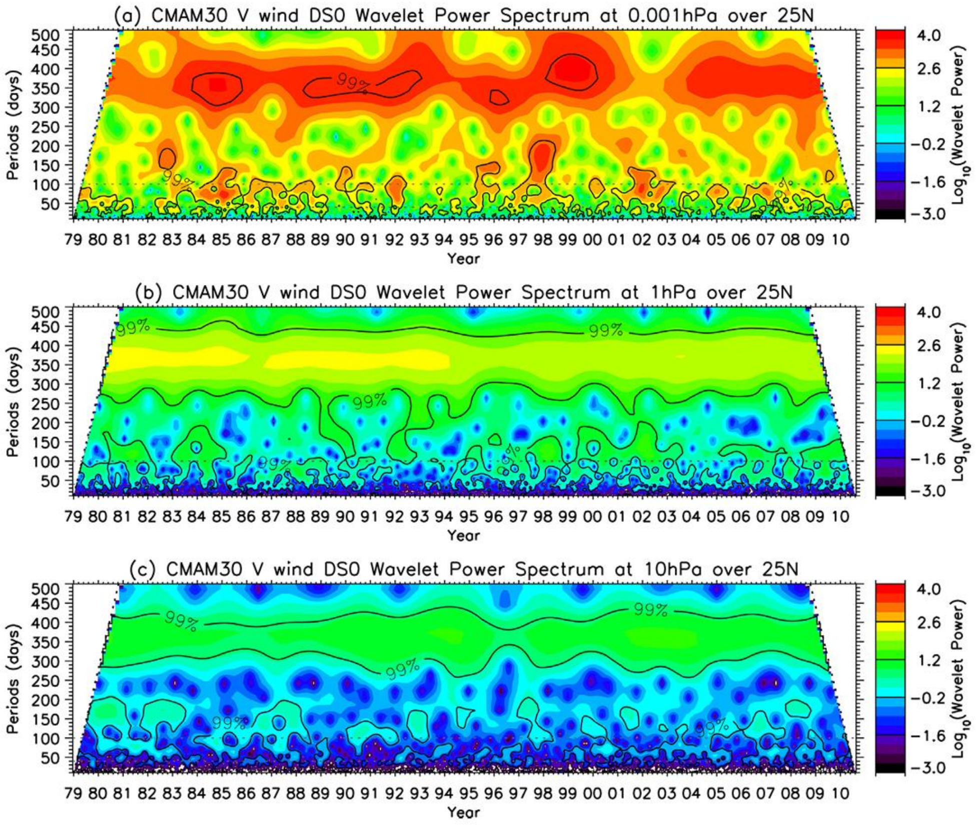
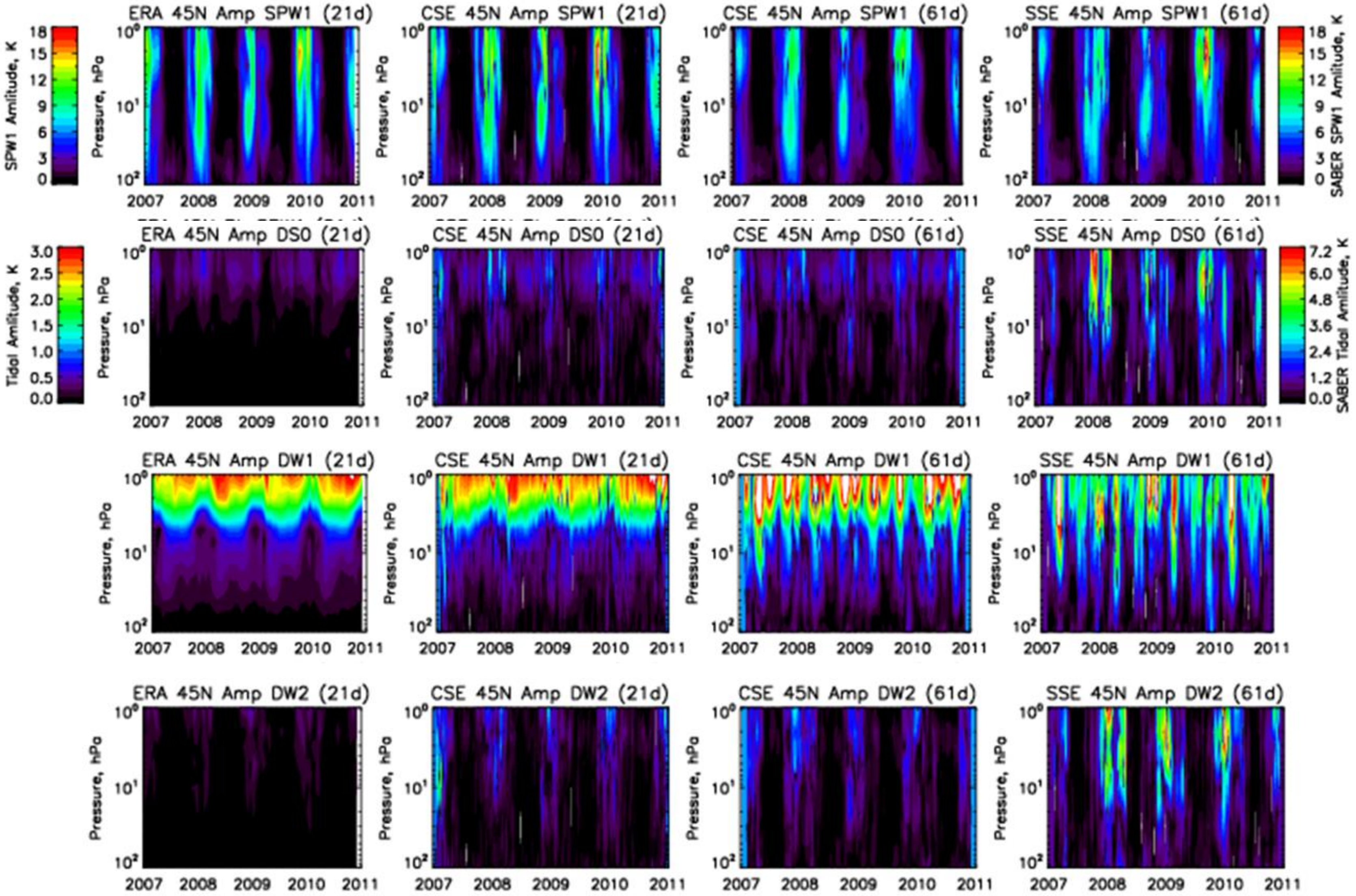


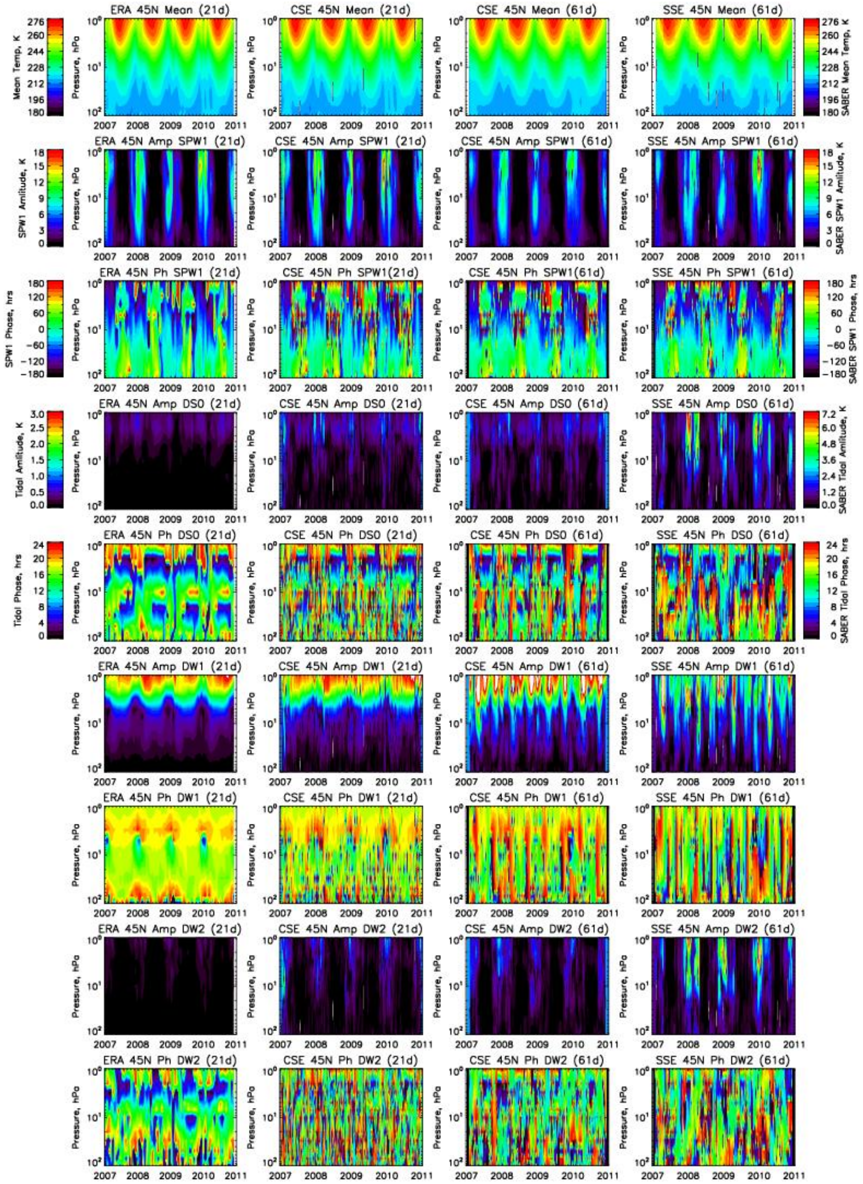
Fig. 6. Wavelet spectrograms of DS0 amplitude at 0.001 hPa, 1 hPa and 10 hPa over 25°N from CMAM30 meridional (V) wind data.

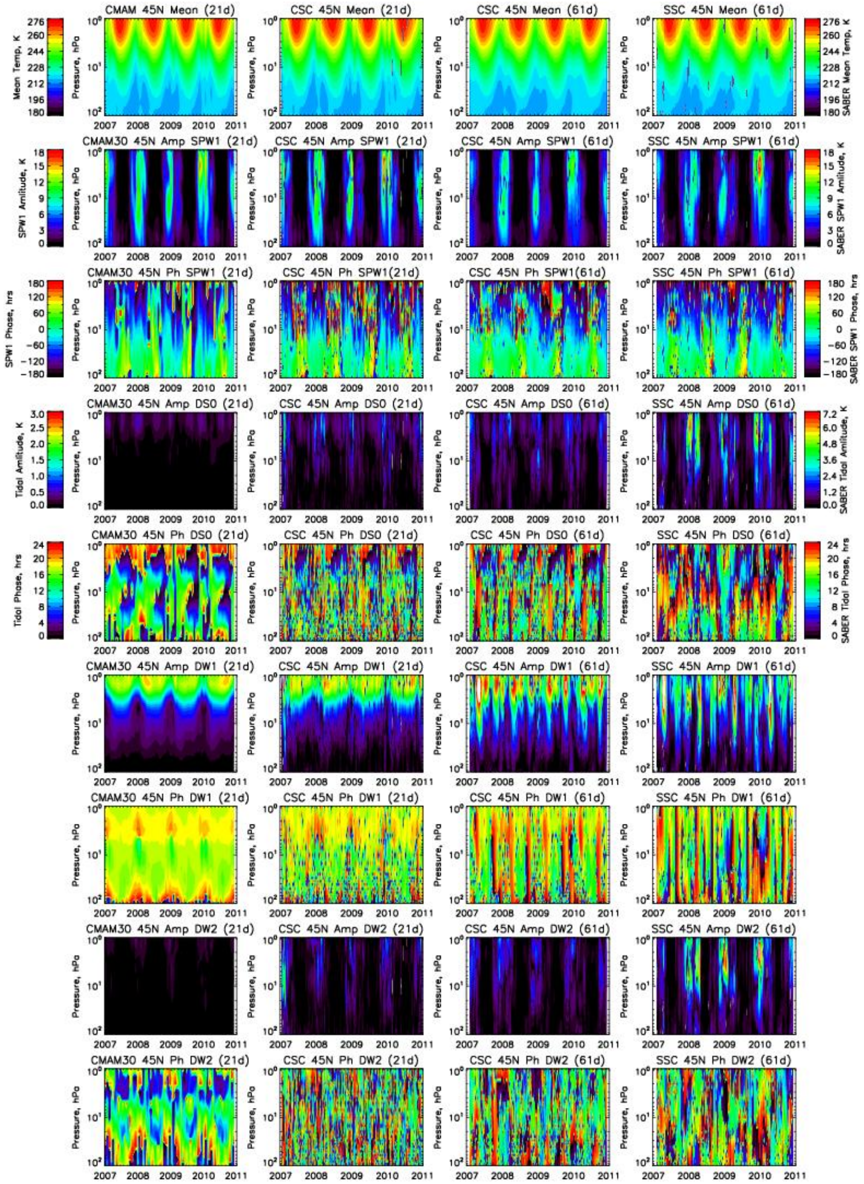
Das et al., 2024, Adv Space Res.

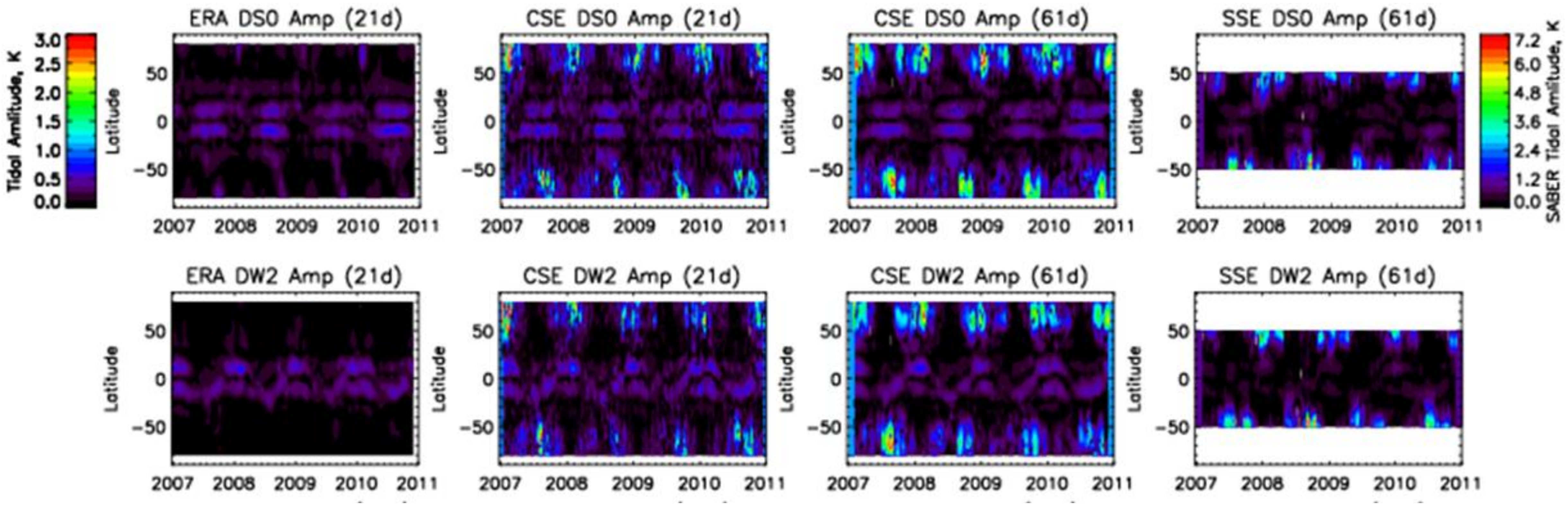
Numerical Experiments to identify aliasing due to satellite sampling

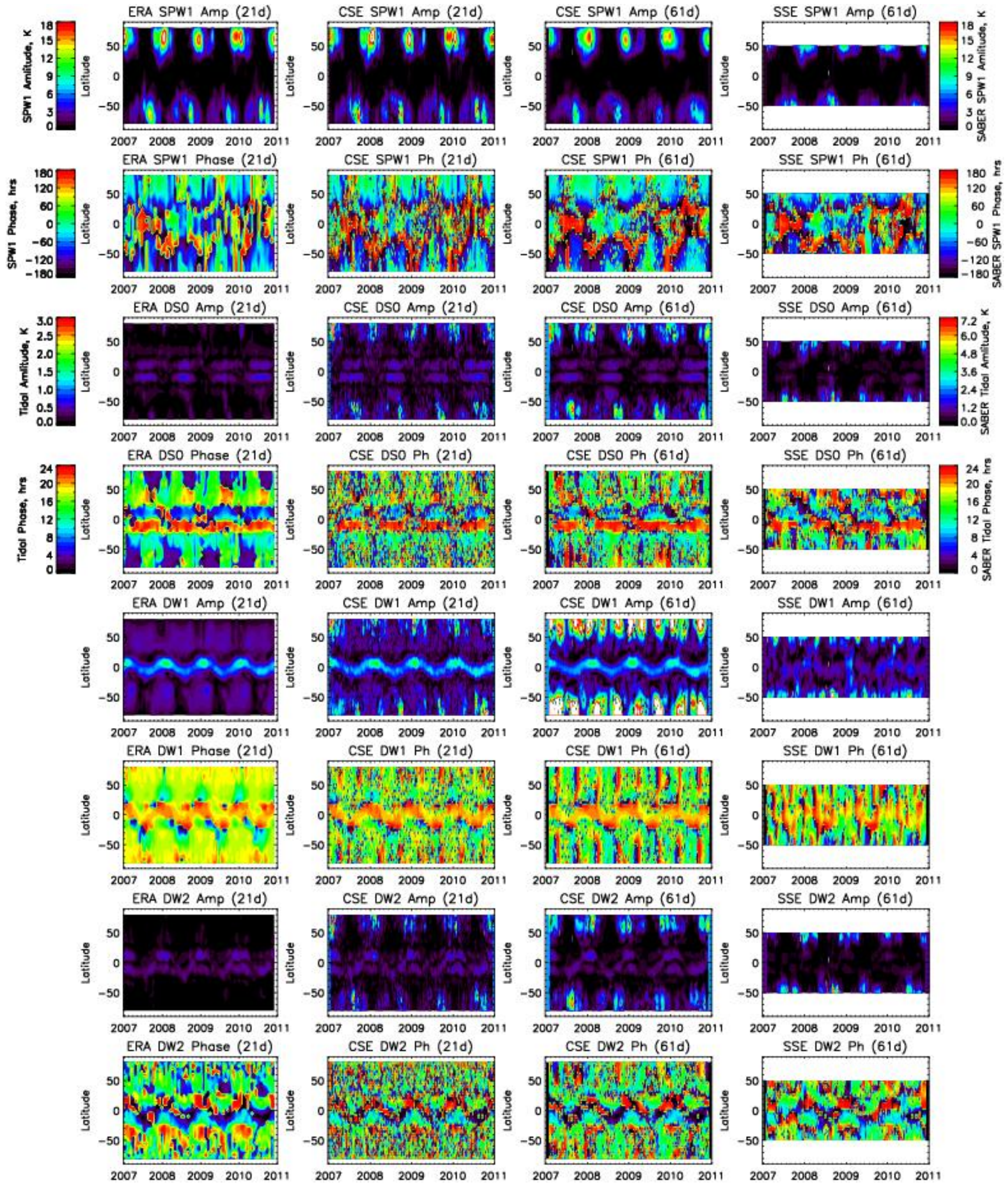
- CMAM30 and ERA-Interim datasets are resampled at times and locations of SABER and COSMIC measurements
- New datasets – CSE, SSE, CSC, SSC – are analyzed by same methods as the satellite datasets.
- Comparisons with Fourier spectra of CMAM30 and ERA-Interim show the aliasing effects, particularly in the high latitude regions.



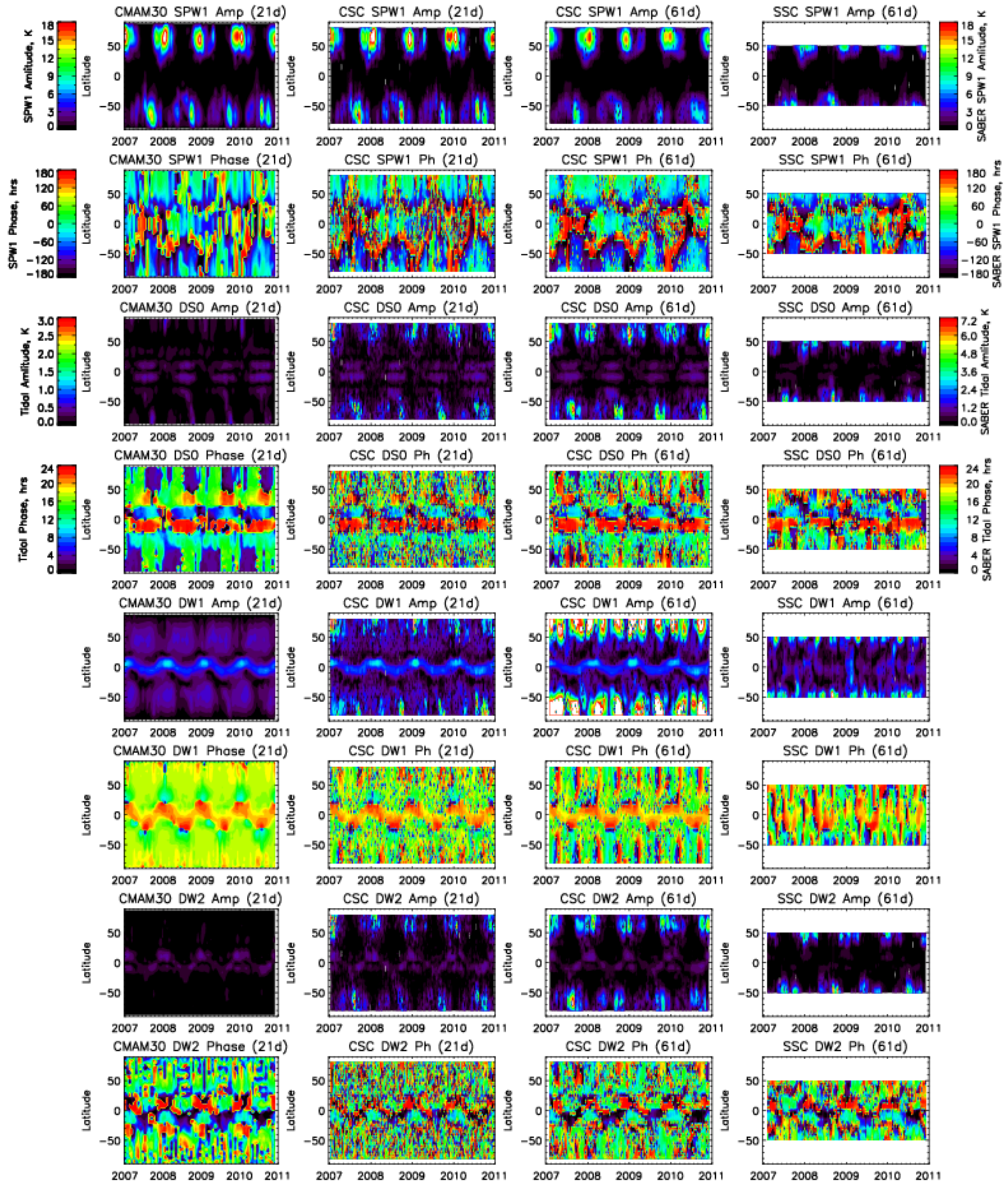

ERA 45N Mean (21d)
CSE 45N Mean (21d)
CSE 45N Mean (61d)
SSE 45N Mean (61d)
ERA 45N Amp SPW1 (21d)
CSE 45N Amp SPW1 (21d)
CSE 45N Amp SPW1 (61d)
SSE 45N Amp SPW1 (61d)
ERA 45N Ph SPW1 (21d)
CSE 45N Ph SPW1(21d)
CSE 45N Ph SPW1(61d)
SSE 45N Ph SPW1 (61d)
ERA 45N Amp DS0 (21d)
CSE 45N Amp DS0 (21d)
CSE 45N Amp DS0 (61d)
SSE 45N Amp DS0 (61d)
ERA 45N Ph DS0 (21d)
CSE 45N Ph DS0 (21d)
CSE 45N Ph DS0 (61d)
SSE 45N Ph DS0 (61d)
ERA 45N Amp DW1 (21d)
CSE 45N Amp DW1 (21d)
CSE 45N Amp DW1 (61d)
SSE 45N Amp DW1 (61d)
ERA 45N Ph DW1 (21d)
CSE 45N Ph DW1 (21d)
CSE 45N Ph DW1 (61d)
SSE 45N Ph DW1 (61d)
ERA 45N Amp DW2 (21d)
CSE 45N Amp DW2 (21d)
CSE 45N Amp DW2 (61d)
SSE 45N Amp DW2 (61d)
ERA 45N Ph DW2 (21d)
CSE 45N Ph DW2 (21d)
CSE 45N Ph DW2 (61d)
SSE 45N Ph DW2 (61d)
Mean Temp, K
SABER Mean Temp, K
SPW1 Amlitude, K
SABER SPW1 Amlitude, K
SPW1 Phase, hrs
SABER SPW1 Phase, hrs
Tidal Amplitude, K
SABER Tidal Amplitude, K
Tidal Phase, hrs
SABER Tidal Phase, hrs
Pressure, hPa


CMAM 45N Mean (21d)
CSC 45N Mean (21d)
CSC 45N Mean (61d)
SSC 45N Mean (61d)
CMAM30 45N Amp SPW1 (21d)
CSC 45N Amp SPW1 (21d)
CSC 45N Amp SPW1 (61d)
SSC 45N Amp SPW1 (61d)
CMAM30 45N Ph SPW1 (21d)
CSC 45N Ph SPW1(21d)
CSC 45N Ph SPW1(61d)
SSC 45N Ph SPW1 (61d)
CMAM30 45N Amp DS0 (21d)
CSC 45N Amp DS0 (21d)
CSC 45N Amp DS0 (61d)
SSC 45N Amp DS0 (61d)
CMAM30 45N Ph DS0 (21d)
CSC 45N Ph DS0 (21d)
CSC 45N Ph DS0 (61d)
SSC 45N Ph DS0 (61d)
CMAM30 45N Amp DW1 (21d)
CSC 45N Amp DW1 (21d)
CSC 45N Amp DW1 (61d)
SSC 45N Amp DW1 (61d)
CMAM30 45N Ph DW1 (21d)
CSC 45N Ph DW1 (21d)
CSC 45N Ph DW1 (61d)
SSC 45N Ph DW1 (61d)
CMAM30 45N Amp DW2 (21d)
CSC 45N Amp DW2 (21d)
CSC 45N Amp DW2 (61d)
SSC 45N Amp DW2 (61d)
CMAM30 45N Ph DW2 (21d)
CSC 45N Ph DW2 (21d)
CSC 45N Ph DW2 (61d)
SSC 45N Ph DW2 (61d)
Mean Temp, K
SABER Mean Temp, K
SPW1 Amlitude, K
SABER SPW1 Amlitude, K
SPW1 Phase, hrs
SABER SPW1 Phase, hrs
Tidal Amplitude, K
SABER Tidal Amplitude, K
Tidal Phase, hrs
SABER Tidal Phase, hrs
Pressure, hPa

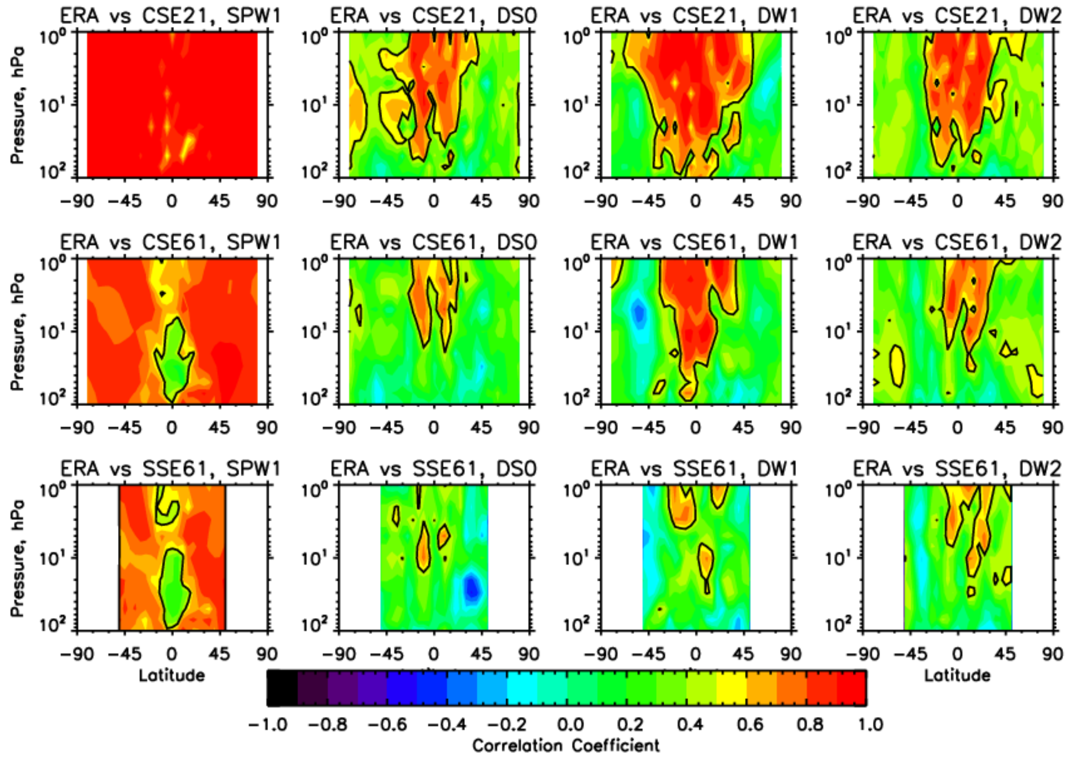

ERA DS0 Amp (21d)
CSE DS0 Amp (21d)
CSE DS0 Amp (61d)
SSE DS0 Amp (61d)
ERA DW2 Amp (21d)
CSE DW2 Amp (21d)
CSE DW2 Amp (61d)
SSE DW2 Amp (61d)
Tidal Amlitude, K
3.0
2.5
2.0
1.5
1.0
0.5
0.0
SABER Tidal Amlitude, K
7.2
6.0
4.8
3.6
2.4
1.2
0.0
Latitude
50
0
−50
2007
2008
2009
2010
2011

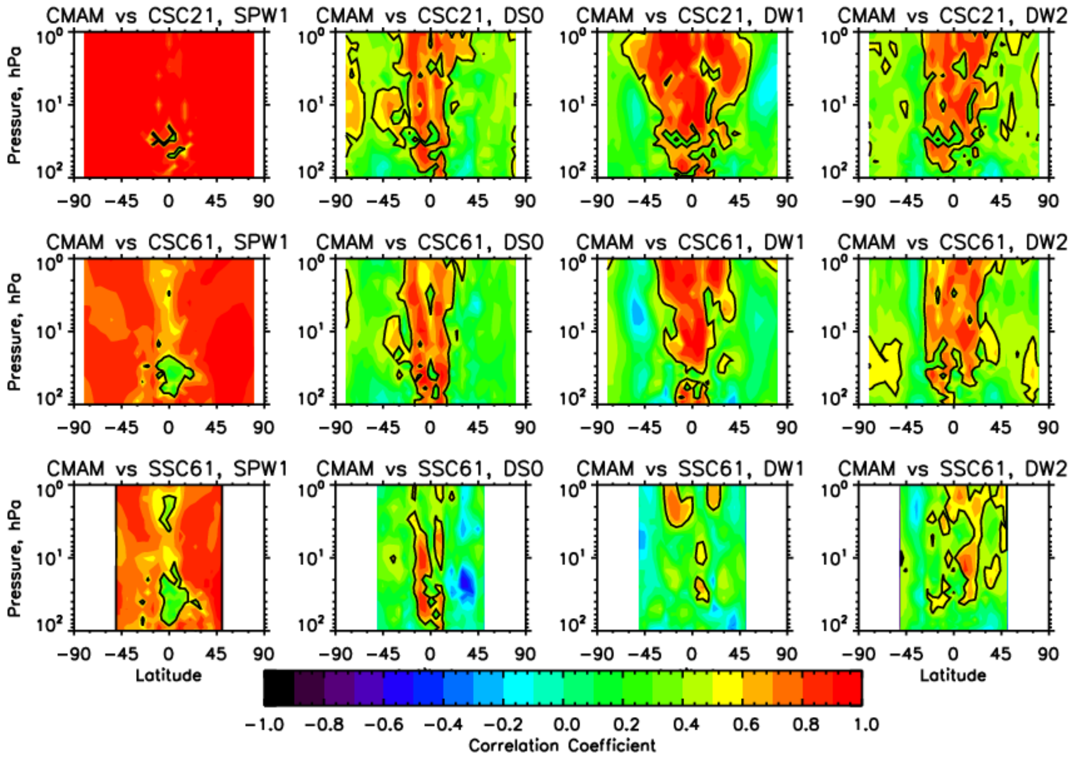


ERA SPW1 Amp (21d)
CSE SPW1 Amp (21d)
CSE SPW1 Amp (61d)
SSE SPW1 Amp (61d)
ERA SPW1 Phase (21d)
CSE SPW1 Ph (21d)
CSE SPW1 Ph (61d)
SSE SPW1 Ph (61d)
ERA DS0 Amp (21d)
CSE DS0 Amp (21d)
CSE DS0 Amp (61d)
SSE DS0 Amp (61d)
ERA DS0 Phase (21d)
CSE DS0 Ph (21d)
CSE DS0 Ph (61d)
SSE DS0 Ph (61d)
ERA DW1 Amp (21d)
CSE DW1 Amp (21d)
CSE DW1 Amp (61d)
SSE DW1 Amp (61d)
ERA DW1 Phase (21d)
CSE DW1 Ph (21d)
CSE DW1 Ph (61d)
SSE DW1 Ph (61d)
ERA DW2 Amp (21d)
CSE DW2 Amp (21d)
CSE DW2 Amp (61d)
SSE DW2 Amp (61d)
ERA DW2 Phase (21d)
CSE DW2 Ph (21d)
CSE DW2 Ph (61d)
SSE DW2 Ph (61d)
SPW1 Amplitude, K
SPW1 Phase, hrs
Tidal Amplitude, K
Tidal Phase, hrs
SABER SPW1 Amplitude, K
SABER SPW1 Phase, hrs
SABER Tidal Amplitude, K
SABER Tidal Phase, hrs
Latitude
2007 2008 2009 2010 2011

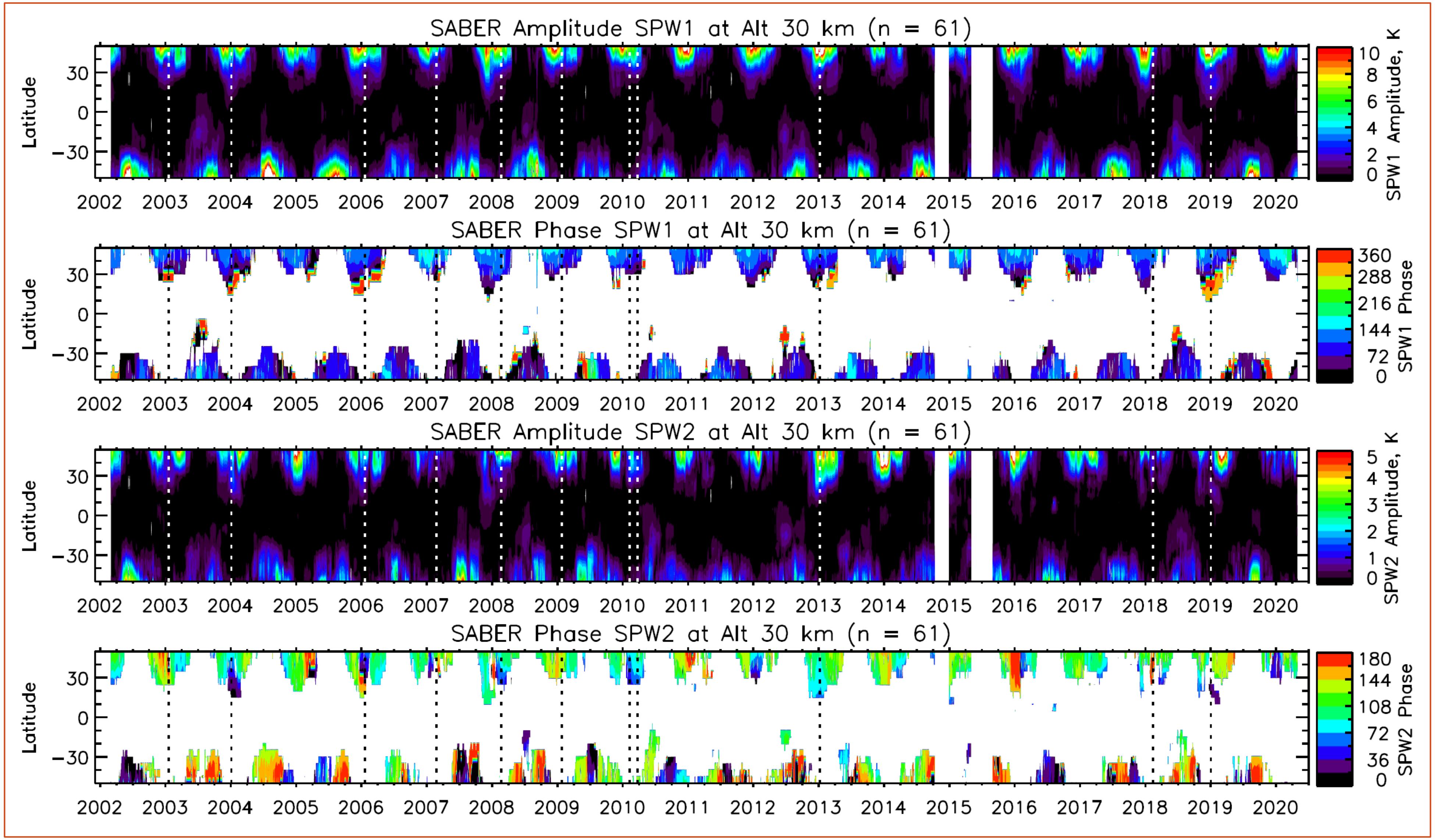


CMAM30 SPW1 Amp (21d)
CSC SPW1 Amp (21d)
CSC SPW1 Amp (61d)
SSC SPW1 Amp (61d)
CMAM30 SPW1 Phase (21d)
CSC SPW1 Ph (21d)
CSC SPW1 Ph (61d)
SSC SPW1 Ph (61d)
CMAM30 DS0 Amp (21d)
CSC DS0 Amp (21d)
CSC DS0 Amp (61d)
SSC DS0 Amp (61d)
CMAM30 DS0 Phase (21d)
CSC DS0 Ph (21d)
CSC DS0 Ph (61d)
SSC DS0 Ph (61d)
CMAM30 DW1 Amp (21d)
CSC DW1 Amp (21d)
CSC DW1 Amp (61d)
SSC DW1 Amp (61d)
CMAM30 DW1 Phase (21d)
CSC DW1 Ph (21d)
CSC DW1 Ph (61d)
SSC DW1 Ph (61d)
CMAM30 DW2 Amp (21d)
CSC DW2 Amp (21d)
CSC DW2 Amp (61d)
SSC DW2 Amp (61d)
CMAM30 DW2 Phase (21d)
CSC DW2 Ph (21d)
CSC DW2 Ph (61d)
SSC DW2 Ph (61d)
SPW1 Amplitude, K
SPW1 Phase, hrs
Tidal Amplitude, K
Tidal Phase, hrs
SABER SPW1 Amplitude, K
SABER SPW1 Phase, hrs
SABER Tidal Amplitude, K
SABER Tidal Phase, hrs
Latitude
2007 2008 2009 2010 2011





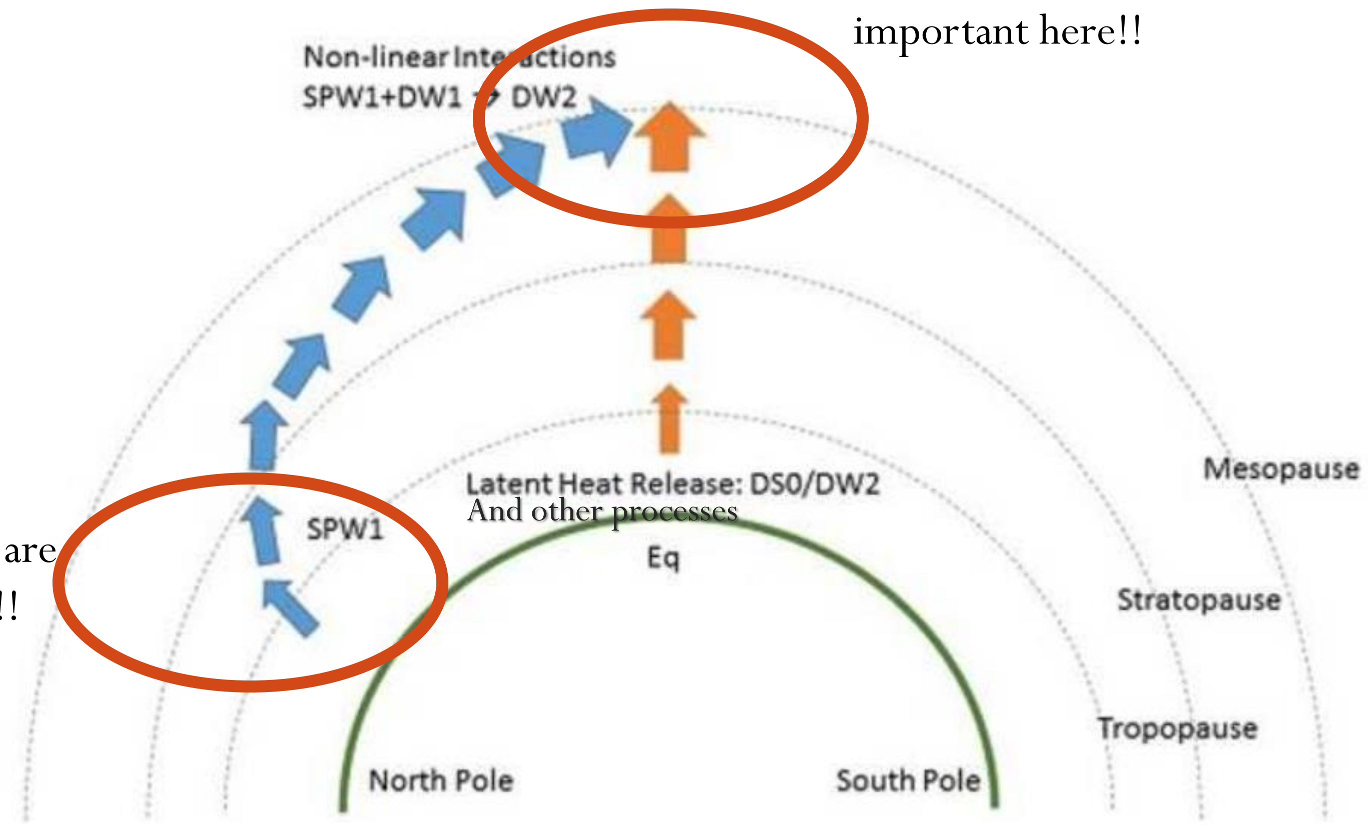
- SPW1 from CMAM30 and ERA-Interim datasets compare very well with the results from the resampled datasets.
- Tidal amplitudes extraction is very poor by SSE61 & SSC61 and relatively poor by CSE61 & CSC61.
- COSMIC provides a better sampling for extraction of tidal characteristics but has limited altitude coverage.
- SABER has good altitude coverage but sampling suffers from significant aliasing problems.



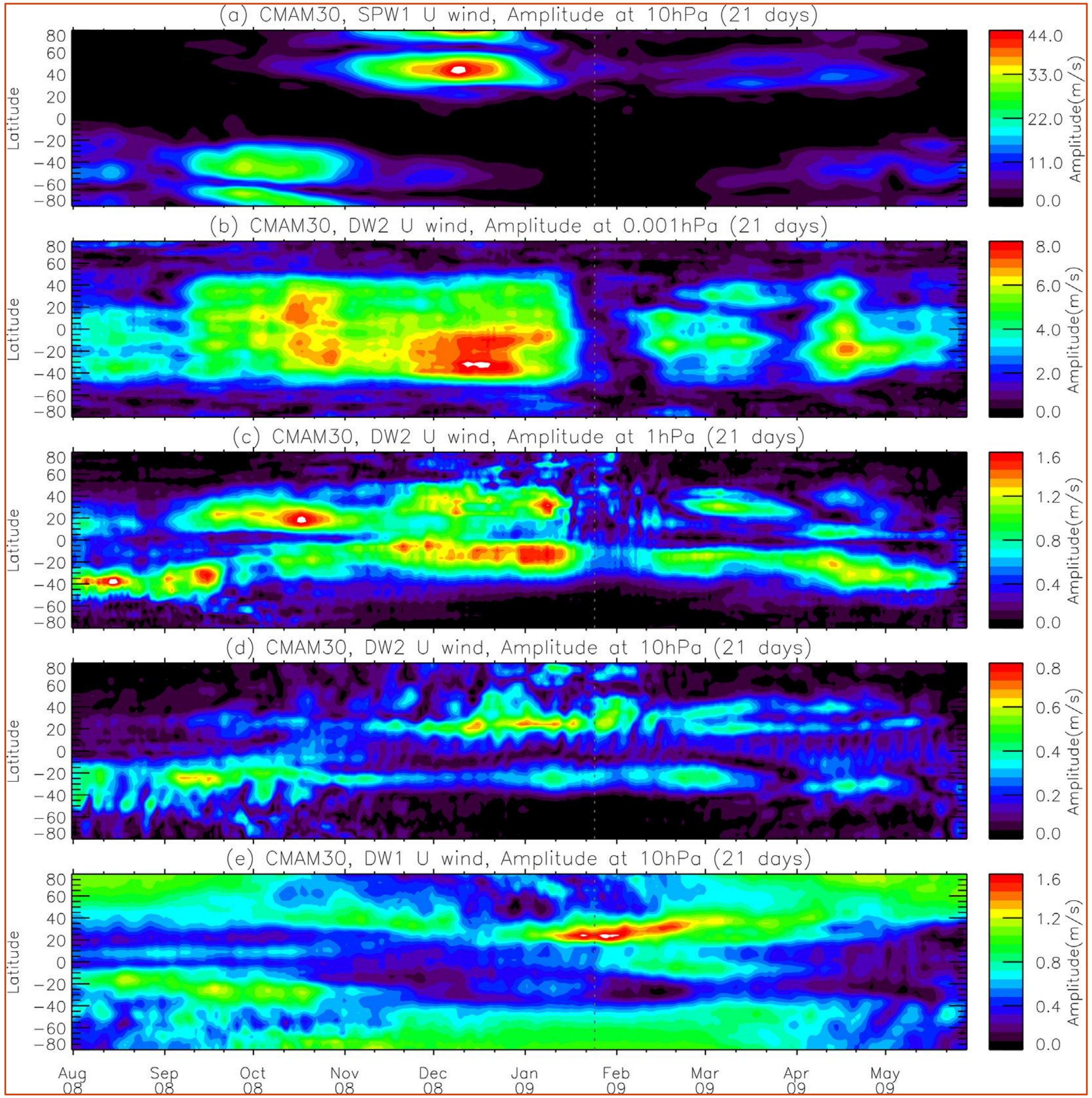
Das, 2022, JASTP

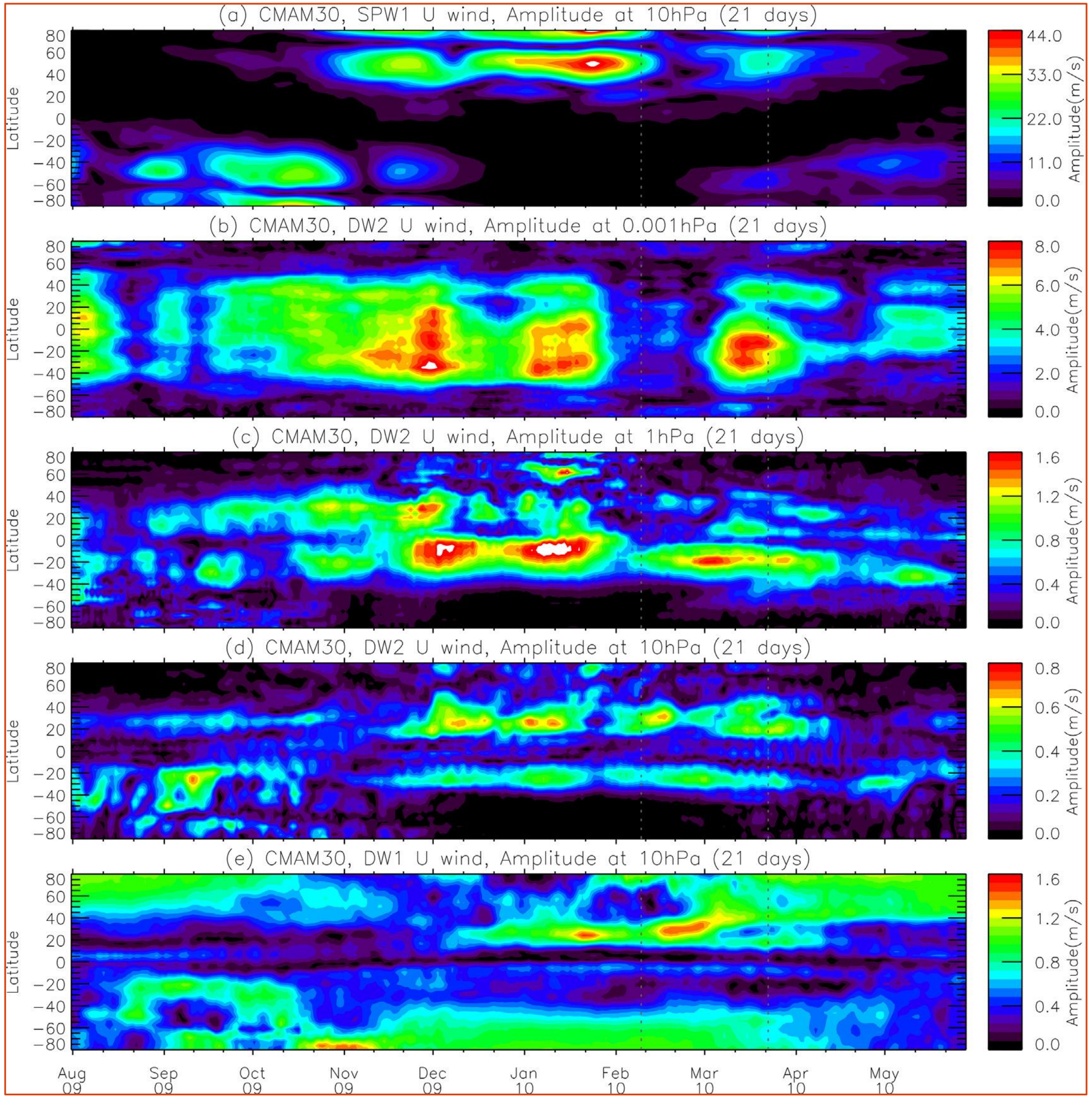
The processes...

Non-linear interactions are important here!!

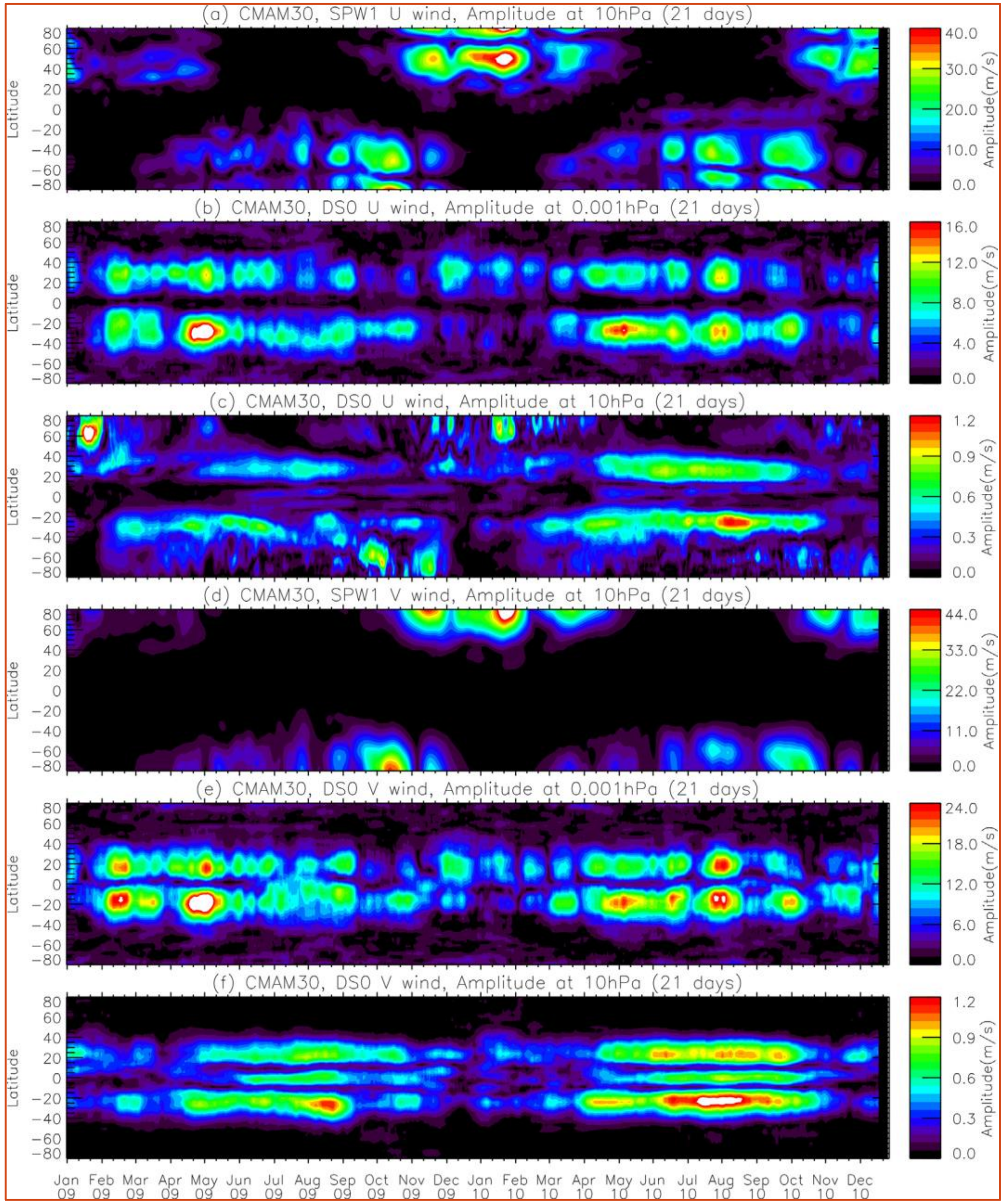


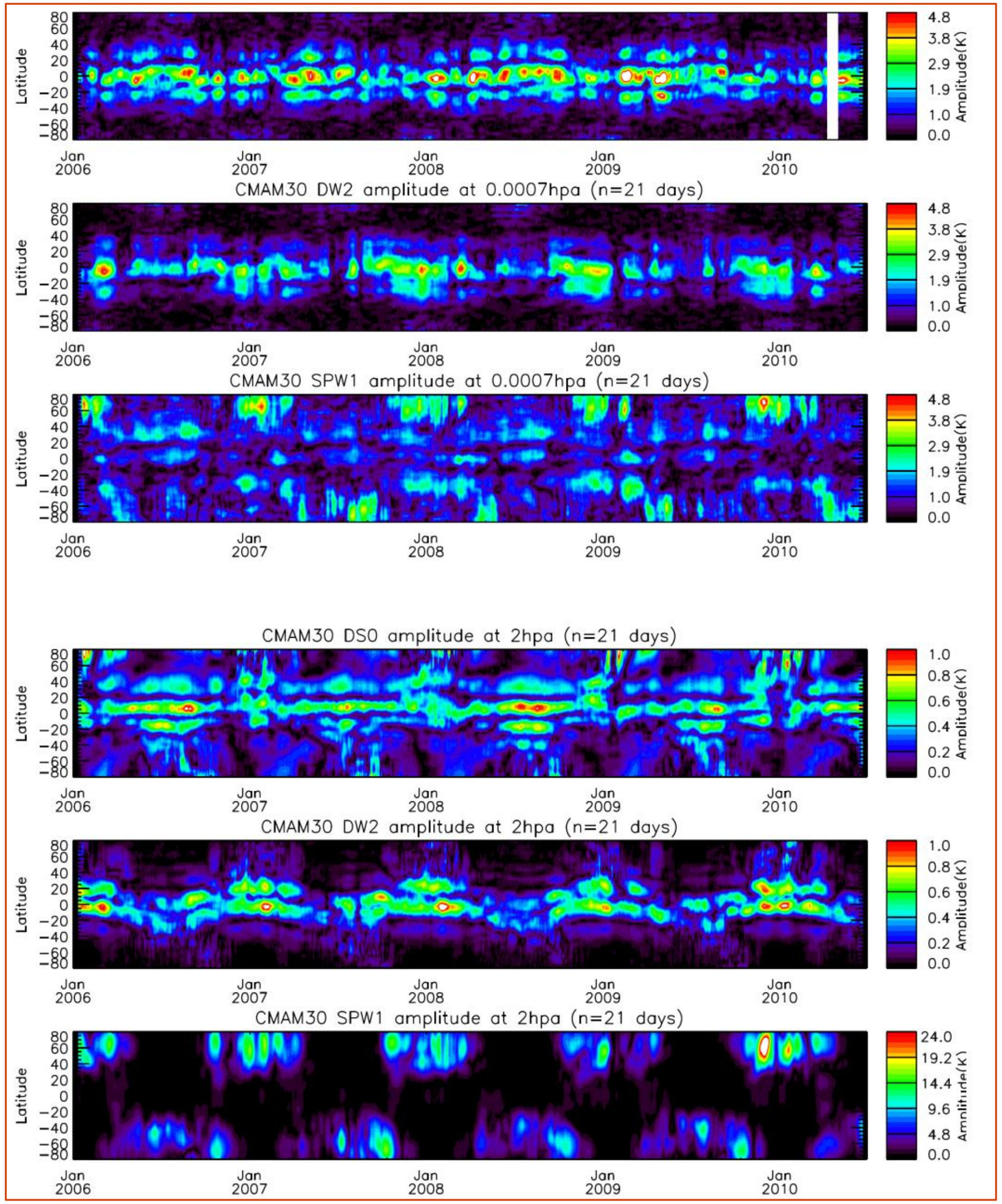
Non-linear interactions are **NOT** important here!!





Das et al., 2024, Adv Space Res.





Das et al., 2024, Adv Space Res.

Conclusions

- COSMIC gives better results compared to SABER as it is a constellation of six satellites and has better sampling required for investigation of tides.
- However, COSMIC, although having good global sampling, has limited altitude coverage and SABER having good altitude coverage, lacks sufficient sampling.
- Thereby, accurate deduction of tidal variability in middle and upper atmosphere from actual measurements is still a pending job!
- The current study via investigations of model and reanalysis data confirms that
  - Non-linear interactions are not important for generation of DS0 and DW2 in the high latitude stratosphere.
  - Non-linear interactions play an important role in generation of DW2 in equatorial and tropical mesosphere.

THANK YOU!