Refining Tropical Atmospheric Dynamics and QBO Representation in the MPAS Model via Data Assimilation of Equatorial Waves from Strateole-2 Balloon Observations

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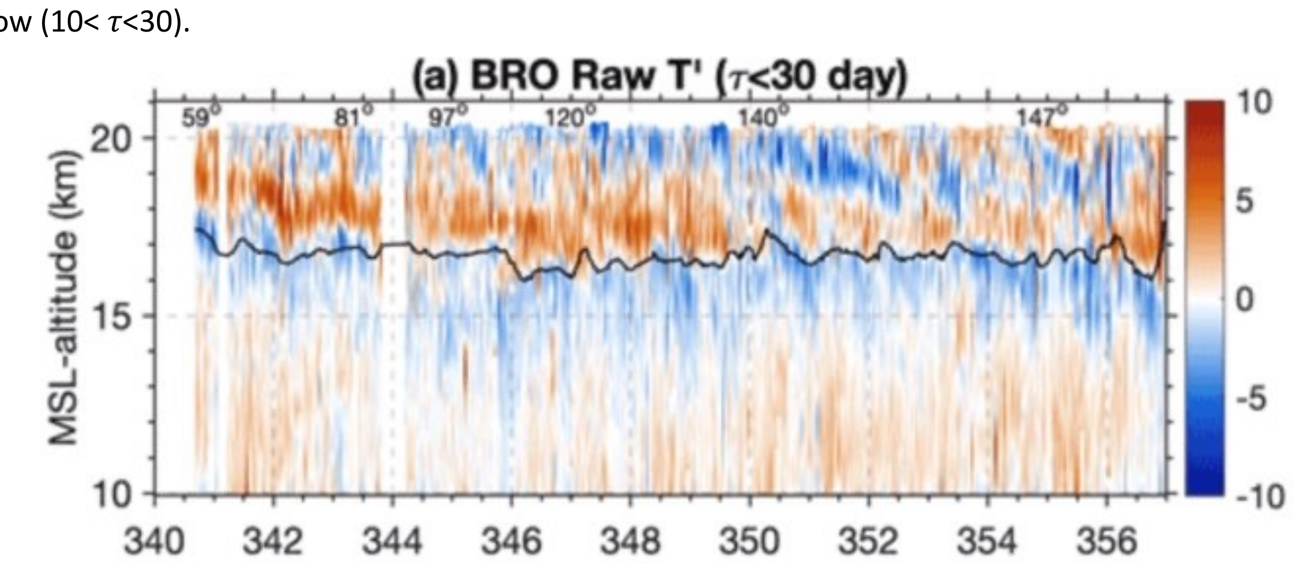
1. Motivation

Tropical Atmospheric Waves

- Kelvin waves are large scale waves resulting from the Coriolis force that are at low latitudes and propagate eastward. They occur in the upper troposphere-lower stratosphere.
- These waves can be identified by the west to east tilt of zonal winds with increasing altitude and a perturbation of warm and cool temperatures.
- Tropical waves influence weather and climate by impacting cirrus cloud formation, stratospheric dehydration, and wave-driven circulation patterns.
- Tropical atmospheric waves contribute to weather and climate effects such as tropical cyclogenesis and the Quasi-Biennial Oscillation (QBO).
- Kelvin waves have multiple periods of propagation. We categorize wave periods τ by fast (τ<10 days) and slow (10< τ<30).



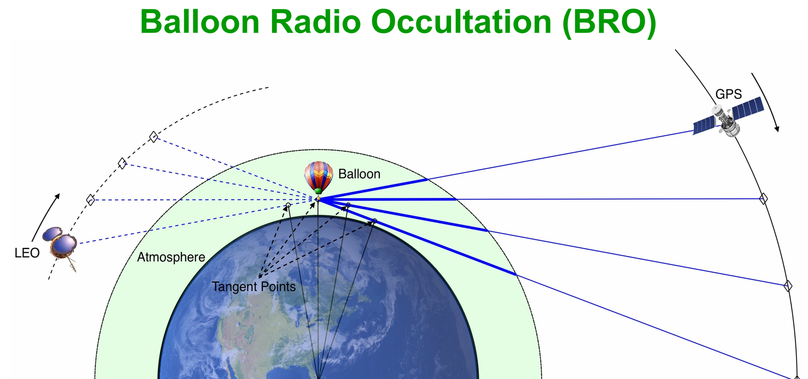
Cao et al., 2022, ACP.: Time–altitude cross-section of the 17 d continuous measurement period from the 2019 Strateole-2 Campaign. BRO temperature perturbations with periods of less than 30 d.

Objectives:

- The objective of this work is to understand the current capabilities of models to resolve waves of different scales through comparison with Balloon Radio Occultation (BRO) observations.
- Additionally, modeling these waves is challenging because it demands a high resolution grid and has unresolved small-scale waves, leading to a bias in the QBO evolution.
- BRO has the potential to observe higher resolution tropical waves and improve our understanding of how models resolve their structure by providing data to quantify wave structures.
- BRO also observes the waves in the Lagrangian reference frame of the floating balloon thus providing measurements that are directly comparable to dispersion relations for the intrinsic period.

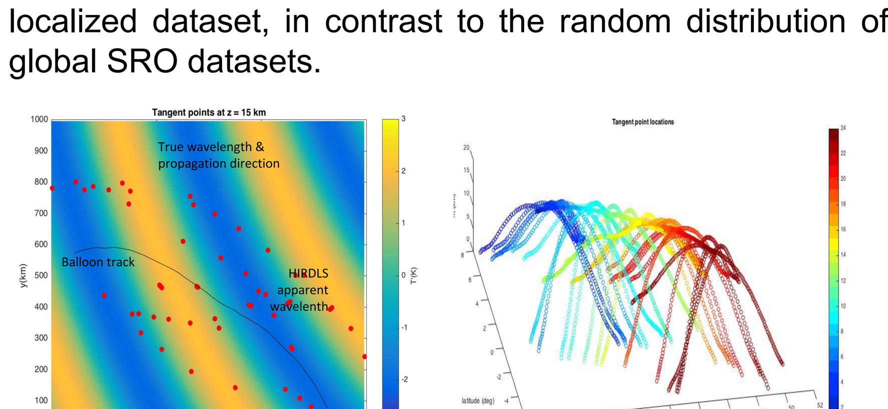
2. Strateole-2 (STR-2)

Balloon Radio Occultation (BRO)



Geometry of Balloon-borne Radio Occultation

- BRO measures the index of refraction using the delay (due to atmospheric pressure, moisture and temperature) of GNSS signal travel times relative to the vacuum path.
- Each balloon carries a radio occultation profiler (ROC2) to sample large horizontal scale, fine vertical scale waves in 3D by sampling on and to the sides of the flight track.
- BRO enables continuous RO measurements over a localized dataset, in contrast to the random distribution of global SRO datasets.



Schematic representation of how ROC observations sample the wavefield in 3D, for example, of waves with ~600 km wavelength.

Strateole-2 Campaign

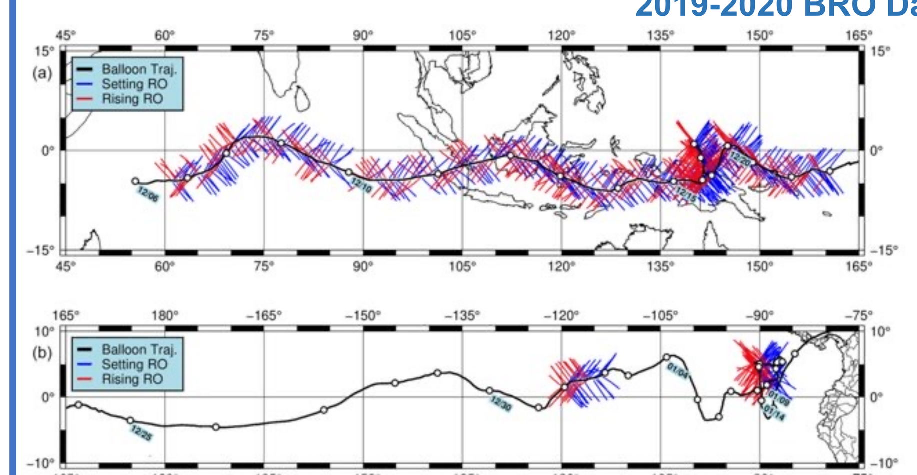
- An international, multi-year series of campaigns utilizing long-duration stratospheric pressure balloons to study the atmospheric dynamics and composition of the tropical tropopause layer.
- Technology validation campaign began in November 2019 from Seychelles, South Indian Ocean, and ended in February 2020.
- Eight balloons launched, equipped with instruments to measure atmospheric temperature, water vapor, aerosol, and more.
- Conducted a test launch in Kiruna, Sweden in June 2024 to validate the new hardware.
- Final Campaign scheduled for October 2025 with 7 balloons flying along the equator in the upper troposphere and lower stratosphere.

Spherical Helium Super Pressure Balloons, 11 and 13 -m diameter, fly at 18 and 20 km altitude, respectively.

One STR-2 flight carried ROC2 as well as the BeCOOL backscatter LIDAR for detecting cirrus clouds.

3. Waves in Observations

2019-2020 BRO Dataset

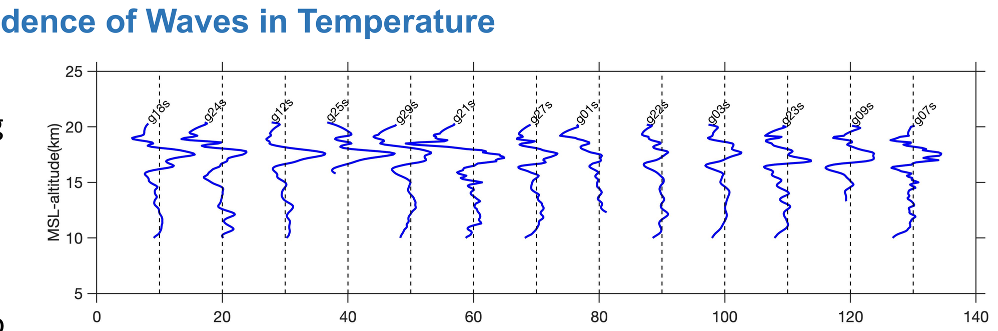


Cao et al., 2022, ACP.: Dataset available for modeling study. Blue are setting occultations and red are rising occultations.

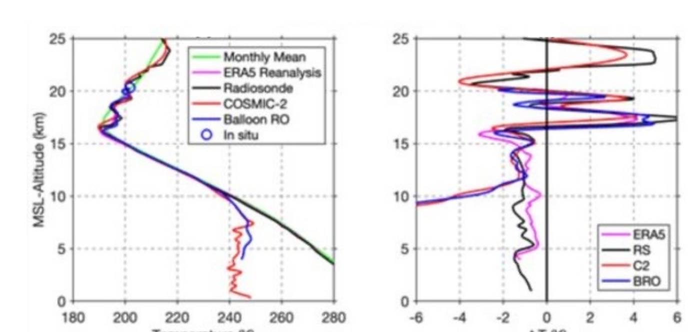
- Super pressure balloons flew around equator at 18-20 km altitudes, measuring 40-50 profiles daily.
- Temperature profiles were retrieved from flight altitude down to 6-8km altitude.
- Dates of data availability are 2019-12-06-18z – 2019-12-23-00z & 2020-01-01-00z – 2020-01-13-18z.
- Each tangent point profile at right starts from the balloon location at ~10 km and samples further from the flight path as the tangent point descends.
- Large scale wave motion is evident in the balloon flight path.

Evidence of Waves in Temperature

- Previous work investigated bending angle in retrieved temperature finding that a coherent wave structure with ~4 km wavelength dominates the variability.
- We hypothesize bending angle shows higher vertical resolution compared to retrieved temperatures.



Cao et al., 2022, ACP.: Transect of 11 NW-SE oriented BRO temperature profiles from 12 December 2019 south of balloon trajectory. Large-scale background temperature profile is removed.



Cao et al., 2022, ACP.: Temperature profiles and temperature differences with respect to the COSMIC-2 monthly mean.

- ERA5 reanalysis contains small-scale wave features that are present in BRO observations and COSMIC RO observations and a nearby radiosonde.
- BRO has the resolution to show shorter vertical wavelength and slightly different amplitude than ERA5 and COSMIC RO.
- The current work seeks to make a more detailed comparison among models and BRO, in temperature and bending angle.

4. Forecast Experiment & Verification

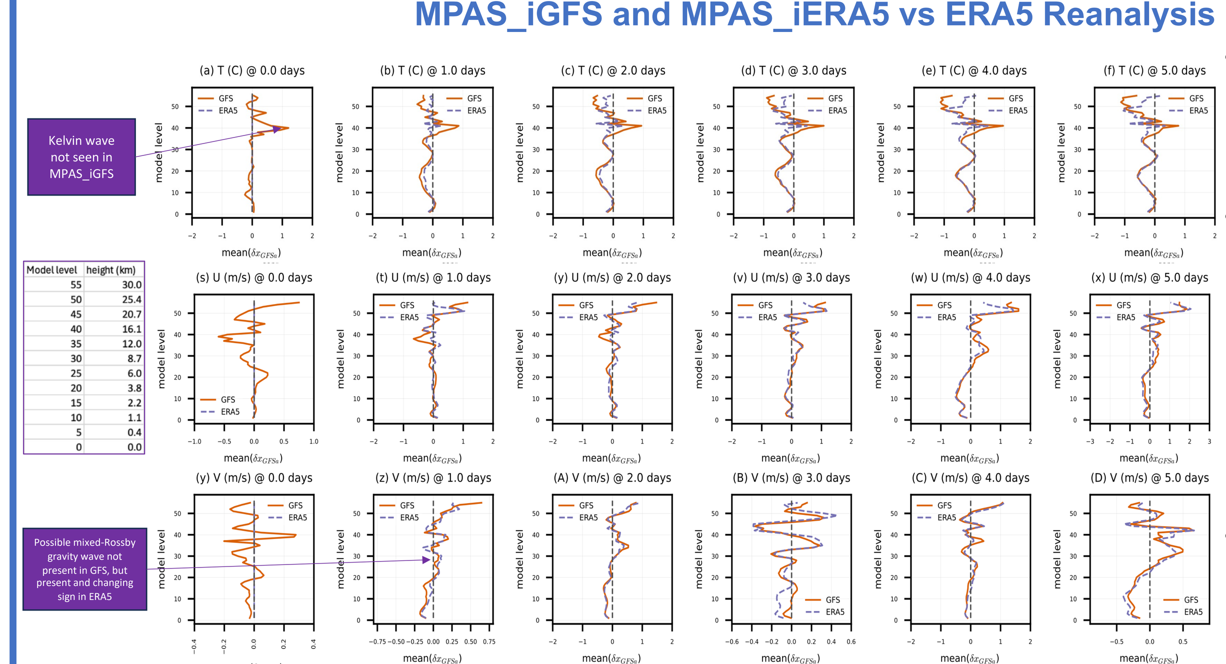
MPAS Forecast Run

- MPAS-A model is used to do forecast runs for the MPAS-JEDI data assimilation workflow.
- We conducted a 5 day forecast to see how well current global climate models can detect a presence of short term atmospheric waves and long term propagation.
- Initial conditions are from the National Center for Environmental Prediction (NCEP) Global Forecast System (GFS) analysis (MPAS_iGFS) and European Center for Medium-Range Weather Forecasting (ECMWF) Reanalysis 5 (ERA5) (MPAS_iERA5).

MPAS-A Configuration

- Initialized 2019-12-06-06Z
- 120 hour (5 day) run
- 60-15 km variable mesh in a band centered at the equator
- 55 vertical levels with 30 km top
- Mesoscale Reference Parameterizations

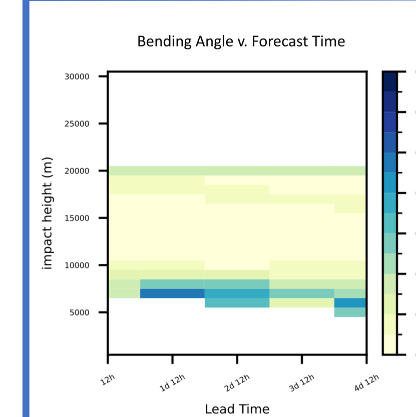
MPAS_iGFS and MPAS_iERA5 vs ERA5 Reanalysis



Mean from ERA5 reanalysis of temperature, U, V winds at 0 to 5 days forecast points. Top: Temperature, Center: Zonal winds, Bottom: Meridional winds

- The forecast results with GFS initial conditions are compared to the ERA5.
- Variability in the stratosphere is increasing greatly in an incoherent manner as time increases indicating the GFS and the ERA5 contain waves of different scales.
- Kelvin waves likely can be seen in the MPAS_iERA5 but not the MPAS_iGFS. τ <3 waves may not be present in the MPAS_iERA5.

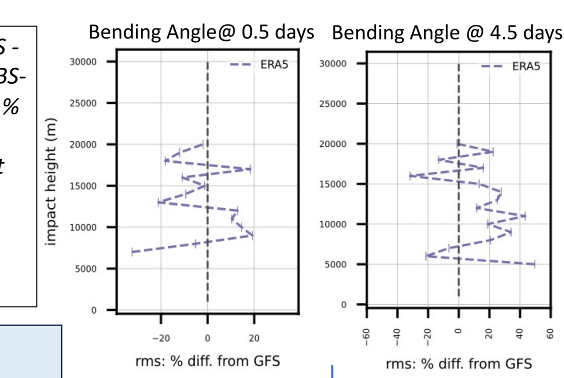
5. Forecast Verification Against BRO



***Left Figure:** (OBS – MPAS_iGFS) RMS Difference from ERA5 renalysis over 12 hr to 96 hrs vs impact height. Averaged globally.*

***Right figure:** |OBS - MPAS_iERA5|-|OBS-MPAS_iGFS| RMS % Difference from ERA5 reanalysis at 12 and 96 hrs vs impact height. Averaged over tropics.*

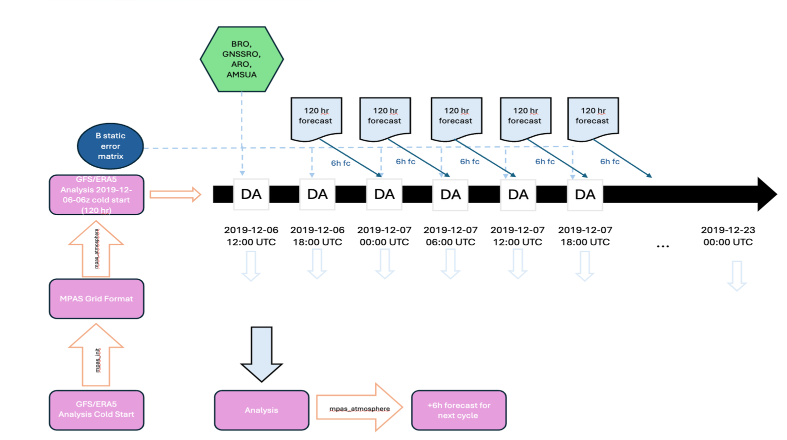
Strong wave signal** **Weak wave signal
|OBS -MPAS_iERA5|-|OBS-MPAS_iGFS| RMS% Difference



- Verification of MPAS_iERA5 and MPAS_iGFS experiments by comparing with BRO bending angle as a function of impact height.
- MPAS_iGFS differs from BRO observations in the height range of the Kelvin wave 15-19 km (left) over the 5 days.
- The sign of the difference changes over the 5 day period (right).
- There is an indication MPAS_iERA5 resolves atmospheric waves in the tropics better than MPAS_iGFS, so we will be using the ERA5 initial conditions in our data analysis experiment.

6. Next Steps: Data Assimilation

- Next, to test if BRO can impact Kelvin wave structures, MPAS-JEDI will be used for data assimilation (DA) experiments.
- 60-15 km variable outer mesh, 60 km inner mesh, 55 vertical levels, initial cold start of the ERA5 initialized at 2019-12-06 00:UTC .
- **DA Times:** 2019-12-06-06z through 2019-12-13-00z & 2020-01-01-00z through 2020-01-13-00z
- **Cycle:** 30 six-hour cycles per observation period
- **Method:** 3DVar



Flowchart of MPAS-JEDI workflow for the data assimilation experiment.

Summary

- Previous work showed ERA5 reanalysis captured 20-day Kelvin waves but underestimated the amplitude (Cao et al., 2022).
- Previous work also indicated the presence of 3-5 day waves.
- We implemented a modeling experiment with MPAS to test the hypothesis that the large horizontal scale Kelvin waves would be present in the 5-day forecast based on GFS initial conditions, but the 3-5 day waves may not be.
- The MPAS model grid and workflow was tested and successfully ran 5 day forecasts initialized at each day for which data was available.
- There is a preliminary indication that some wave signatures are missing from GFS.

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Acknowledgements

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