Assessment of Stratospheric Balloon Observations towards Assimilation in NOAA's Global Data Assimilation System (GDAS)

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Outline

- Motivation, Objectives, Background
- In Situ Balloon Data Description
- Balloon Data Evaluation
- Concluding Remarks & Next Steps

Motivation & Objectives

Stratospheric observations in the present earth observing system architecture are derived primarily from satellite data.

Such observations are difficult to validate as few in situ measurements in the stratosphere exist.

Overarching Goal:
To provide a comprehensive evaluation of the value, capability, and potential benefit that long-duration balloon data add to the observation architecture, towards the improvement of analyses and forecasts, and to the calibration and anchoring of satellite measurements in conjunction with NOAA missions.

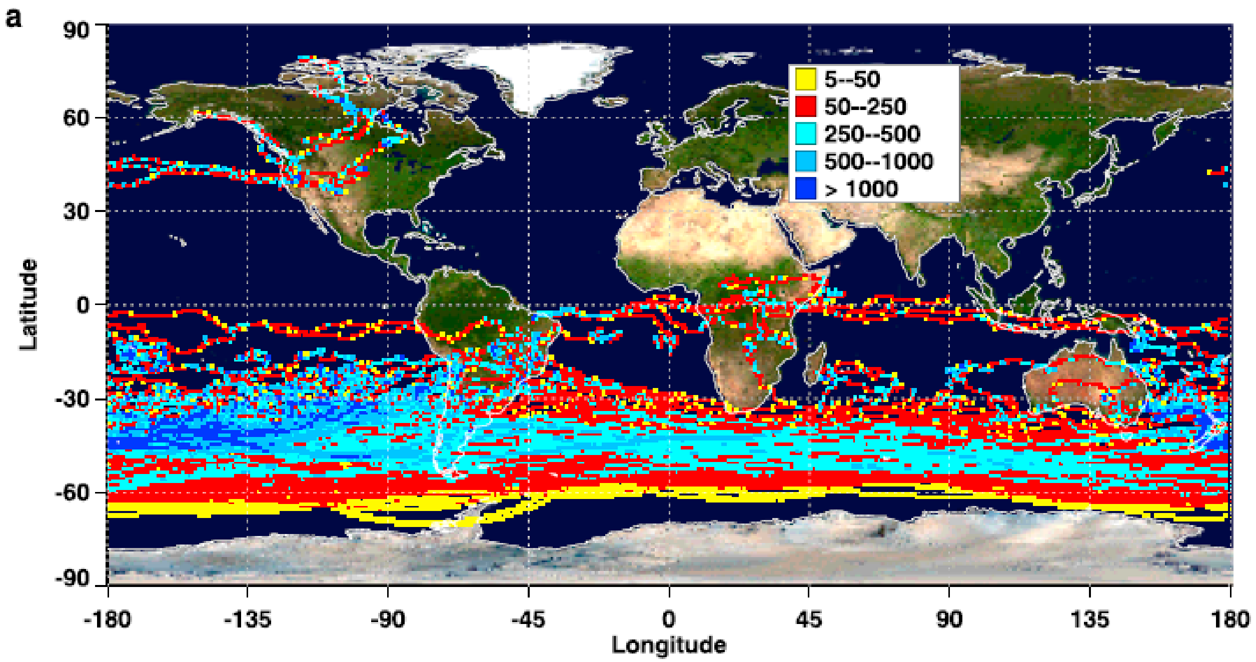
Specific objectives in pursuit of this goal as outlined in this presentation:

1. Evaluation of Loon data quality, including comparison of temperature and wind observations to other datasets including NWP analyses.
2. Establishing data ingest and storage mechanisms, and evaluation of potential near-real time processing workflow capability.

Background

In recent years, long-duration balloon data have been used in a number of applications, including:

- Validation of (re)analysis using balloon wind observations
- Simulation of trajectories using initial positions of balloons and advected using analyzed velocity fields
- Evaluation of lower stratospheric gravity wave spectra
- Forecast impact assessments in global data assimilation studies

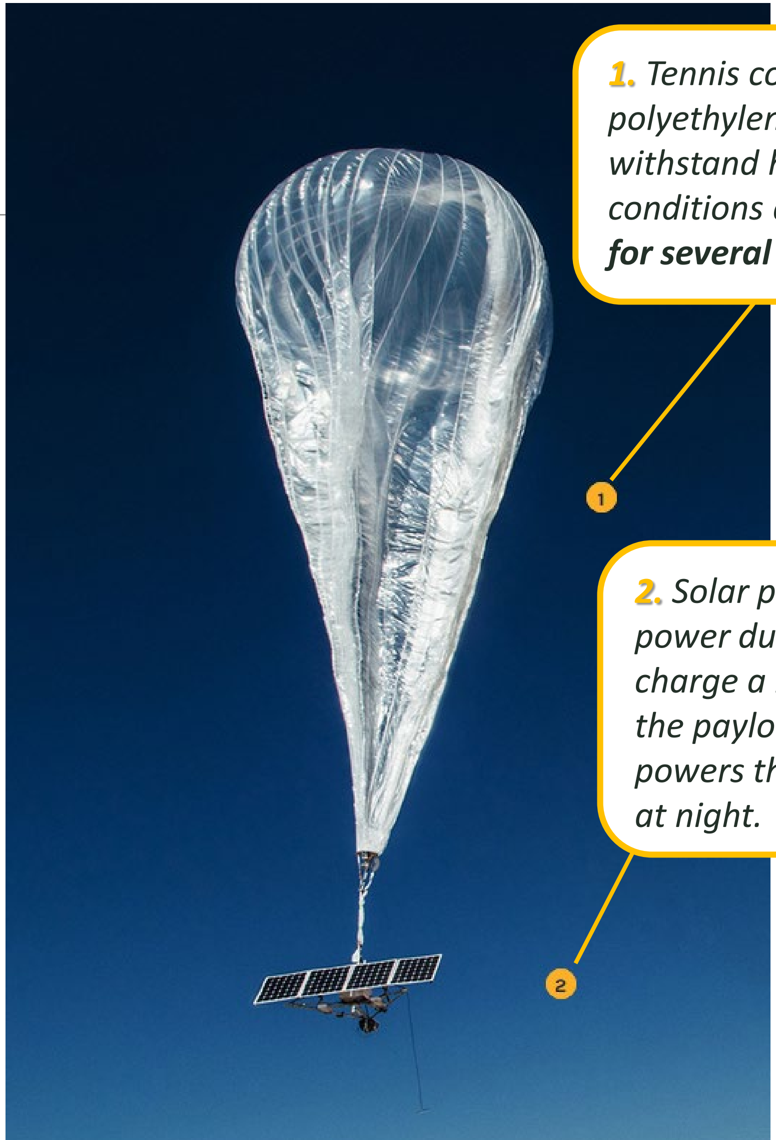


Balloon number density for June-August 2014 (*Fig. 1a from Coy et al. 2019*)

Loon Balloon System

- **Long-duration balloon data provided by Loon™**.
  - Loon system is a network of balloons designed to provide internet connectivity to regions with limited or no internet access.
- In addition to connectivity instrumentation, each balloon payload has a wire temperature sensor and GPS from which wind components are derived.
- **Temperature and wind observations are:**
  - **Recorded at ~1 min intervals at a single level in the upper atmosphere** (18-20 km).
  - Downlinked to Loon at ~1 Gb/s (assuming the balloon is connected to an inter-balloon mesh network or directly to a ground station). → Valuable for potential near-real time processing.

Loon is a registered trademark of Loon LLC.



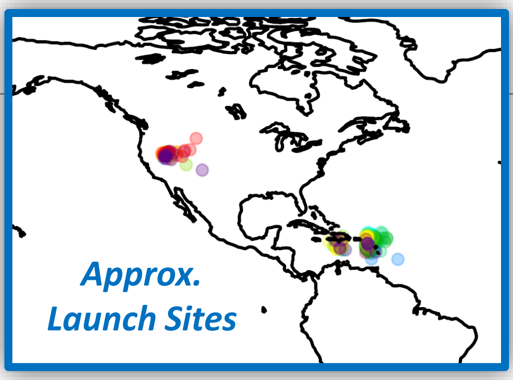
*1. Tennis court-sized sheets of polyethylene designed to withstand harsh stratospheric conditions and carry balloon **for several months** at ~20 km.*

2. Solar panels provide power during the day and charge a battery onboard the payload platform that powers the instrumentation at night.

Image source: https://loon.com/

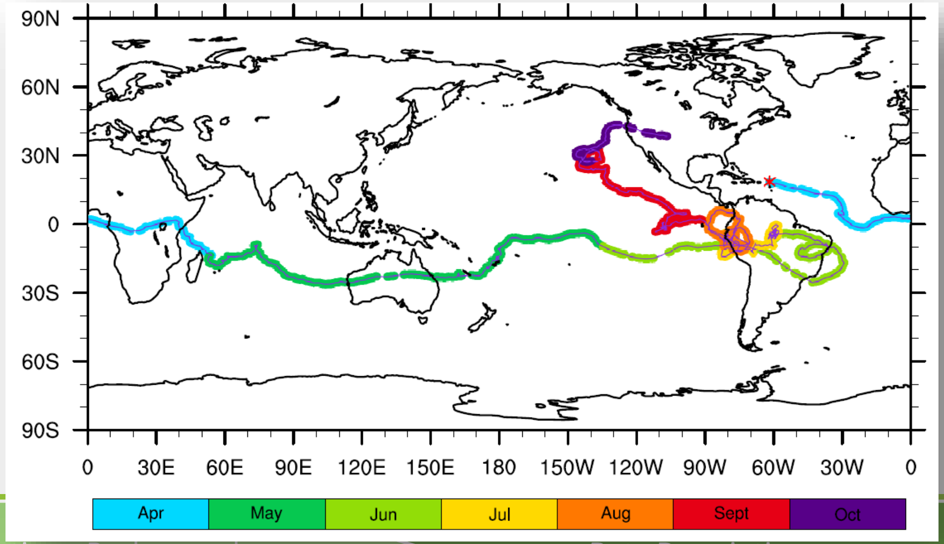
Loon Balloon Flights

- Acquired 2014-2018 data from Loon.
- Balloons are capable of flying for over 6 months in the upper atmosphere.
- 1182 balloons were launched in 2014-2018, with 142 balloons launched in 2018.

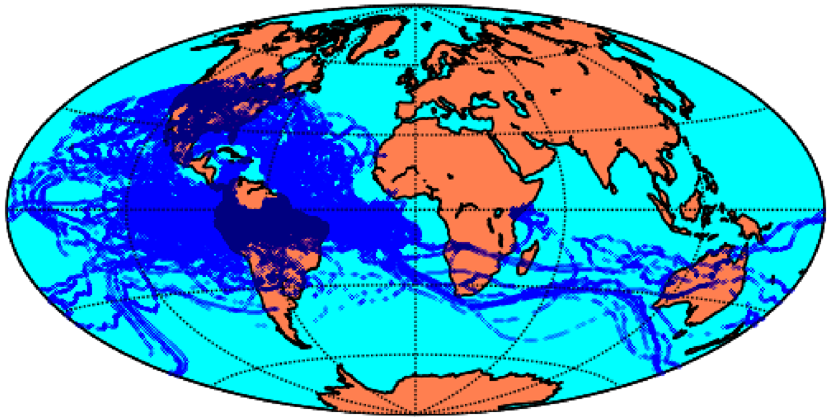


***Example*: Flight path of single balloon in 2017**

Red star indicates approx. launch sight



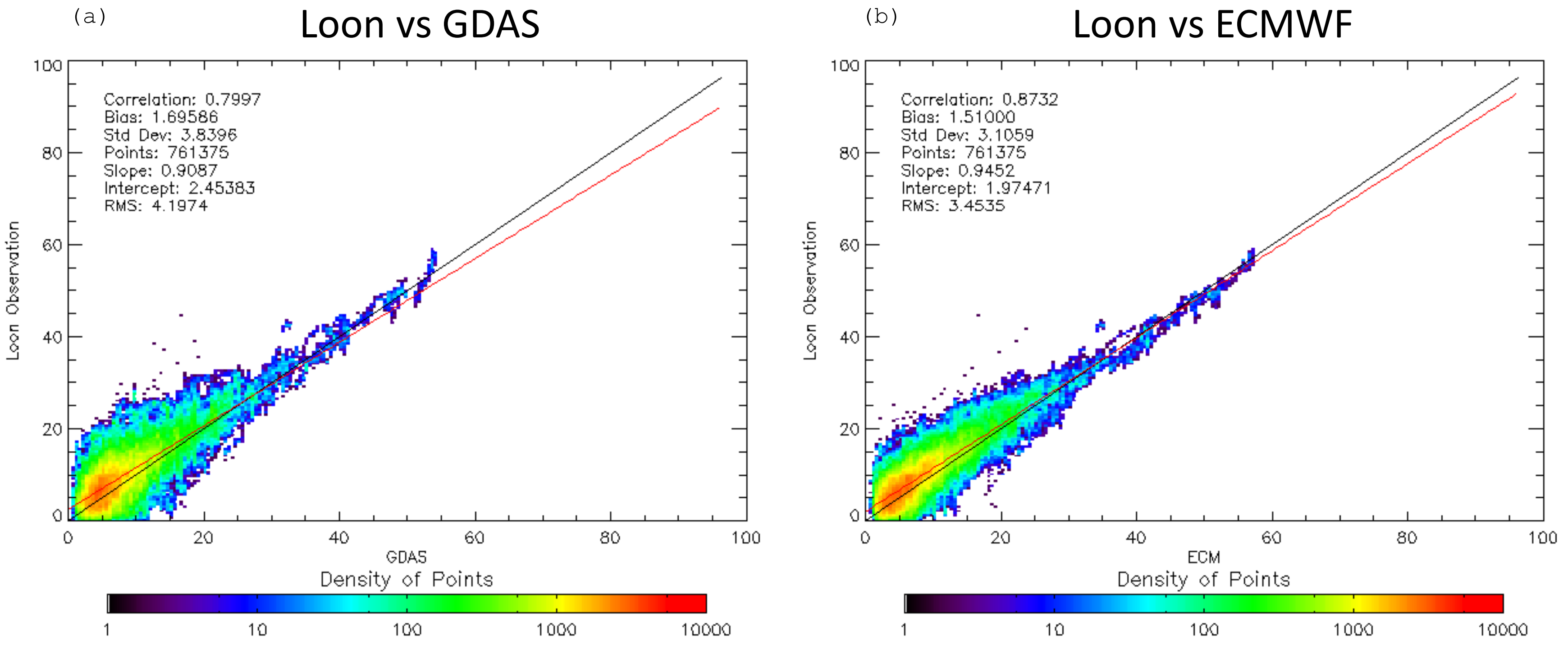
Loon Trajectories 2018



Wind Speed

- Loon wind speed is compared with (a) NCEP Global Data Assimilation System (GDAS) analysis, and (b) European Centre for Medium-Range Weather Forecasts (ECMWF) analysis data at 1° x 1° horizontal resolution.

- **Statistics comparing Loon and GDAS correspond well to those comparing Loon and ECMWF.**



Density scatter plots comparing Loon wind speed observations on y-axis with (a) GDAS analysis on x-axis, and (b) ECMWF analysis on x-axis for all flights in October 2017. Colors indicate the number of observations. Red line indicates the best linear fit. Black line is the one-to-one line. A list of statistics are provided in the top left corner of each plot. Units are m/s.

Wind Speed Biases

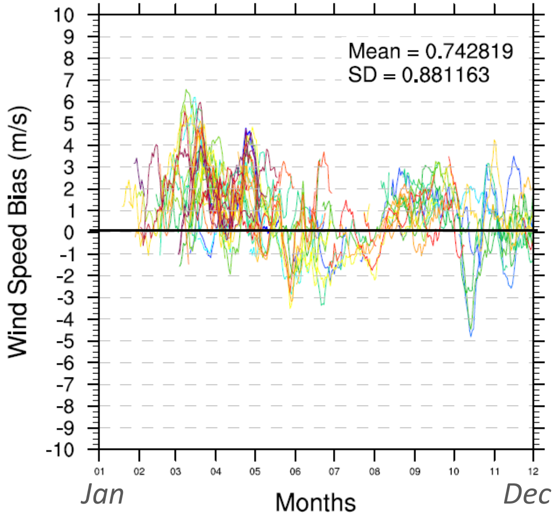
(Loon – GDAS) 2018

Time series show that biases per flight tend to be small and positive, and generally follow the pattern of number of observations.

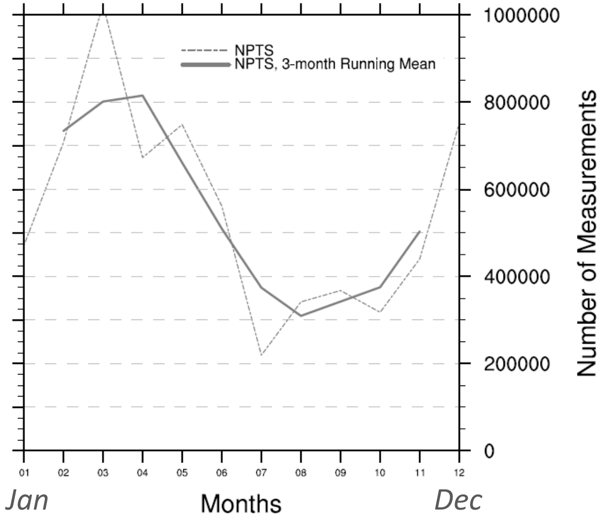
Flight bias distribution is slightly skewed to the right (positive) side.

Distribution becomes more Gaussian (centered about zero) after average flight biases are removed.

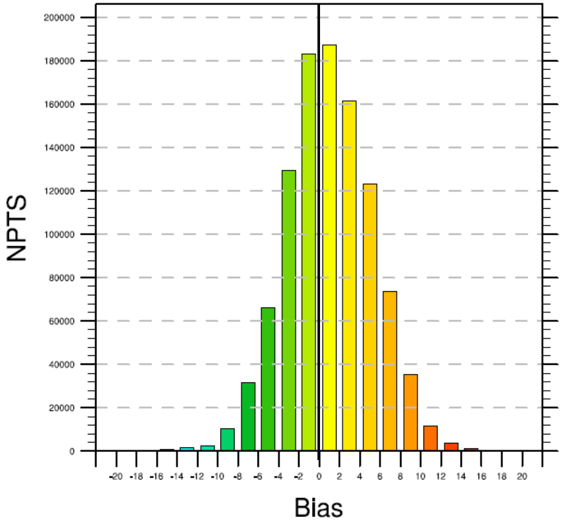
2018 Time series of flight biases, 10-day running mean



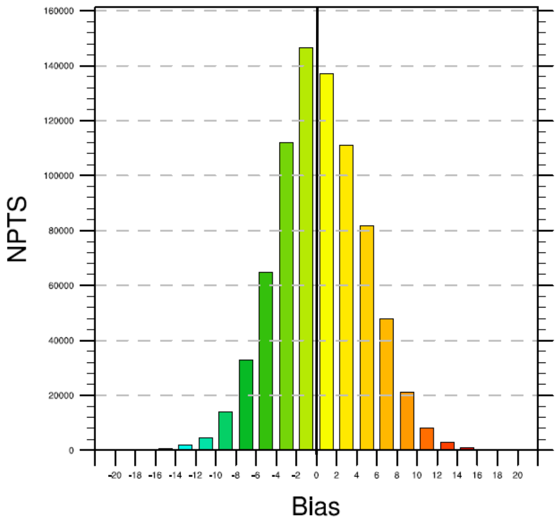
2018 Time series of number of observations



Histogram of wind speed biases, averaged per flight in 2018

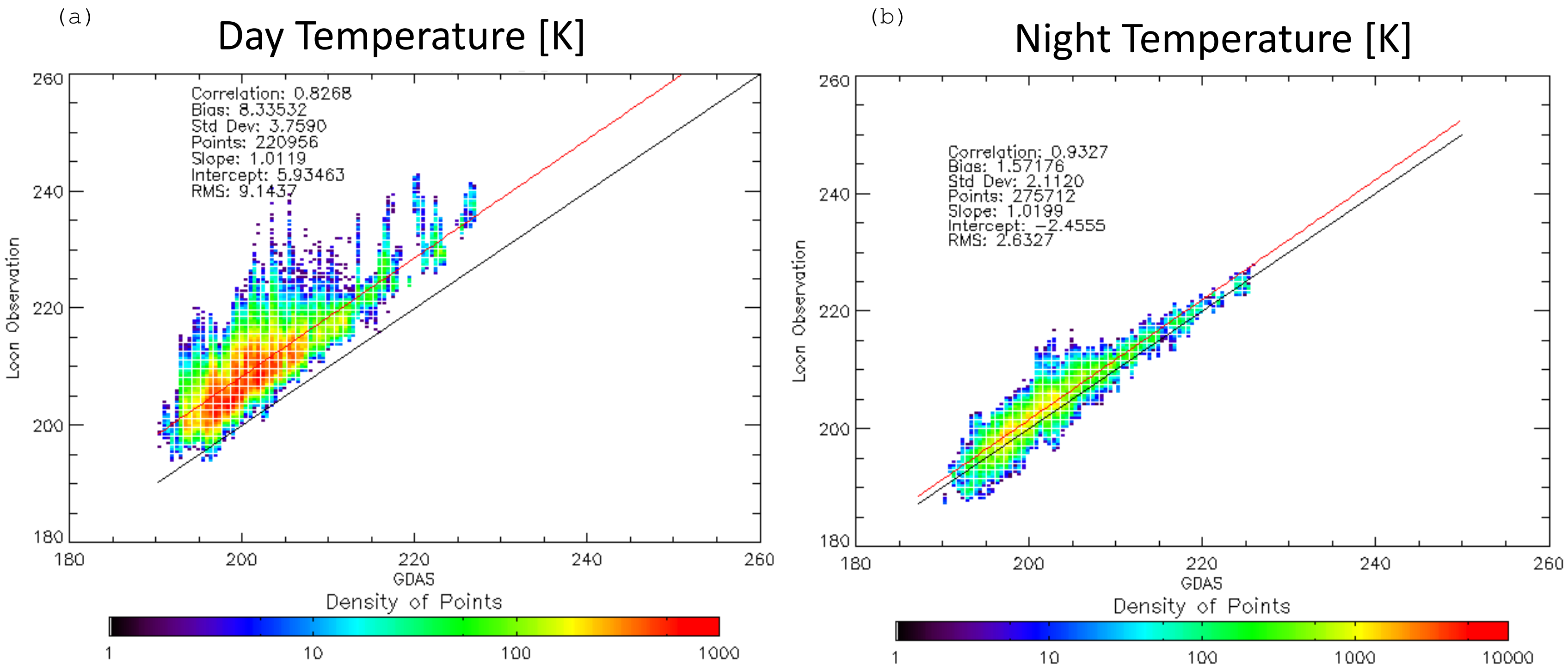


Histogram of wind speed biases, averaged per flight in 2018, after average flight biases are removed



Temperature

- Statistics of Loon temperatures compared with GDAS analysis differ depending on presence of solar radiation.
- **Loon daytime temperatures are overestimated**. This is likely due to:
    1. Temperature of wire sensor is what is reported and provided in the dataset.
    2. Temperature is not corrected for solar radiative effects. Onboard wire sensor does not have a solar shield.
- **Loon nighttime temperatures correspond well with GDAS analysis**.



Density scatter plots comparing Loon temperature observations on y-axis with GDAS analysis on x-axis for all flights in October 2017. (a) Local daytime T, and (b) local nighttime T. Colors indicate the number of observations. Red line indicates the best linear fit. Black line is the one-to-one line. A list of statistics are provided in the top left corner of each plot. Units are K.

Night T Biases

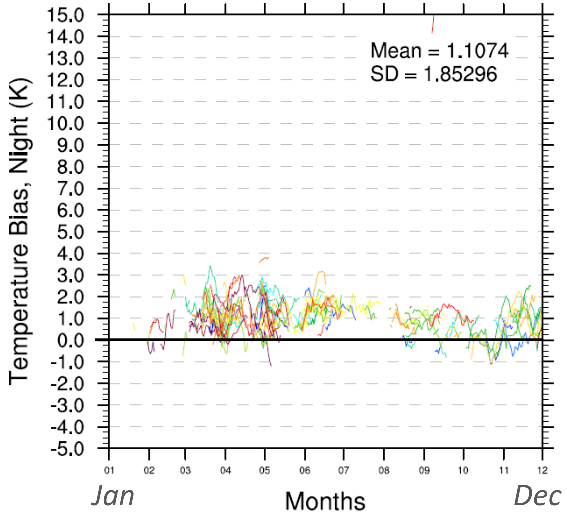
(Loon – GDAS) 2018

Biases per flight tend to be ~1 K throughout the year, regardless of the number of observations.

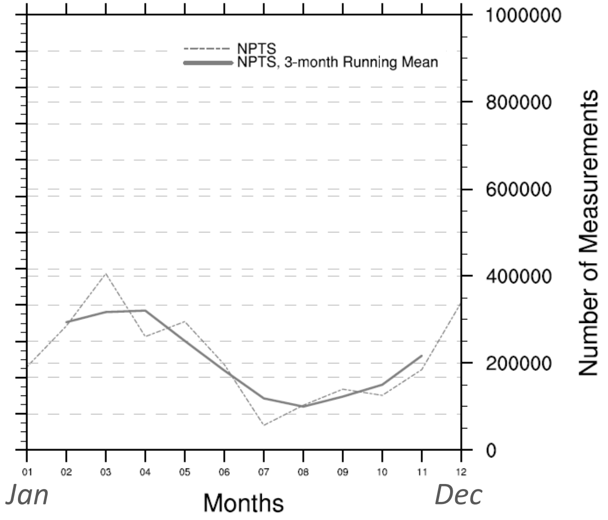
Flight bias distribution is skewed to the right (positive) side.

Distribution becomes more Gaussian (centered about zero) after average flight biases are removed.

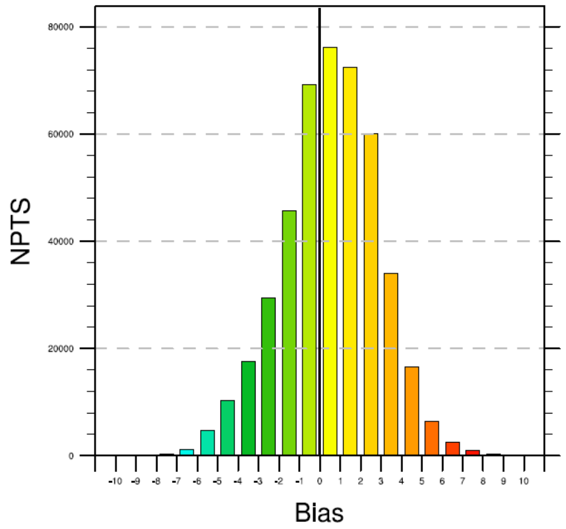
2018 Time series of flight biases, 10-day running mean



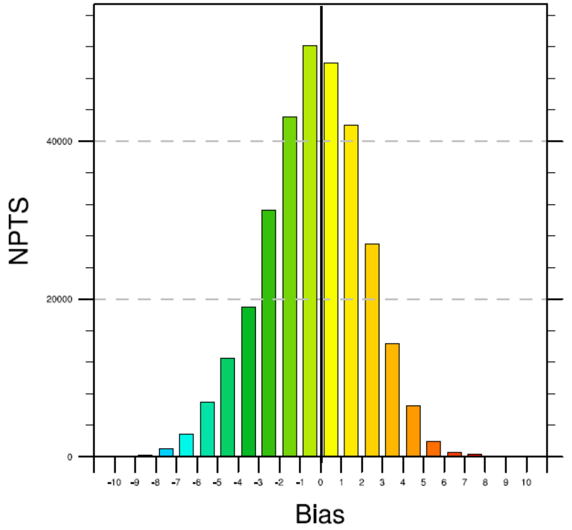
2018 Time series of number of nighttime observations



Histogram of Night T biases, averaged per flight in 2018



Histogram of Night T biases, averaged per flight in 2018, after average flight biases are removed



Concluding Remarks

- Loon stratospheric balloon observations provide in situ data in information-sparse upper atmosphere.
- Loon winds and nighttime temperatures provide good quality data for assimilation.
  - Solar shield on platform may improve quality of daytime T observations.
- Limited value as a global validation dataset for NESDIS operational products (e.g., 2018 observations are concentrated in tropical latitudes over the Americas).

Next Steps

- Implement stratospheric balloon data assimilation capacity in NOAA GDAS (quality controls, bias correction, observation errors)
- Run impact assessment of stratospheric balloon data for NOAA global forecast system.
- Compare NESDIS soundings to stratospheric nighttime temperatures obtained by balloons.

Thank you!

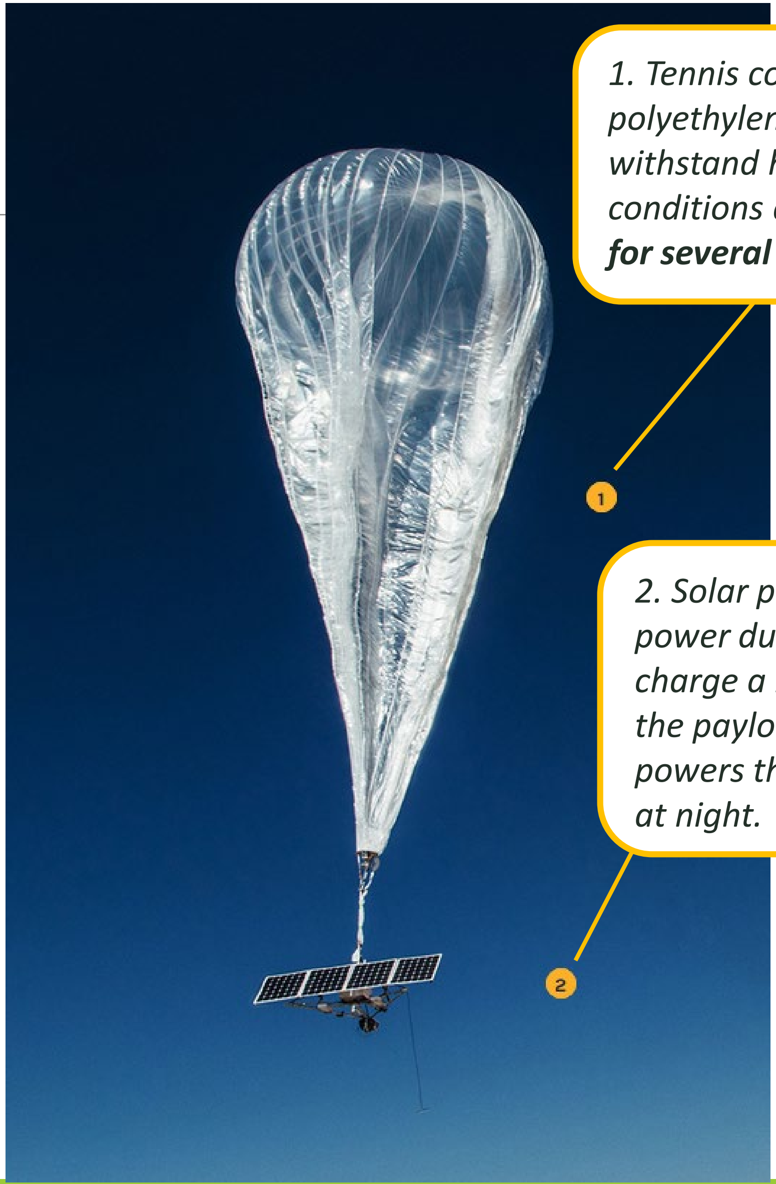
Questions?

Acknowledgements:
NOAA/NESDIS/OPPA Technology Maturation Program (TMP)
NOAA/NESDIS/STAR
UMD/ESSIC/CISESS
Max Kamenetsky at Loon LLC
SSEC at UW-Madison

Supplemental

Loon Balloon System

- *Launch process* is largely automated, capable of launching balloons every 30 min (although this is not usually done)
- *Altitude stability*: A periodic 10-50 Pa (10-50 m at 20 km) variation with ~4 min period (when the balloon is not experiencing a maneuver (intentional altitude change by adjusting the pressure in the balloon. This drops the payload into different wind streams)). Knowledge of altitude is derived from GPS.
- *Attitude stability*: Loon has passive pitch and roll control (typical error of +/- 2 degrees) and an active yaw control meeting requirement of 7 degree 95th percentile error, over 95% of all 5-min time windows. Roll, pitch, and yaw measurement accuracy is +/- 0.5 degrees.
- *Potential to host additional sensors*
  - *Payload capacity*: Up to 12 kg, 60 W, and a volume of 20x20x25 cm^3 (assuming the platform is only providing mass, power, thermal, data downlink, telemetry, and command capability)
  - *Data transfer capability*: Up to 1 Gb/s (assuming the balloon is connected to an inter-balloon mesh network or directly to a ground station)



1. Tennis court-sized sheets of polyethylene designed to withstand harsh stratospheric conditions and carry balloon ***for several months*** *at ~20 km.*

2. Solar panels provide power during the day and charge a battery onboard the payload platform that powers the instrumentation at night.

Image source: https://loon.com/

Loon Data

- Acquired data for 2014-2018
- Available data formats: NetCDF and CSV
- Loon data do not include observations during maneuver times (i.e., intentional altitude changes by adjusting the pressure in the balloon that drop the payload into different wind streams).

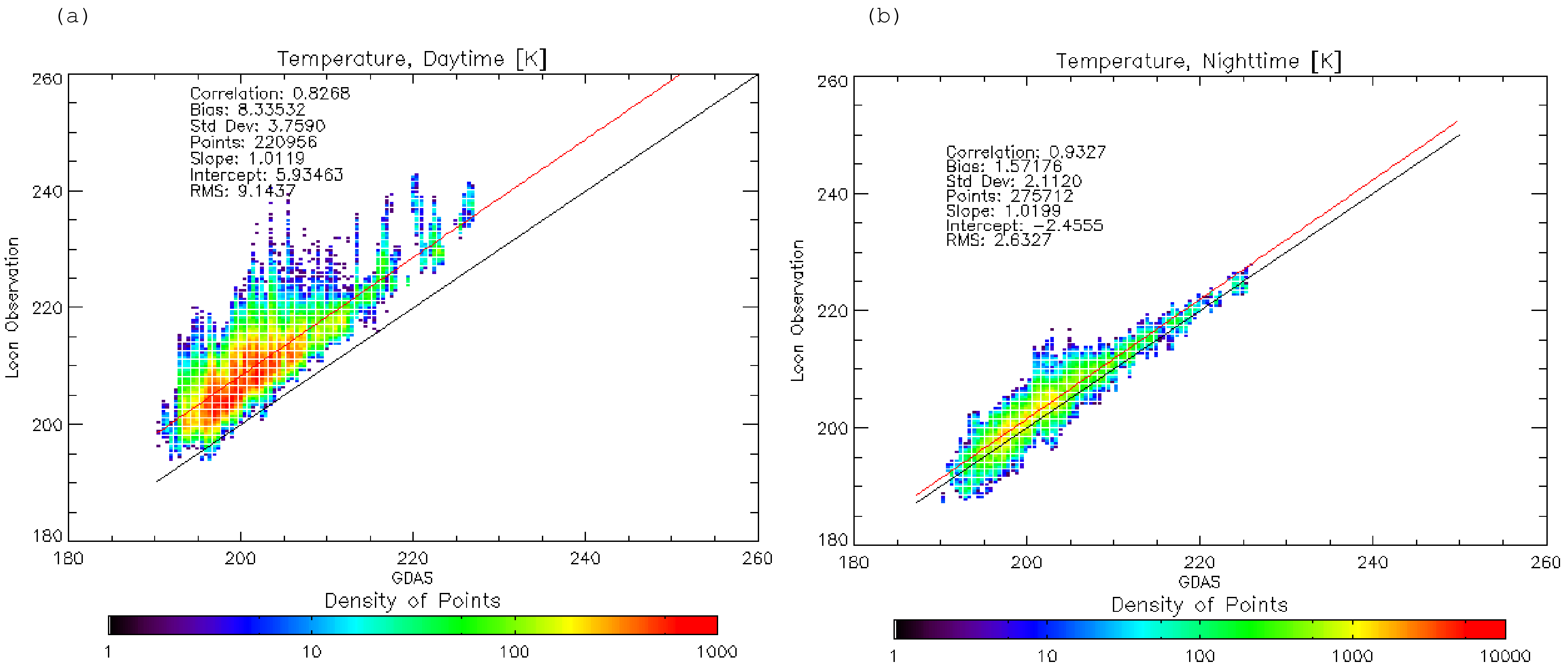
Table of Provided Variables

Variable (units)	Description	Uncertainty
Flight ID	Unique ID number assigned to each distinct balloon flight	
Timestamp (UTC)	Timestamp of measurement including seconds	
Latitude (degrees North)	Latitude of balloon at time of measurement	+/- 2.5 m base don GPS
Longitude (degrees East)	Longitude of balloon at time of measurement	+/- 2.5 m base don GPS
Geometric Altitude (m AMSL)	Altitude of balloon at time of measurement	+/- 2.5 m base don GPS
Ambient Pressure (Pa)	Pressure at time of measurement	+/- 100 Pascals
Ambient Temperature (K)	Temperature at time of measurement	+/- 5 degrees C during day; +/- 2 degrees C during night
U-component of Wind (m/s West)	Negative value indicates east-to-west directionality	
V-component of Wind (m/s South)	Negative value indicates north-to-south directionality	
Solar Elevation Angle (degrees)	Relative to horizontal	
Solar Azimuth Angle (degrees)	Relative to North	
Earth IR (W m^{-2})	Earth IR from Melexis sensor. Sensor points straight down. IR flux = $0.000000056704*T^4$	+/- 6 degrees C for T sensor. +/- 2 degrees for IR sensor pointing accuracy.
Earth IR Configuration	Indicates type of IR configuration sensor used: 0 = flights from 2014 to early 2016; 2 = flights starting in late 2015; 3 = flights starting in late 2018	

Temperature, Day & Night

Temperature Issues:

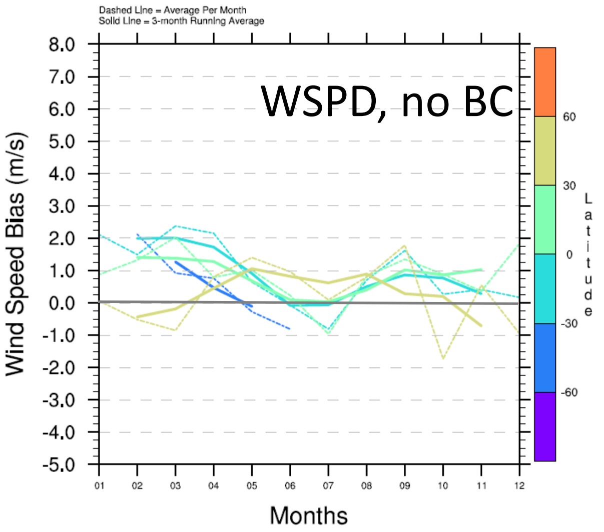
- Most Loon observations before October 2017 report **T=0 K** (~3.18% of points in Oct. 2017 report T=0 K.) This is likely due to:
  1. *Loon hardware is rapidly evolving.* Because flight durations are a few months as opposed to 15+ years for a GEO satellite, Loon has the opportunity to introduce new designs and quickly iterate on hardware. It is possible that specific temperature sensors are not included on some payloads.
  2. *Loon quality control is imperfect.* Because Loon's emphasis is on flying as often as possible and minimizing the cost as much as possible, it is possible that some of the temperature sensors were malfunctioning or not properly calibrated.
     - Very large Loon T obs are indicated as ***"bad T"*** data in the evaluation on the following slides. In Oct. 2017, there are 4 flights that report "bad T" data, and they represent ~6% of the month's observations.
- Loon Temperatures are generally overestimated relative to GDAS or ECMWF analysis, particularly during local daytime, and is likely due to:
  1. Temperature of wire sensor is what is reported and provided in the dataset.
  2. Temperature is not corrected for solar radiative effects. Onboard wire sensor does not have a solar shield.

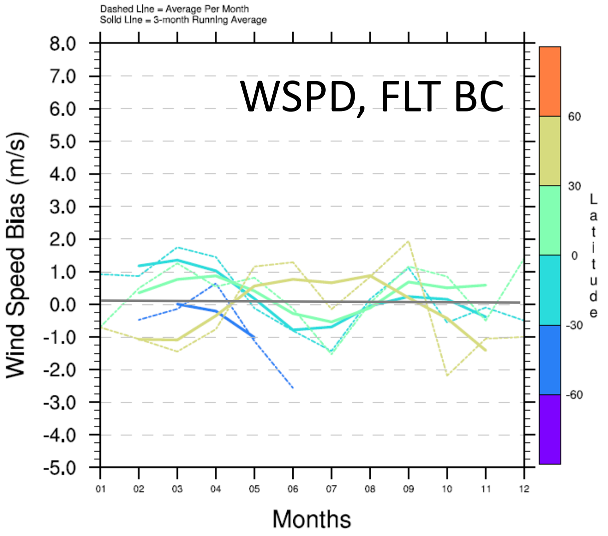


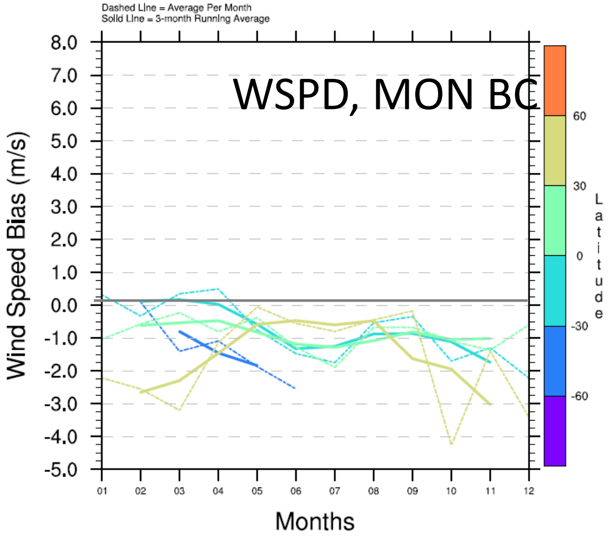
Density scatter plots comparing Loon temperature observations on y-axis with GDAS analysis on x-axis for all flights in October 2017. (a) Local daytime T, and (b) local nighttime T. Colors indicate the number of observations. Red line indicates the best linear fit. Black line is the one-to-one line. A list of statistics are provided in the top left corner of each plot. Units are K.

Monthly Avg WSPD Bias

LATITUDE

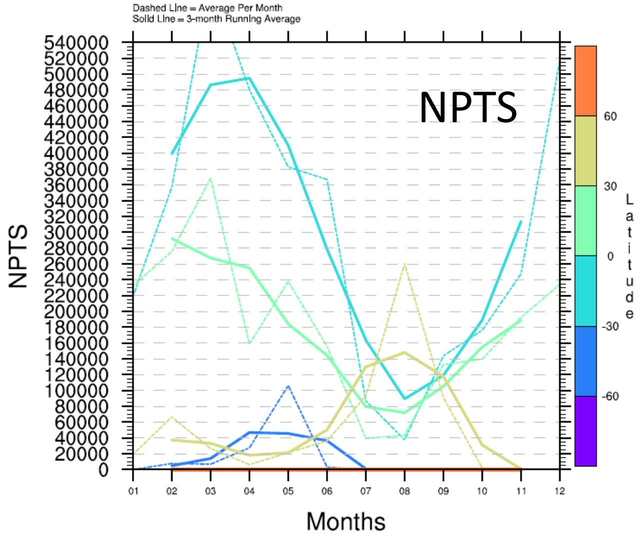






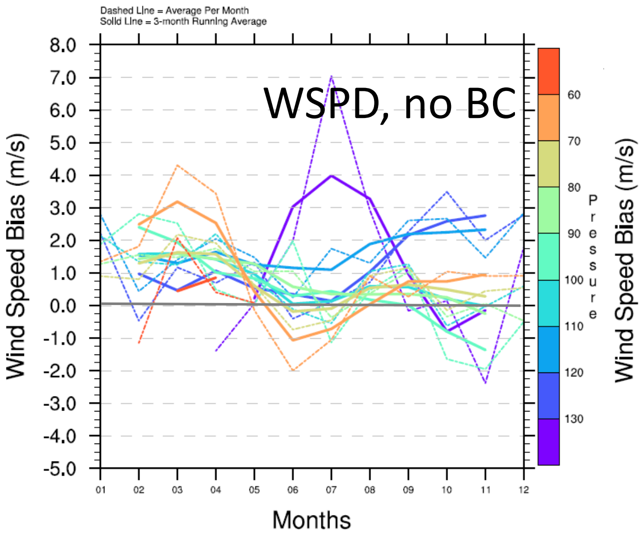
Removal of **flight** bias reduces wind speed bias.

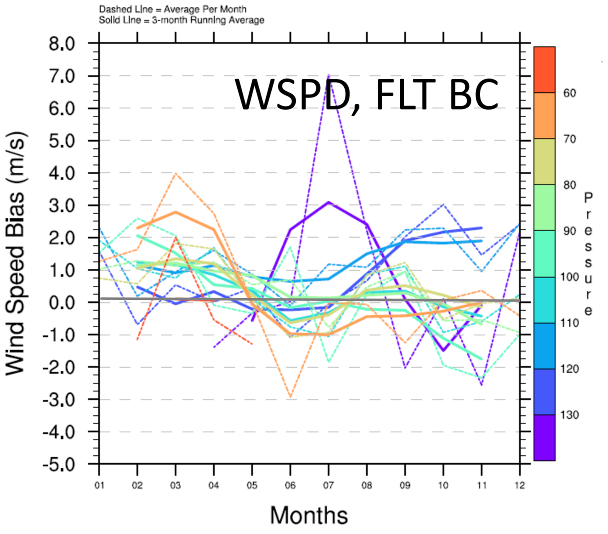
Removal of **monthly** bias over-corrects wind speed (flips bias sign).

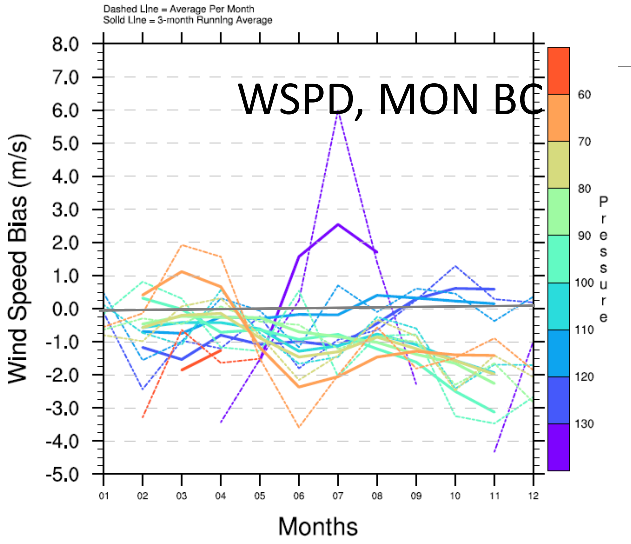


Monthly Avg WSPD Bias

PRESSURE

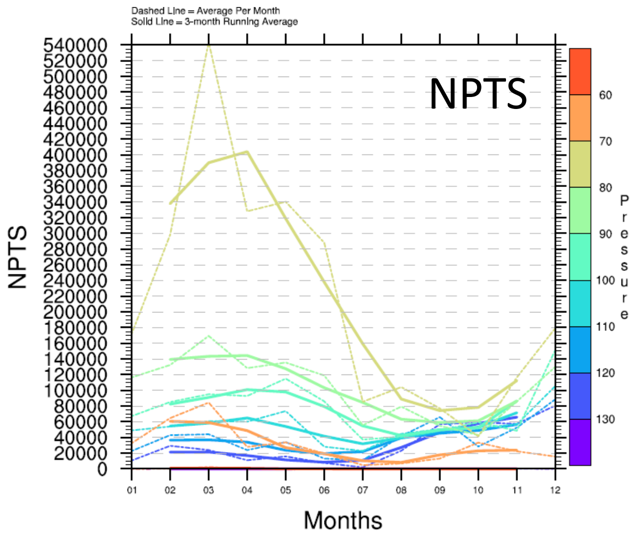






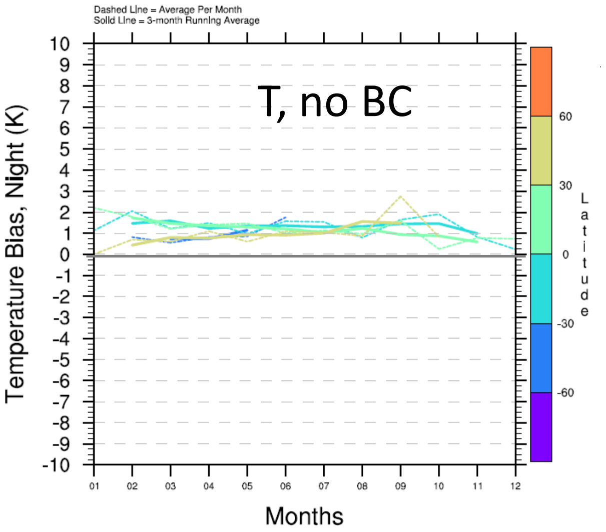
Removal of **flight** bias reduces wind speed bias.

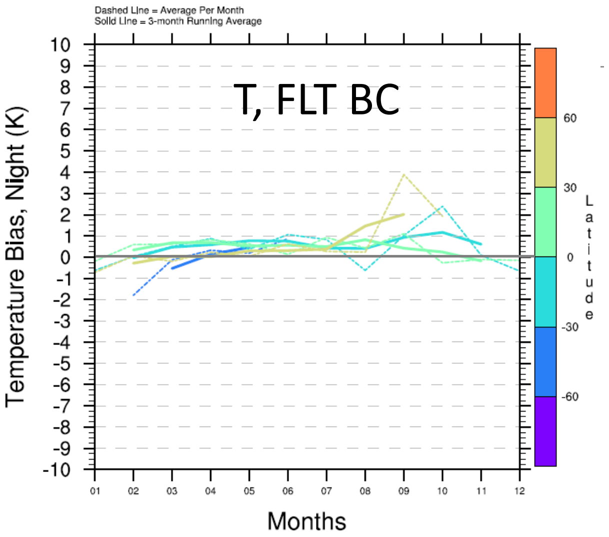
Removal of **monthly** bias over-corrects wind speed (flips bias sign).

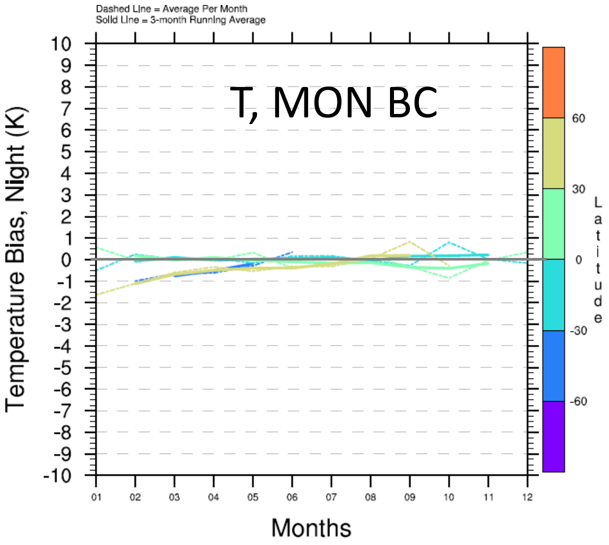


Monthly Avg T(NIGHT) Bias

LATITUDE

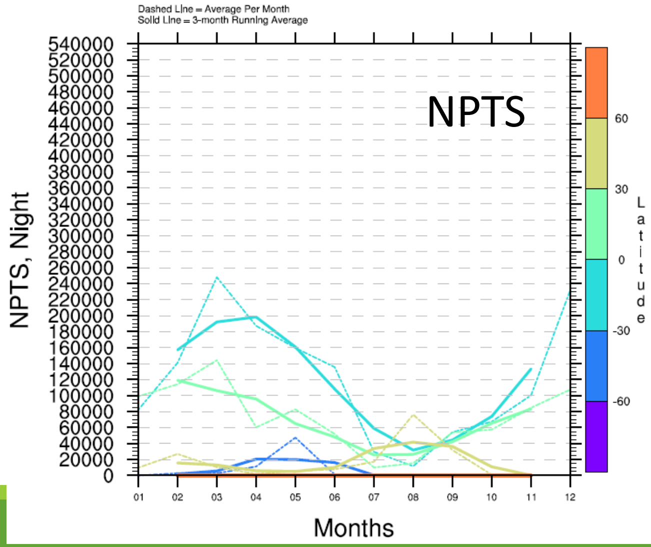






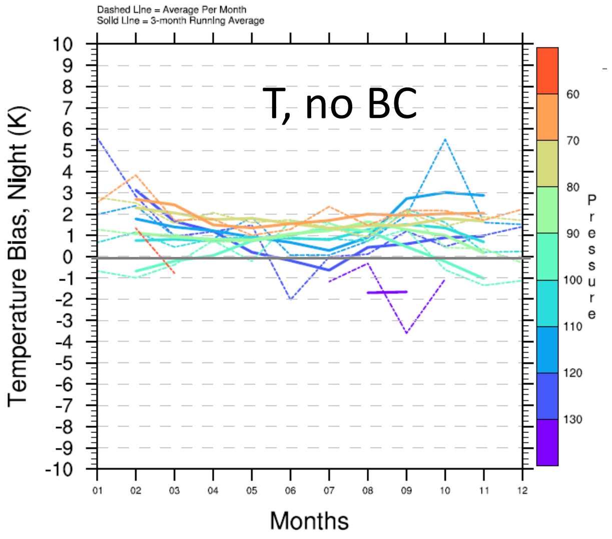
Removal of **flight** bias reduces wind speed bias.

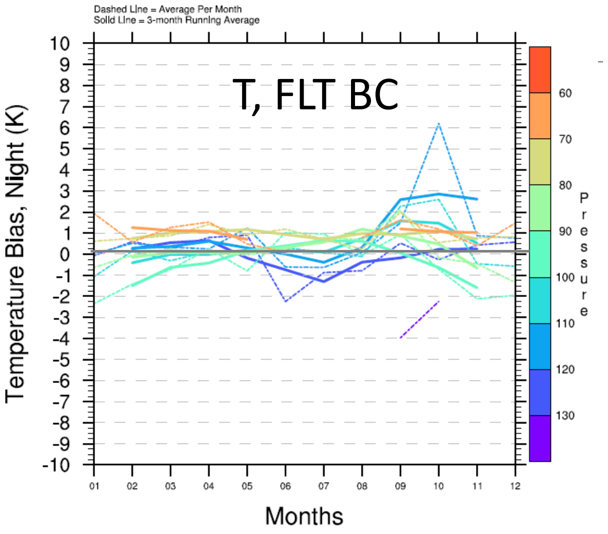
Removal of **monthly** bias reduces bias to near zero in tropics and over-corrects in extratropics (flips bias sign).

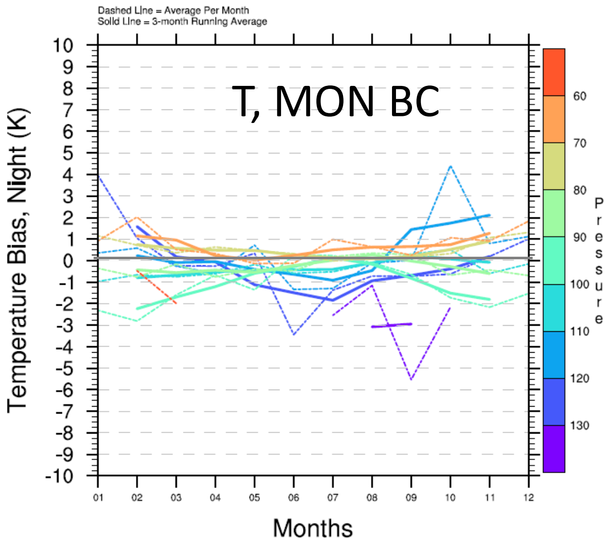


Monthly Avg T(NIGHT) Bias

PRESSURE

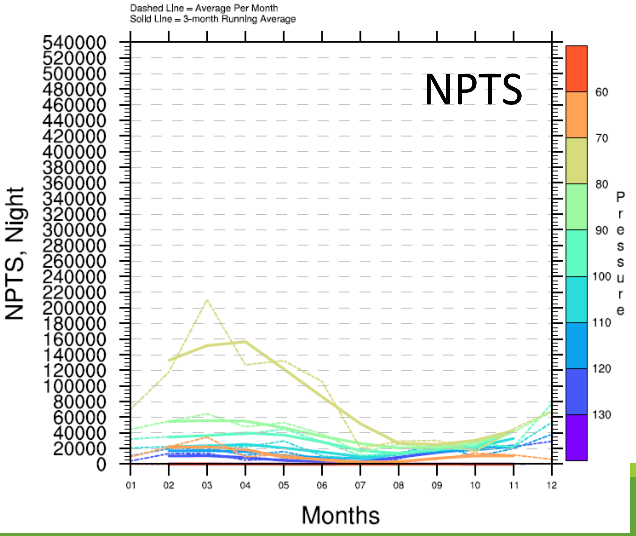






Removal of **flight** bias reduces wind speed bias.

Removal of **monthly** bias reduces bias to near zero at lower pressures and over-corrects at higher pressures (in some cases



Biases

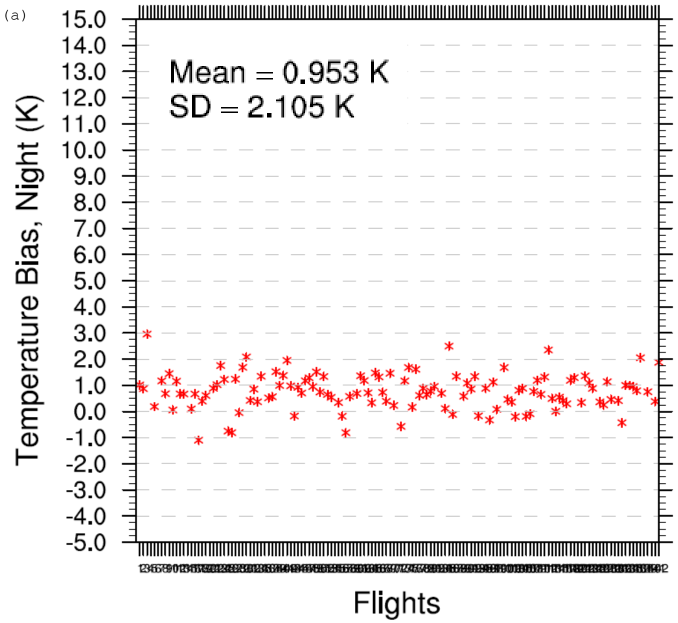


Figure: Scatter plots of average biases per flight relative to GDAS analysis for all flights launched in 2018. Units are K. (a) Nighttime temperature biases, and (b) wind speed biases.