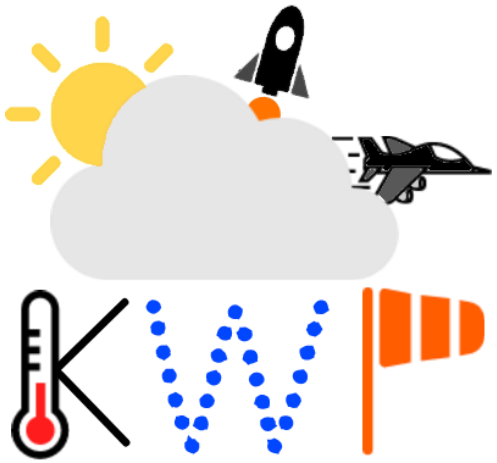
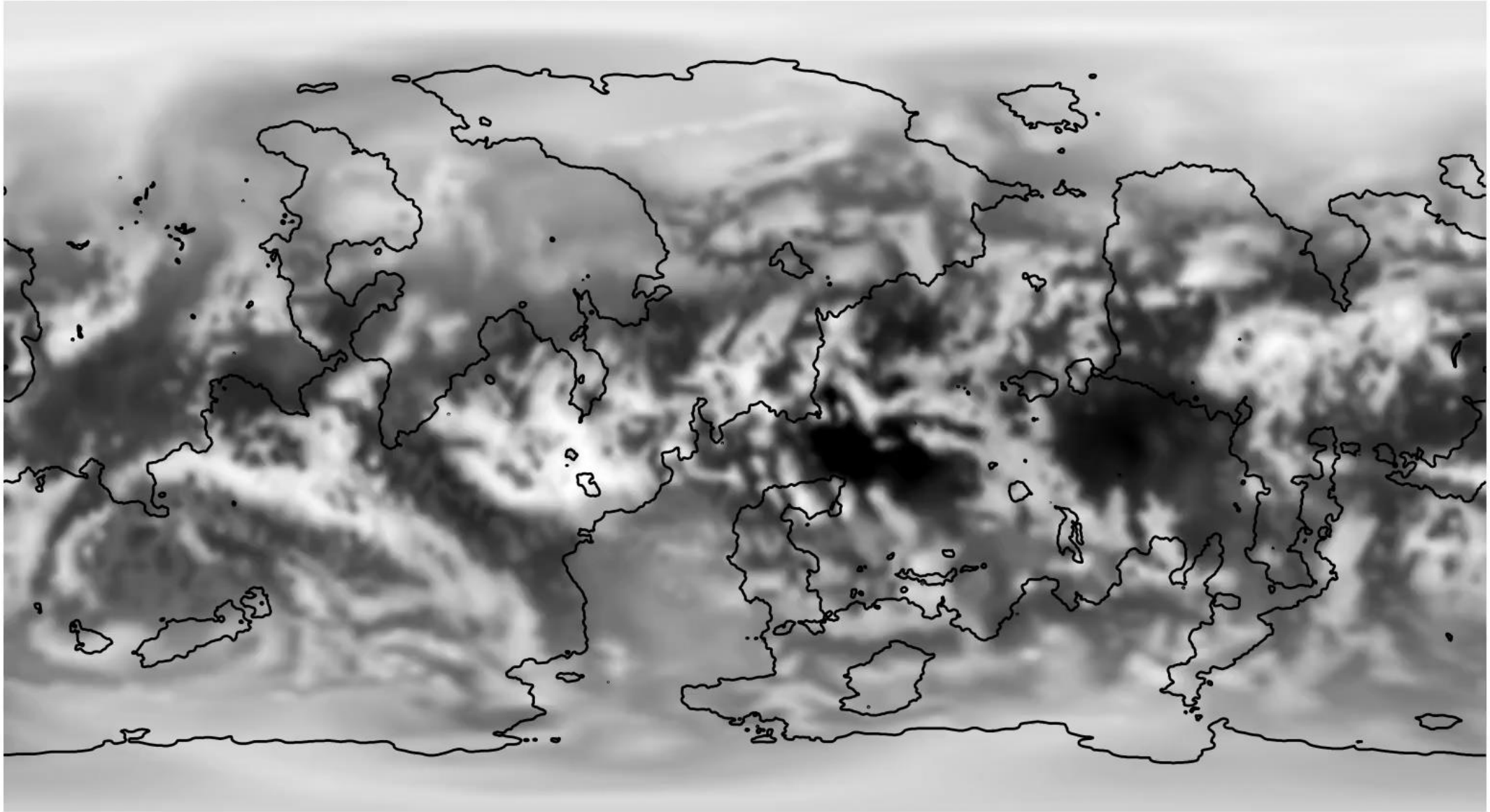
MPAS
Model for Prediction Across Scales

KERBAL
SPACE PROGRAM

Learning Atmospheric Science with MPAS and Kerbal Space Program





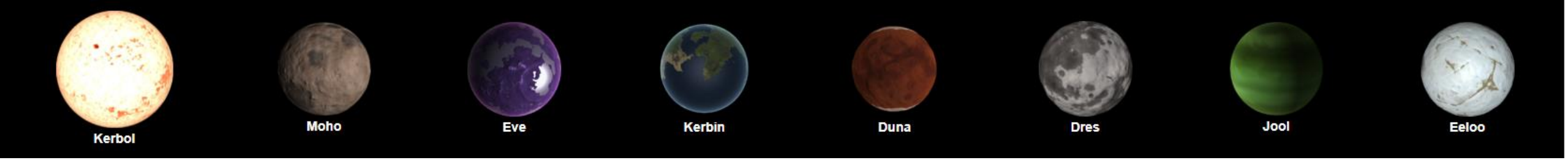
European Space Agency

Jet Propulsion Laboratory
California Institute of Technology

Players direct a budding space program, run by green humanoids known as “Kerbals”.

The game features a realistic physics engine, enabling real-life orbital maneuvers such as Hohmann transfer orbits and bi-elliptic transfer orbits.

Reddit: 1.4M followers | KSP Forums: 207K members with 3.8M posts.



Orbital Characteristics

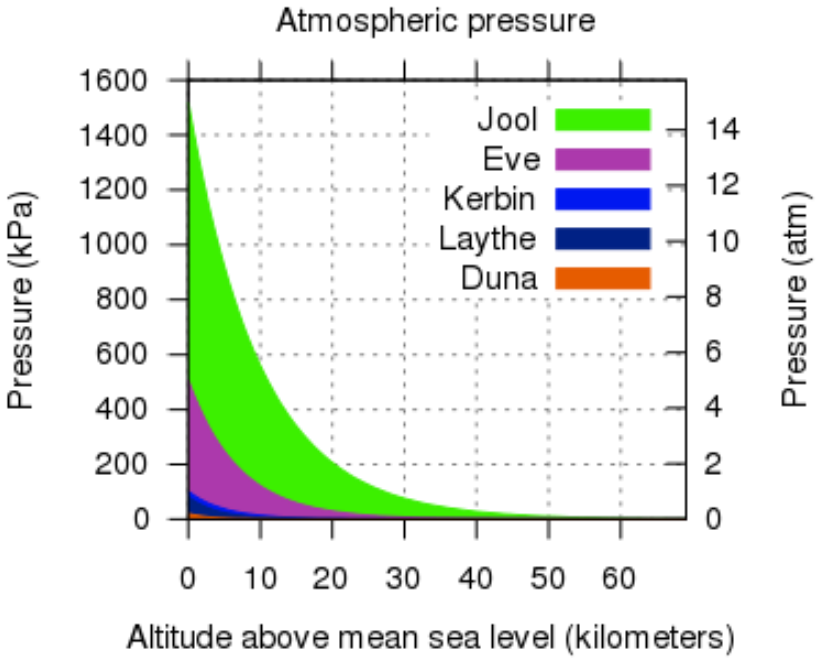
Semi-major Axis	13,599,840,256 m
Orbital Eccentricity	0
Orbital Inclination	0
Sidereal Orbital Period	426 d 32 m
Orbital Velocity	9285 m/s

Physical Characteristics

Mass	52915158 x 10^{22} Kg
Equatorial Radius	600 km
Equatorial Circumference	3769.911 km
Density	58484.090 kg/m^3
Surface gravity	9.81 m/s^2
Escape Velocity	3431.03 m/s
Solar day	21600.0 s

Solar Parameters

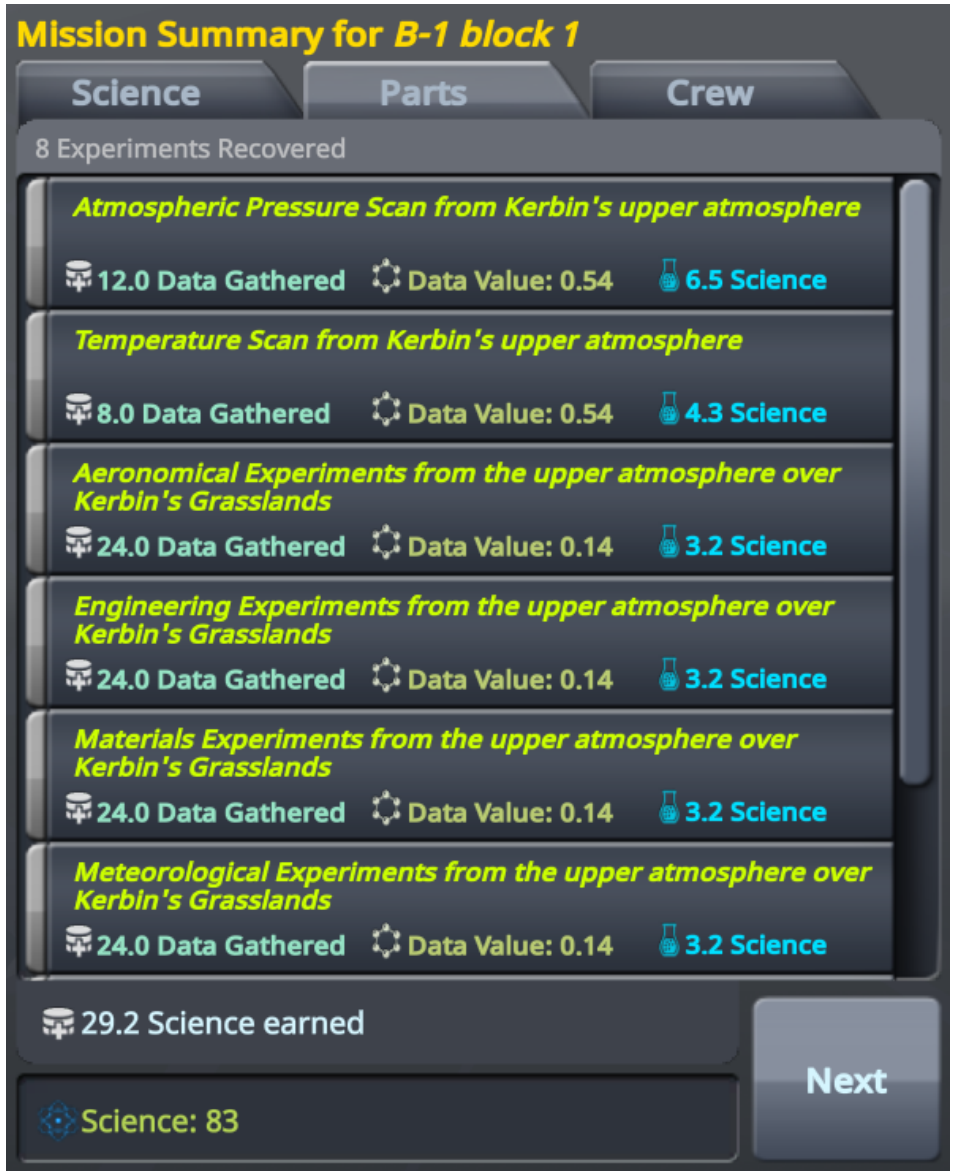
Sol Mass	1.7565459 x 10^{28} kg
Sol Radius	261,600,000 m
Sol Surface Temp	5840 K
Sol Constant @ Kerbin	1360 W/m^2




Pods
Name
Mass
Cost
Size
KerbalX
KERBAL

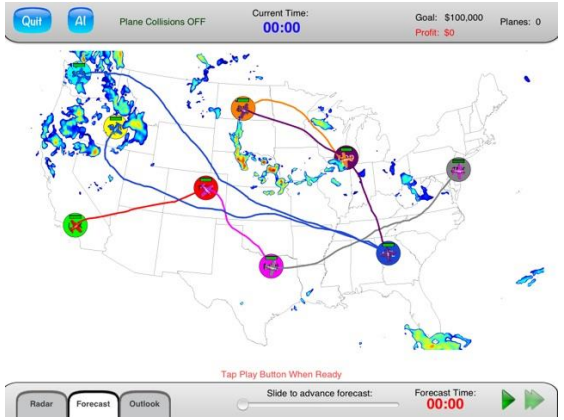

https://kerbalx.com/Pieliker96/Aerobatic-Biplane

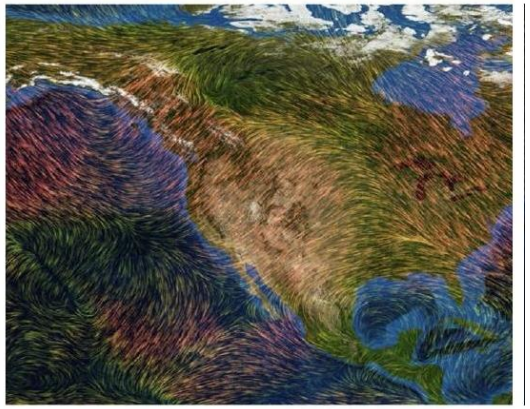

HOT
COLD


Mission Summary for B-1 block 1
Science
Parts
Crew
8 Experiments Recovered
Atmospheric Pressure Scan from Kerbin's upper atmosphere
12.0 Data Gathered
Data Value: 0.54
6.5 Science
Temperature Scan from Kerbin's upper atmosphere
8.0 Data Gathered
Data Value: 0.54
4.3 Science
Aeronomical Experiments from the upper atmosphere over Kerbin's Grasslands
24.0 Data Gathered
Data Value: 0.14
3.2 Science
Engineering Experiments from the upper atmosphere over Kerbin's Grasslands
24.0 Data Gathered
Data Value: 0.14
3.2 Science
Materials Experiments from the upper atmosphere over Kerbin's Grasslands
24.0 Data Gathered
Data Value: 0.14
3.2 Science
Meteorological Experiments from the upper atmosphere over Kerbin's Grasslands
24.0 Data Gathered
Data Value: 0.14
3.2 Science
29.2 Science earned
Science: 83
Next

Video Games as A Teaching and Visualization Tool in Atmospheric Science

- Universe Sandbox *(Goldenson, 2014)*
- TerraViz (NEIS) – Unity Game Engine *(Stewart et al., 2015)*
- Storm Evader *(McGovern et al., 2015)*
- UCAR Center for Science Education *(Russel, 2018)*
- Earth Games *(Frierson et al.)*





KSP as a potential teaching tool

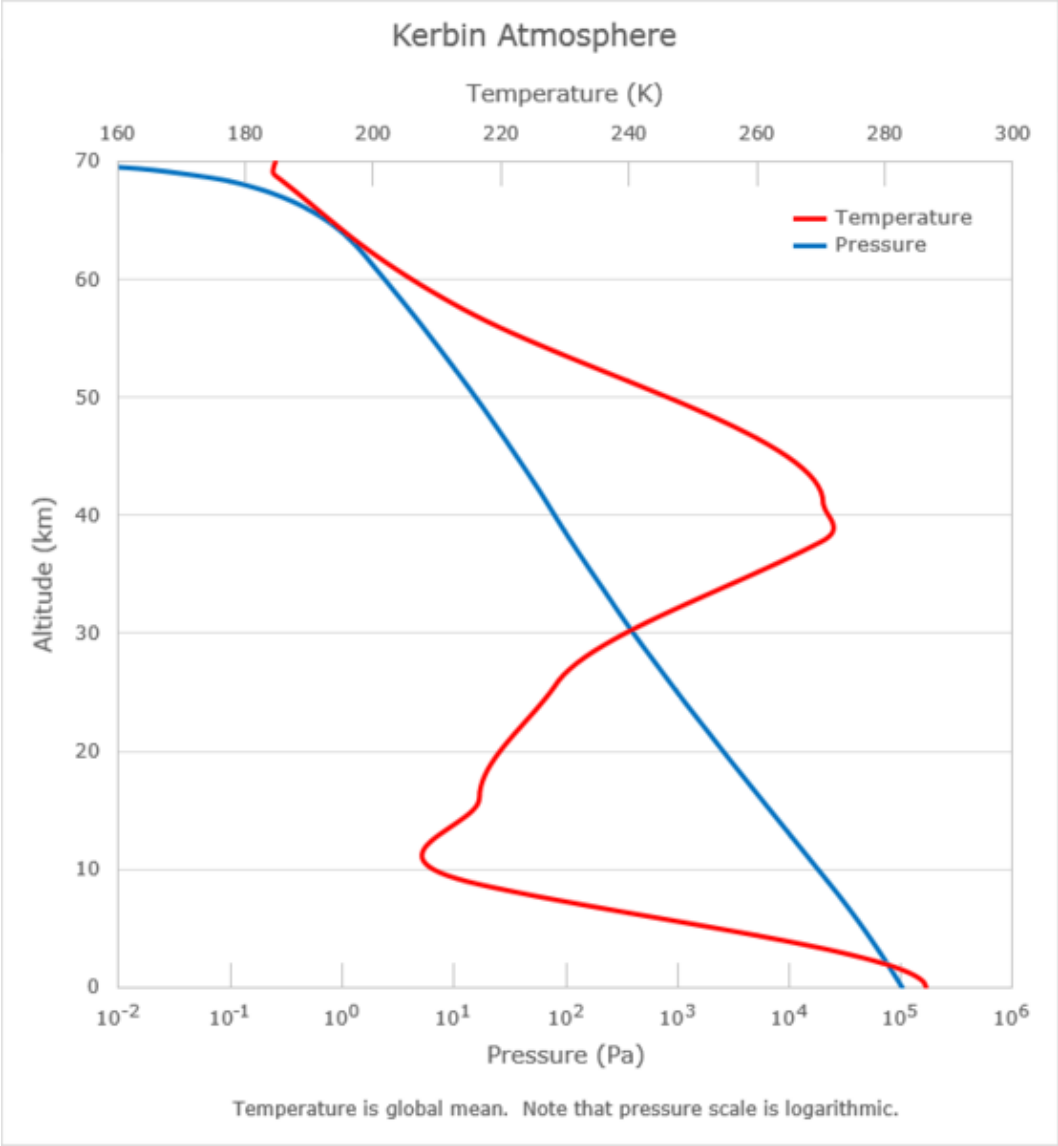
- KerbalEdu: Provides lesson plans and in-game scenarios for teachers and educators. Covers historical rocketry and teaches basic physics concepts (e.g. kinetic vs potential energy) in a tangible and experiential manner.

European Space Agency

Jet Propulsion Laboratory
California Institute of Technology

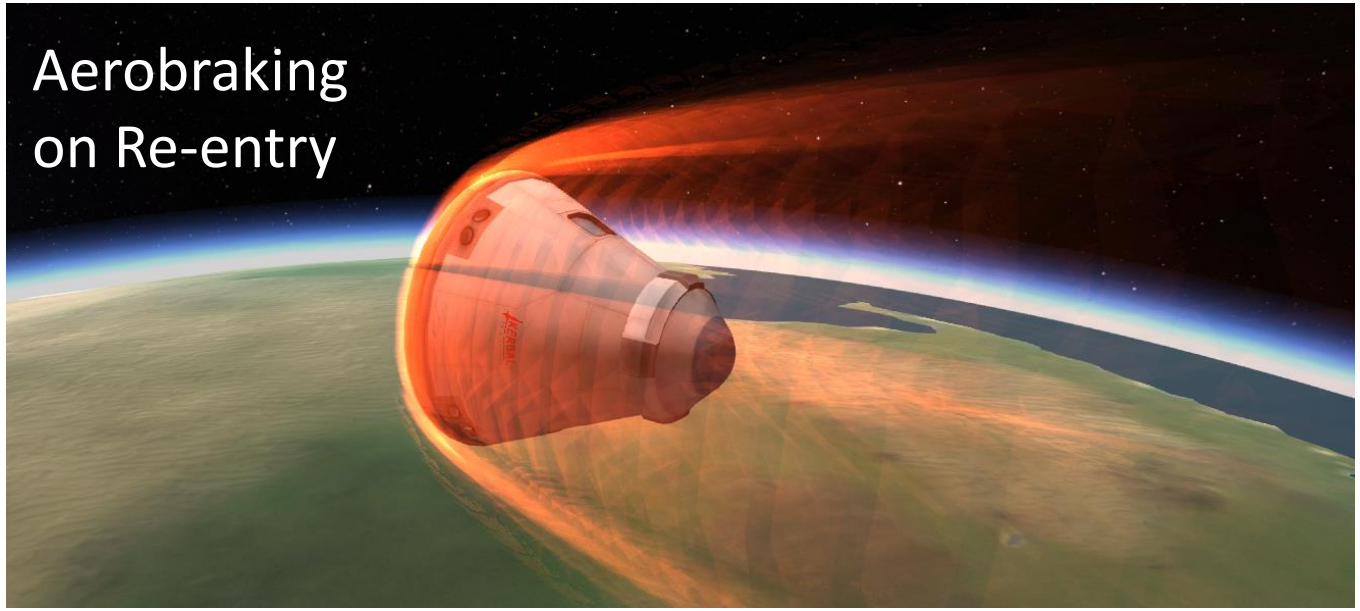
B612 FOUNDATION

The Atmosphere of Kerbin



Atmospheric Characteristics

Mass	4.7×10^{16} kg
MSLP	1013.25 hPa
Depth	70-km.
Molecular Weight	28.96 g/mol
Adiabatic Index	1.4
Scale Height	5.6 km
Gas Constant	287 J/kg-K



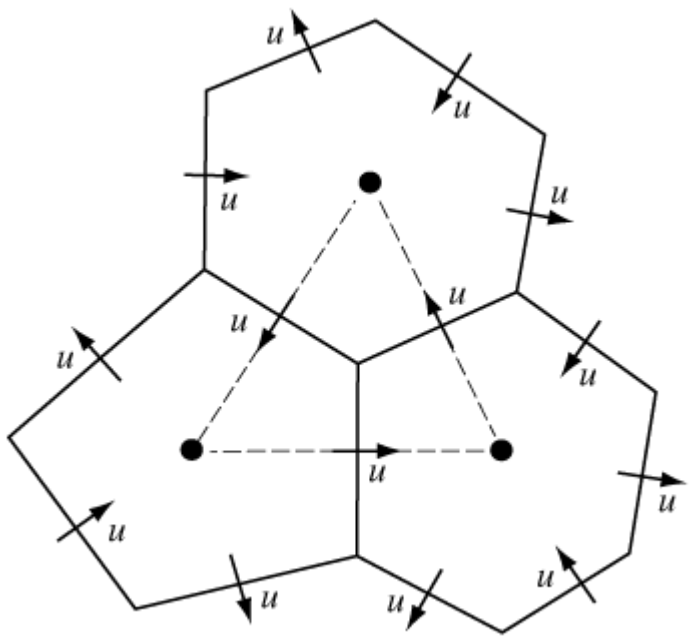
MPAS Model Setup

MPAS
Model for Prediction Across Scales

Physics Suite: "Mesoscale Reference"

Microphysics	WSM6
Convection	New Tiedke
Planetary Boundary Layer	YSU
Shortwave Radiation	RRTMG
Longwave Radiation	RRTMG
Surface Layer	SF Monin-Obukhov
Land Surface	Noah

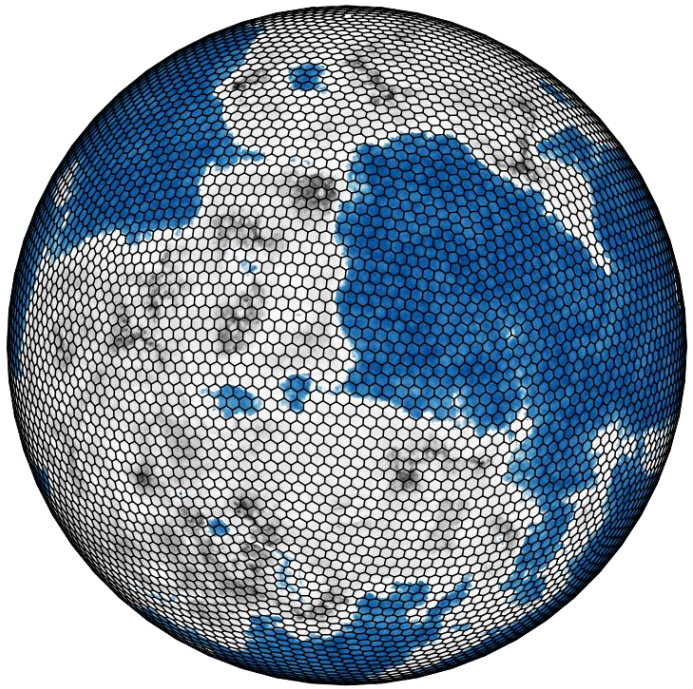
Skamarock et al. 2012



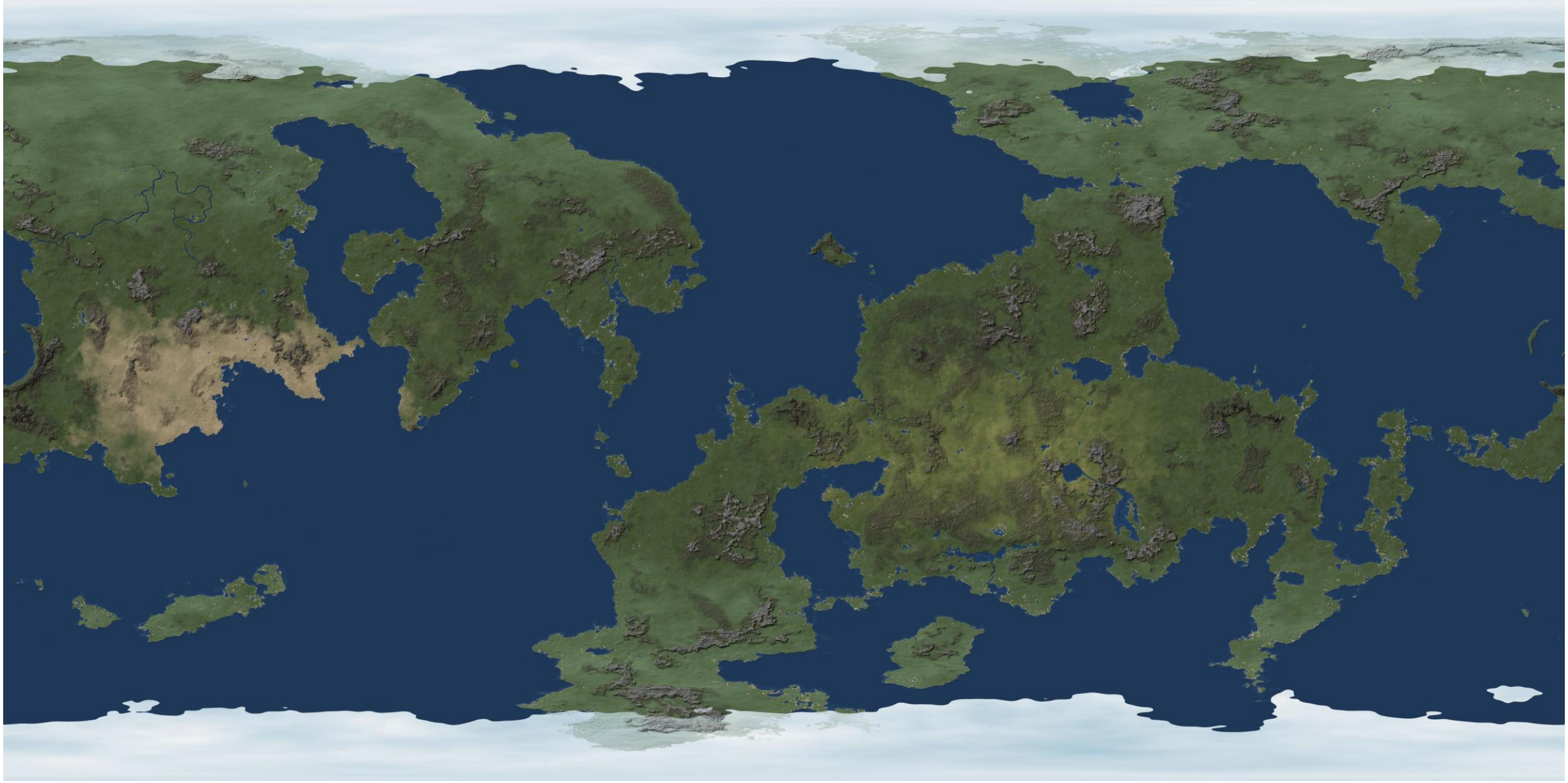
MPAS Grid Mesh (Kerbin)

Western Hemisphere

Eastern Hemisphere



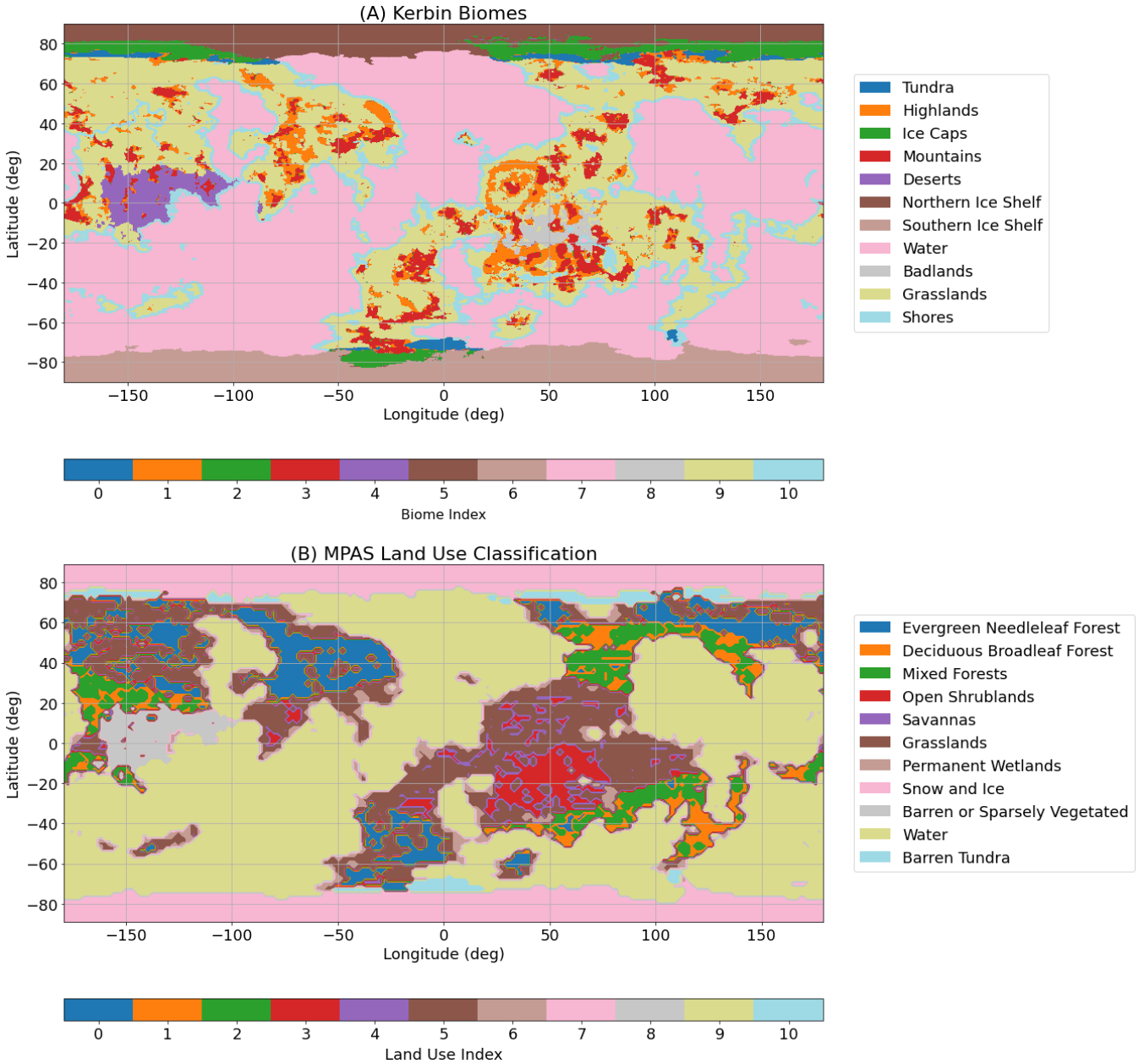
KSC: Kerbal Space Center | **DLS**: Desert Launch Site | **WLS**: Woomerang Launch Site



Model Initialization

- The global forecasting system (GFS) was used to initialize atmospheric fields such as temperature, humidity, pressure, and wind.

- Terrain and biome data from KSP were used to classify land use, vegetation type, green fraction, leaf area index, soil type, and surface albedo.

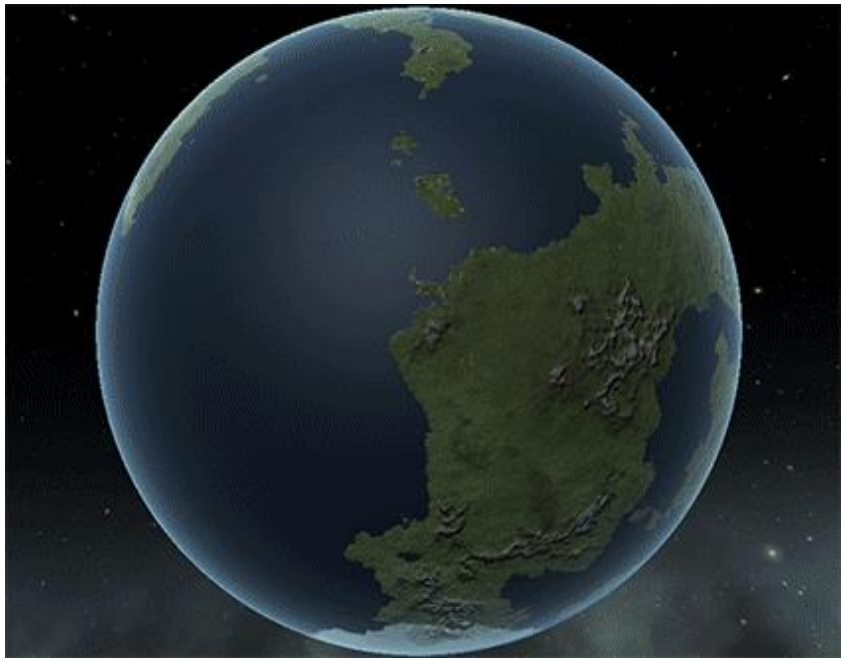


MPAS Land use classification (B) adapted from Kerbin Biomes (A).

Model Adaptations

In addition to land surface modifications, several changes to MPAS were made to enable more realistic simulations of Kerbin's atmosphere. These changes are listed below:

1. Axial obliquity was set to zero.
2. Orbital eccentricity was set to zero.
3. The solar constant was set to 1360 W/m
4. The day length was set to 6 hours (21600 s)
5. The Coriolis parameter was multiplied by a factor of 4.

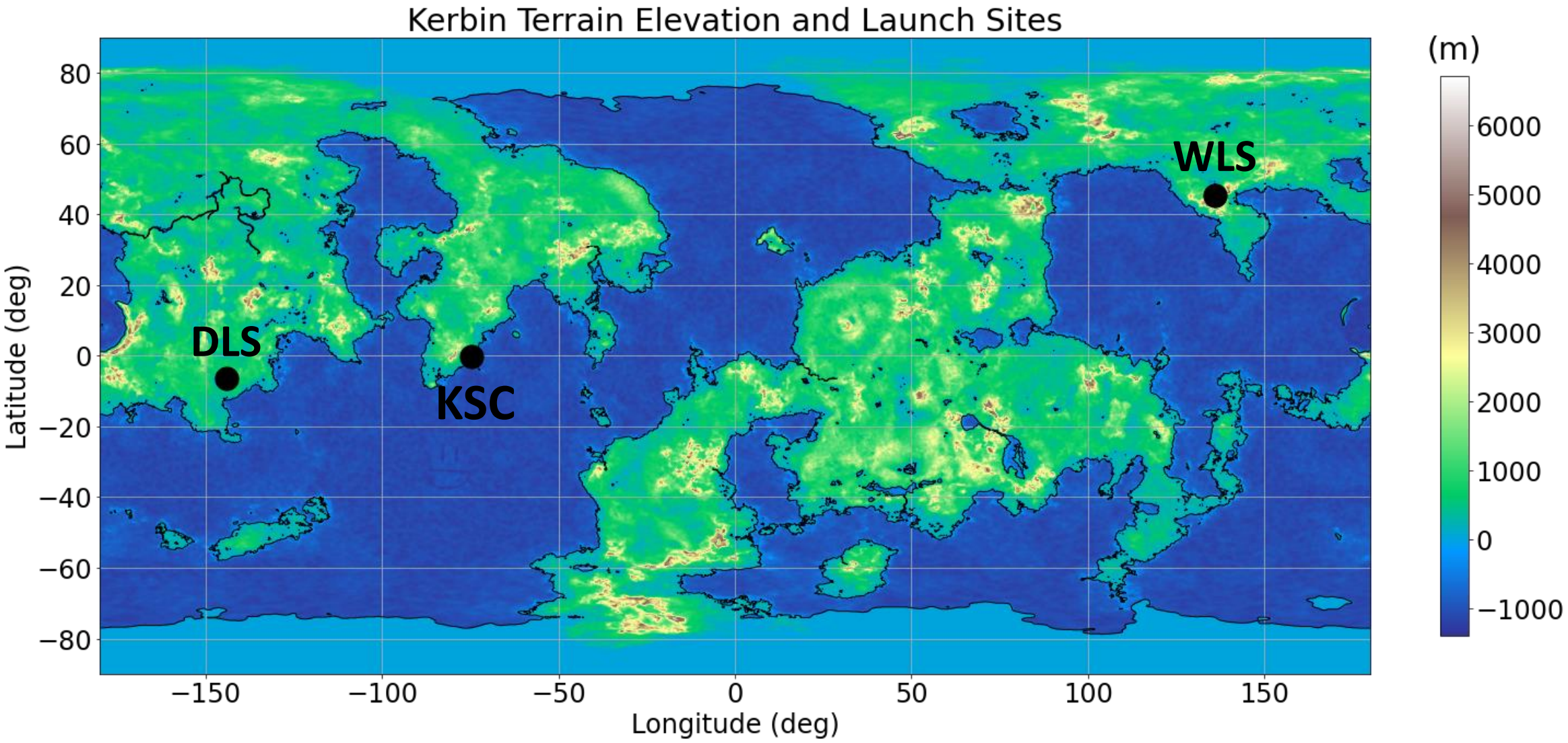


MPAS was run for six-years (1st year: spin-up) at a resolution of 2 x 2 deg.

A climatology of Kerbin was developed by averaging the results of the five-year MPAS simulation, by the hour. A second *Earth-Like* simulation was performed which kept Kerbin's terrain and land use characteristics but utilized Earth's orbital parameters.

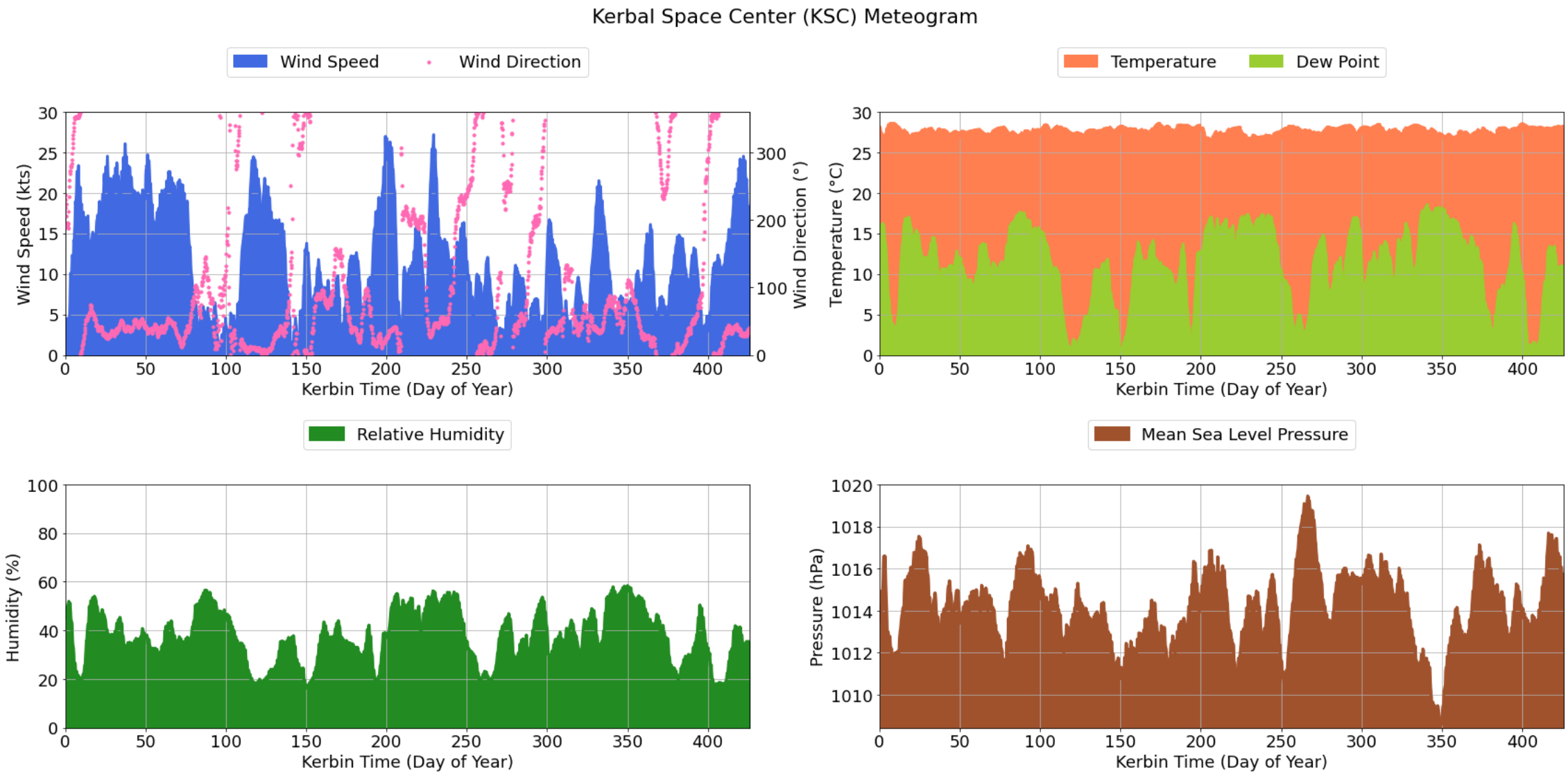
Kerbal Weather Analysis

Weather Analysis at Launch Sites

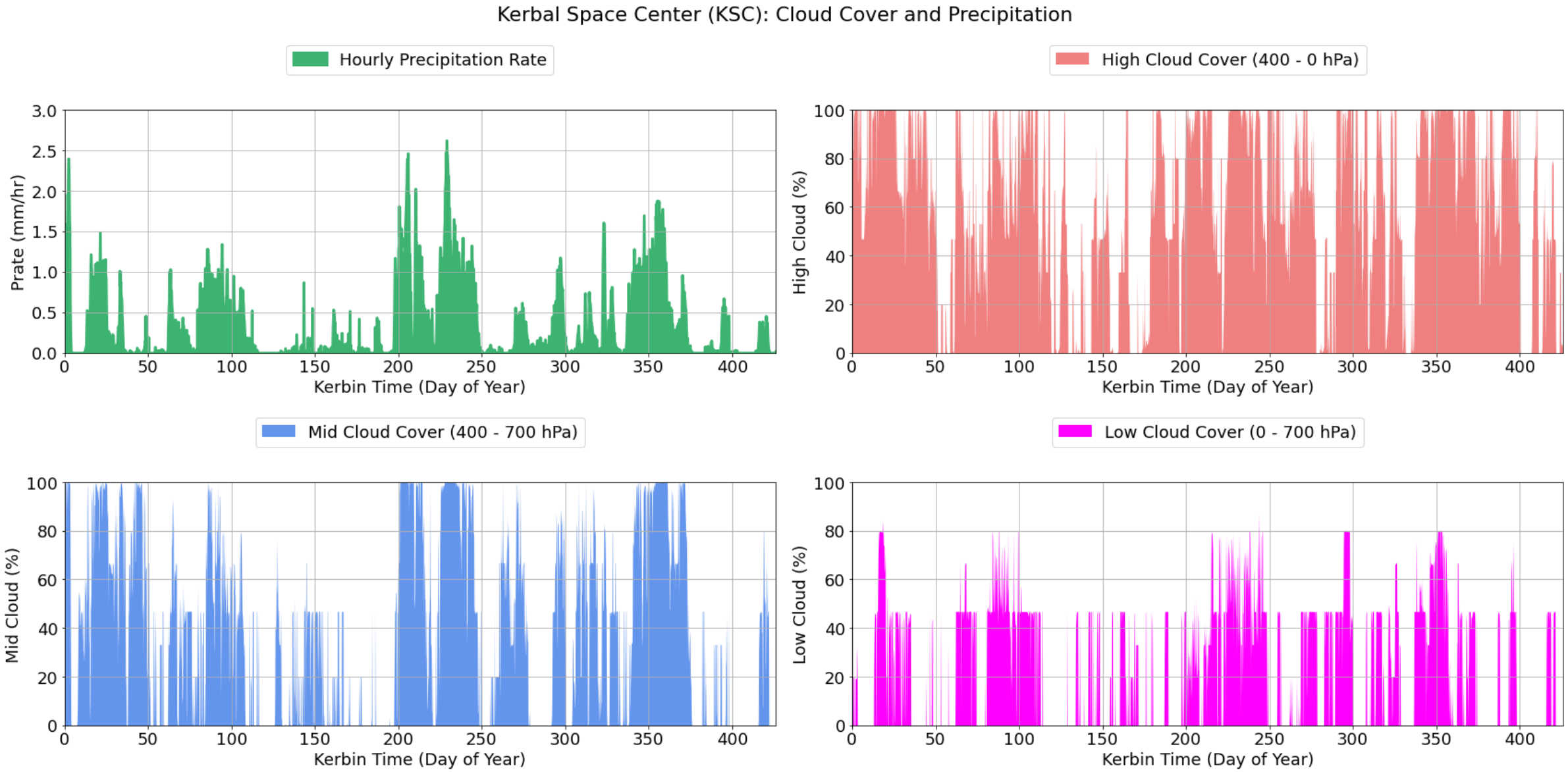


KSC: Kerbal Space Center | **DLS**: Desert Launch Site | **WLS**: Woomerang Launch Site

Weather Analysis at the KSC



Weather Analysis at the KSC

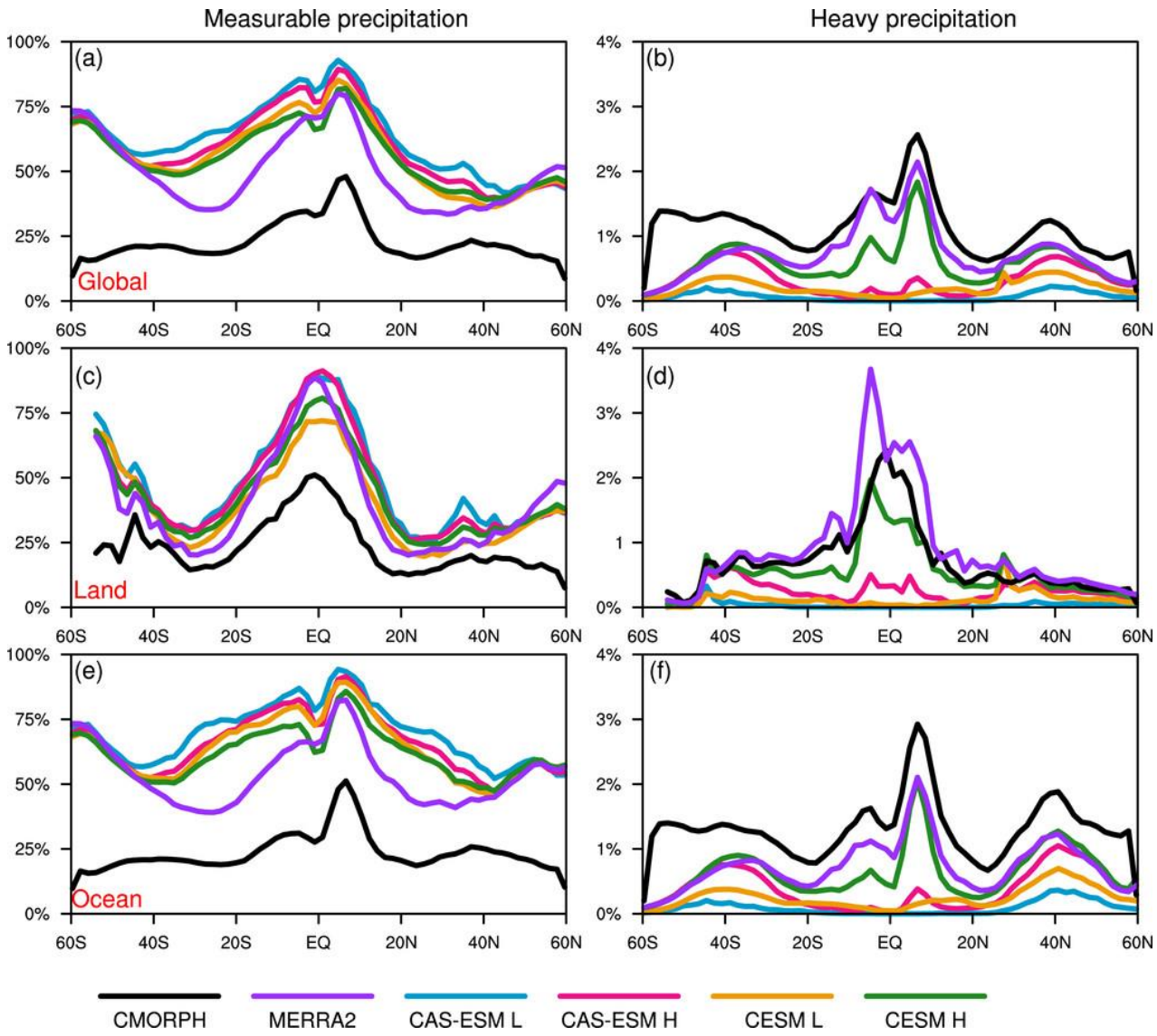


Weather Analysis at the KSC

- Measurable precipitation (> 0.02 mm h^{-1}) at the KSC occurred around 66% of the time and heavy precipitation (2 mm h^{-1}) around 1% of the time.

- These precipitation frequencies are similar to those estimated by atmospheric general circulation models for Earth's equatorial region (*Kong et al., 2020*).

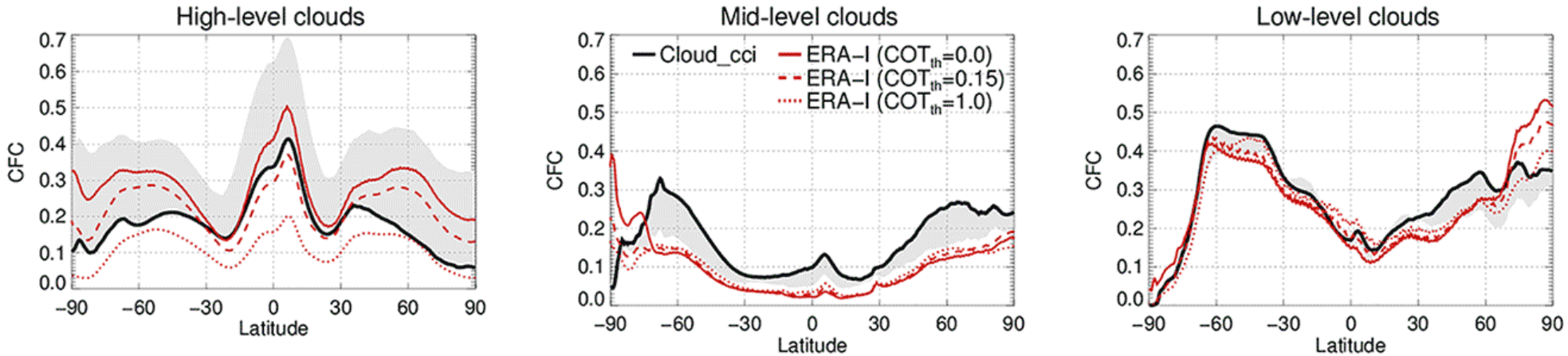
- It should be noted that convective precipitation is often intermittent, complicating the calculation of the precipitation rate (*Trenberth et al., 2017*)



Kong et al., 2020

Weather Analysis at the KSC

Stengel et al., 2018



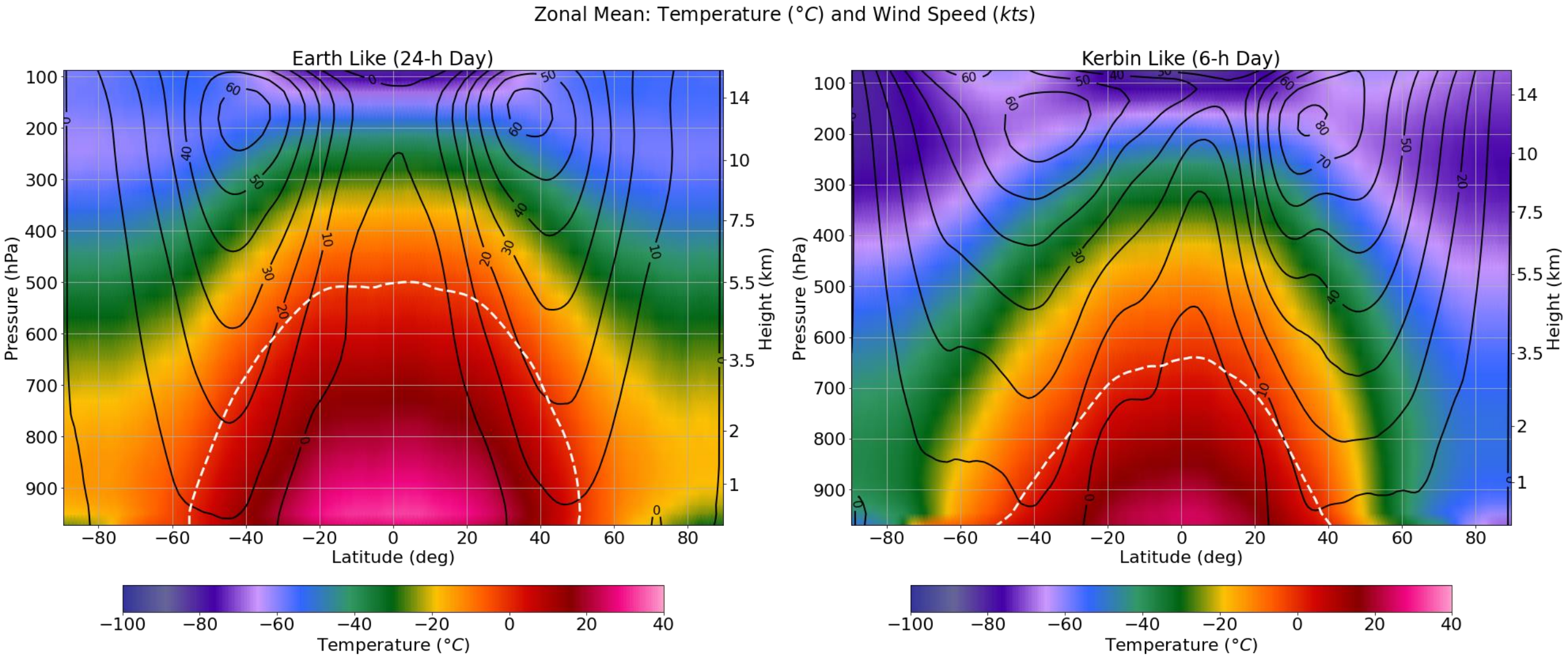
- In general, high-level clouds are more prevalent in the tropics while low and mid-level clouds are more common at high latitudes (*Stengel et al., 2018*).

- Mid-level cloud cover (e.g. altostratus) at the KSC was often associated with precipitation. This is perhaps most notable between days 200-250 when a high percentage of mid-level cloud cover was coincident with the onset of precipitation.

- Low clouds were present during most days at the KSC. Nevertheless, low-cloud fraction was typically around 40%. While models have gotten better at simulating cloud cover (*Kay et al., 2012*) they tend to underestimate low-cloud cover in the tropics (*Chandra et al., 2015; Zhang et al., 2019*).

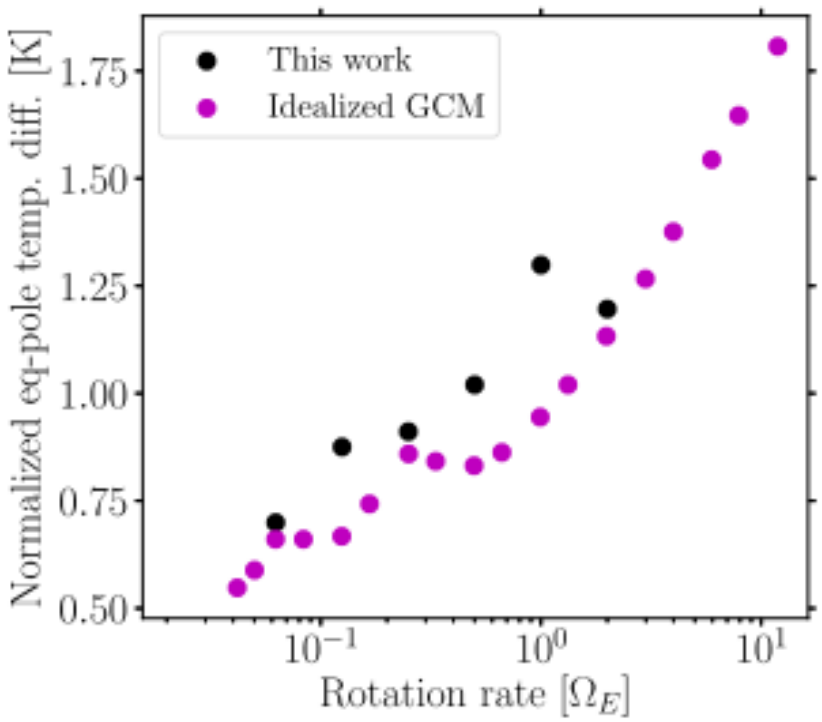
Zonally Averaged Climatology

Climate of the Troposphere



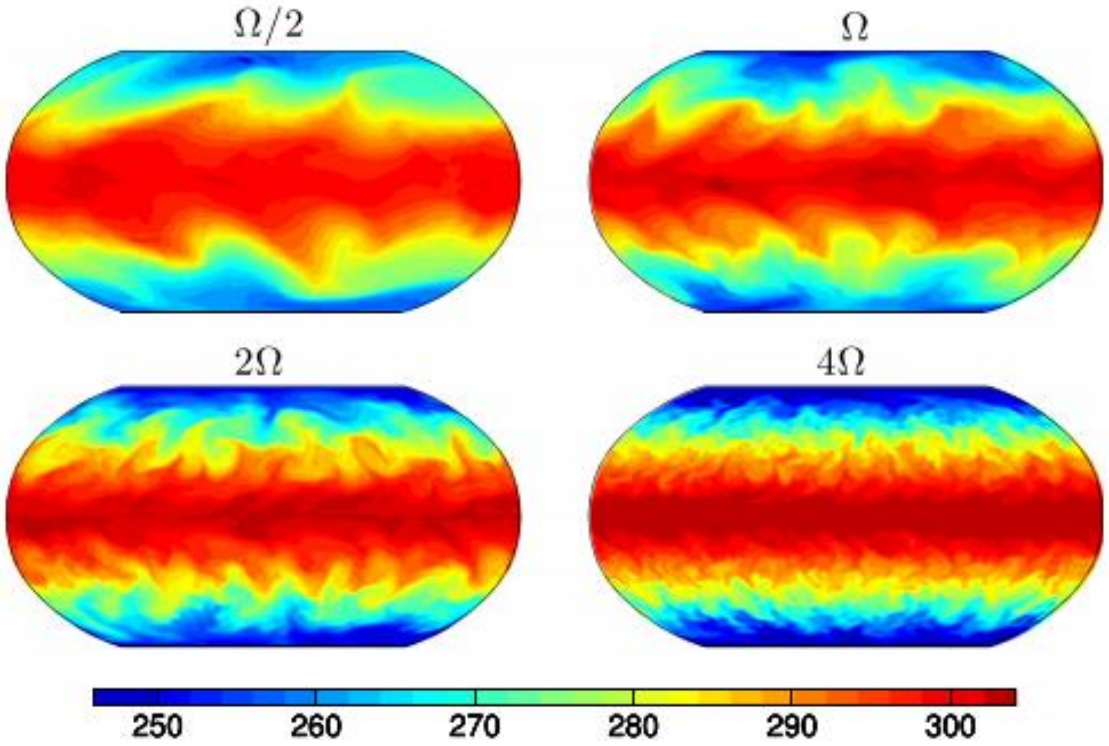
Climate of the Troposphere

(Komacek and Abbot, 2019)



Comparison of the dependence of the normalized equator-to-pole temperature difference on rotation rate between *Komacek and Abbot (2019;* black*)* and *Kaspi and Showman (2015;* pink*).*

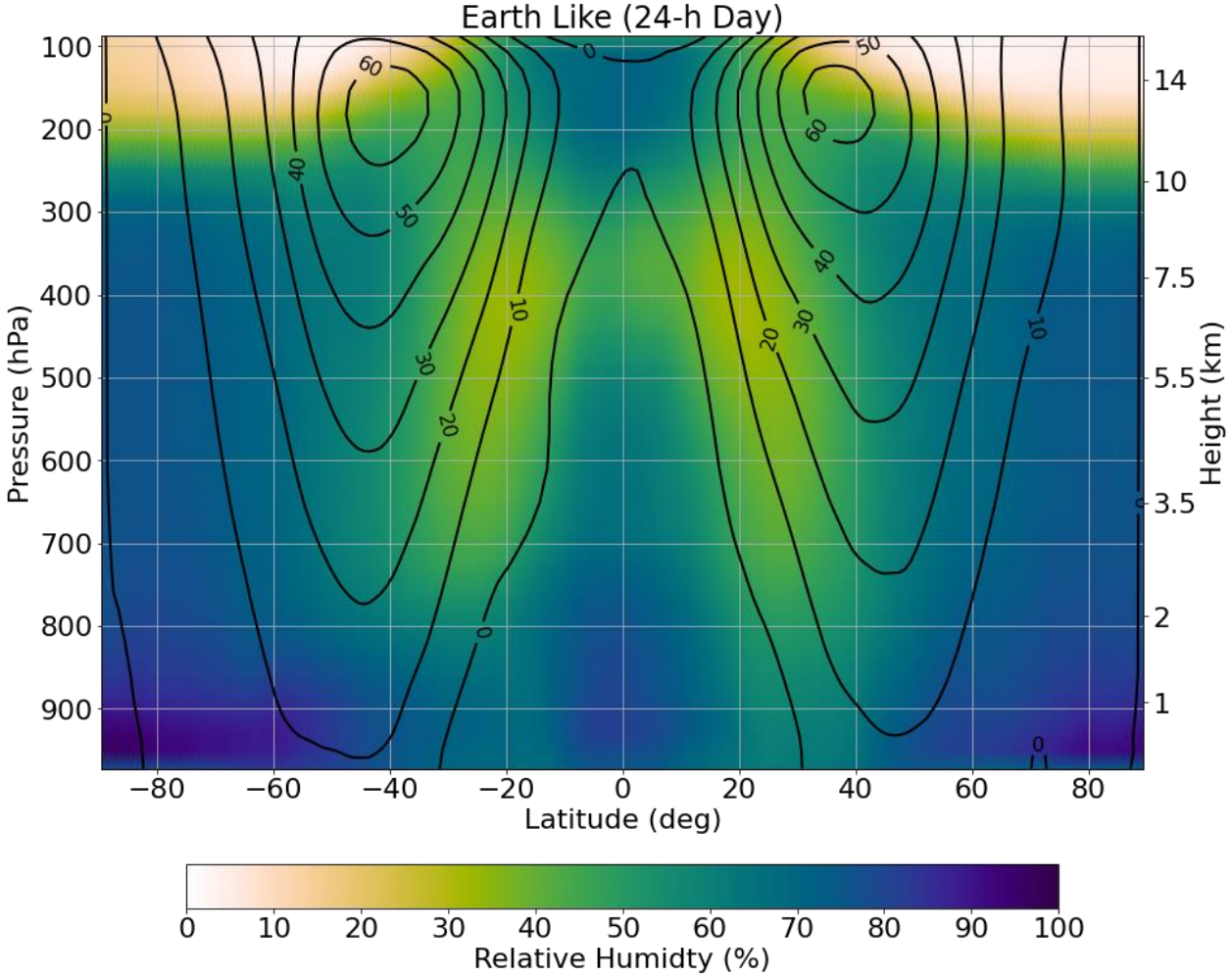
(Kaspi and Showman, 2015)

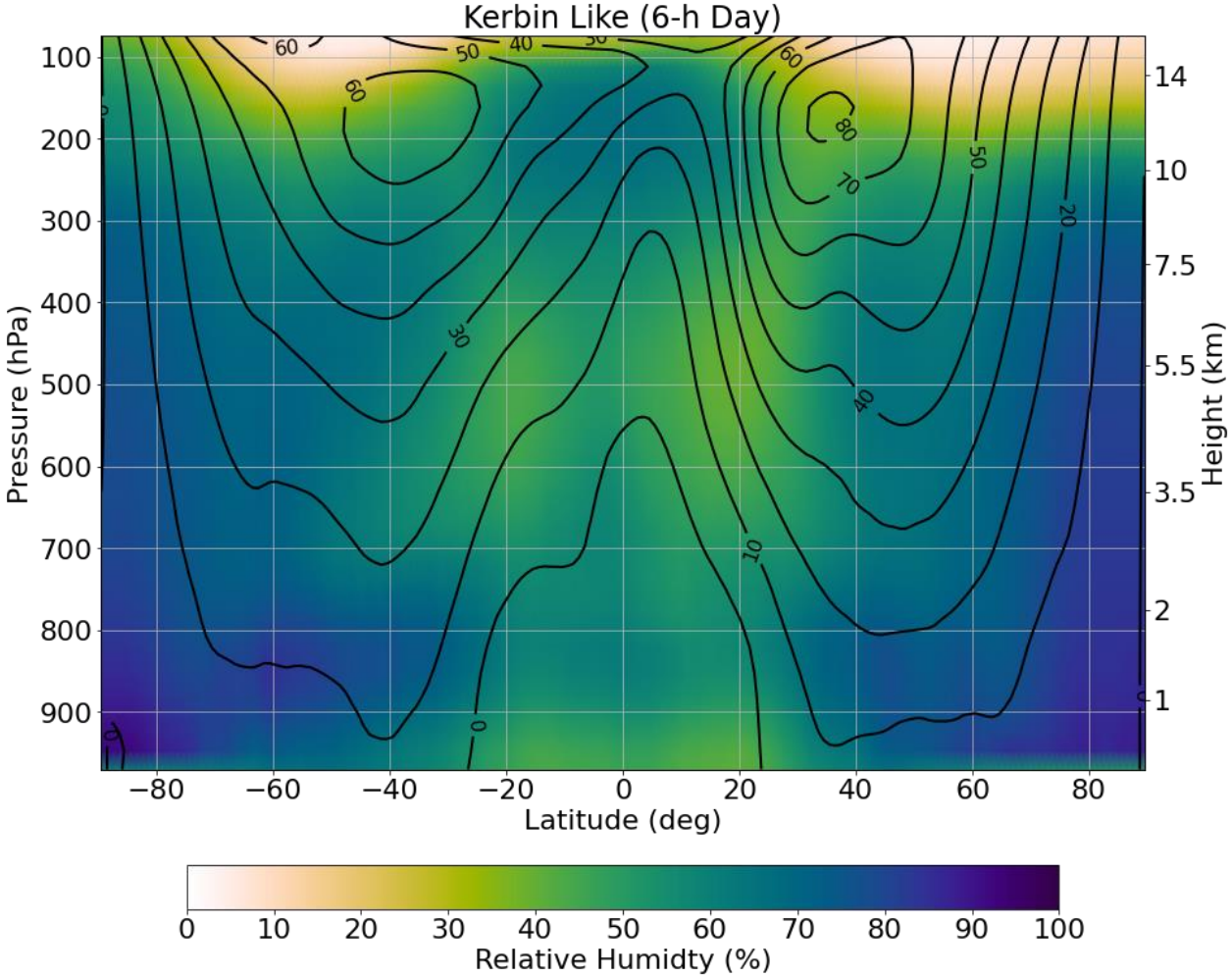


Surface temperature (K) illustrating the dependence of temperature and eddy scale on rotation rate. Baroclinic instabilities dominate the dynamics in mid- and high latitudes, leading to eddies whose length scales decrease with increasing planetary rotation rate.

Climate of the Troposphere

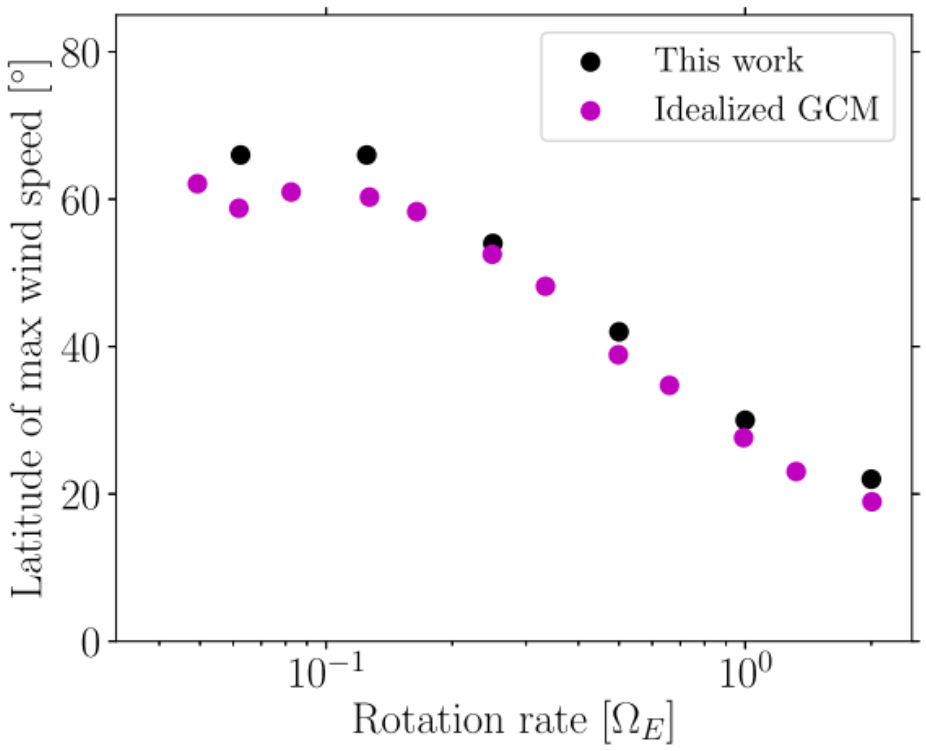
Zonal Mean: Relative Humidity (%) and Wind Speed (*kts*)





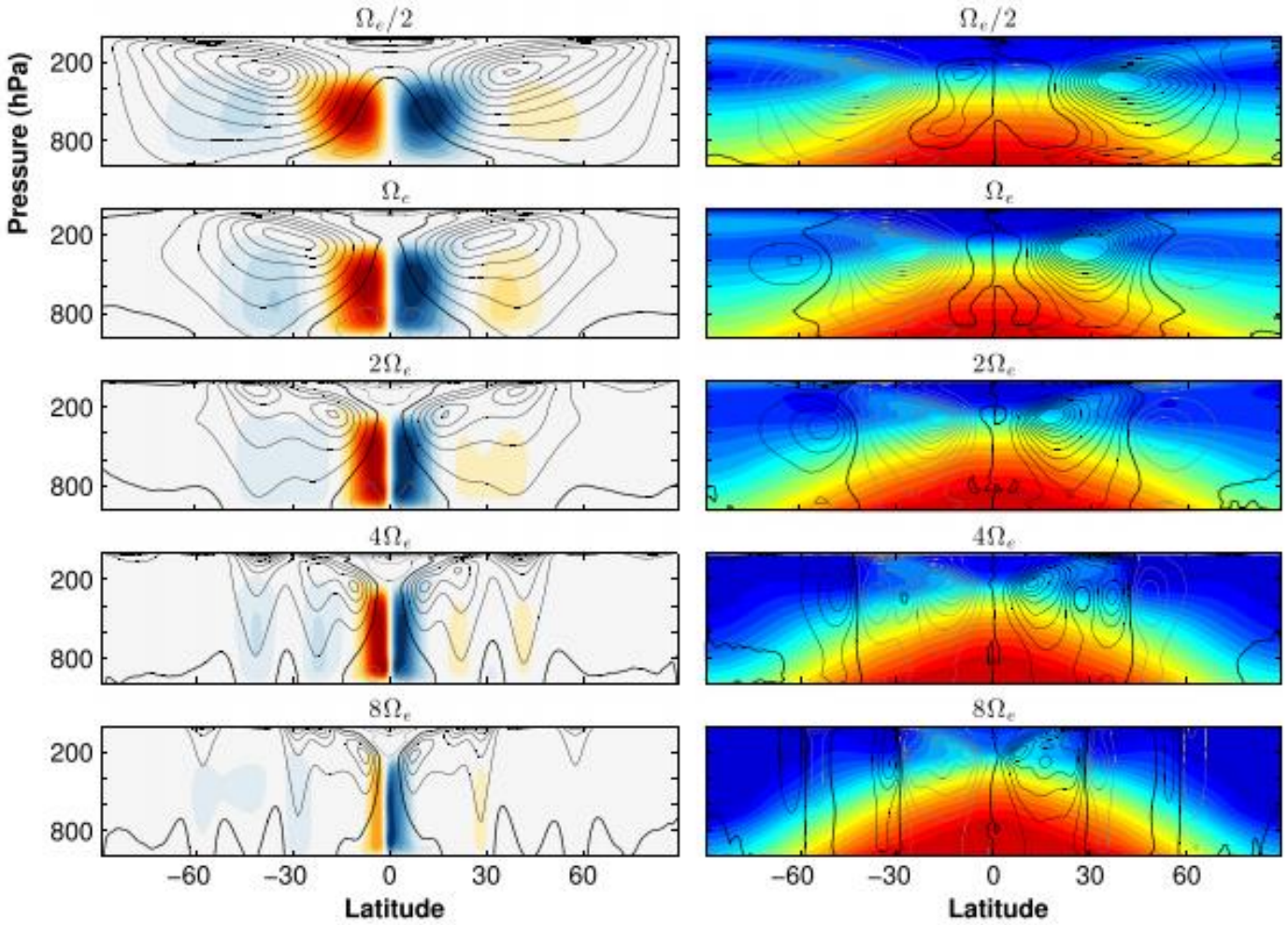
Climate of the Troposphere

(Komacek and Abbot, 2019)



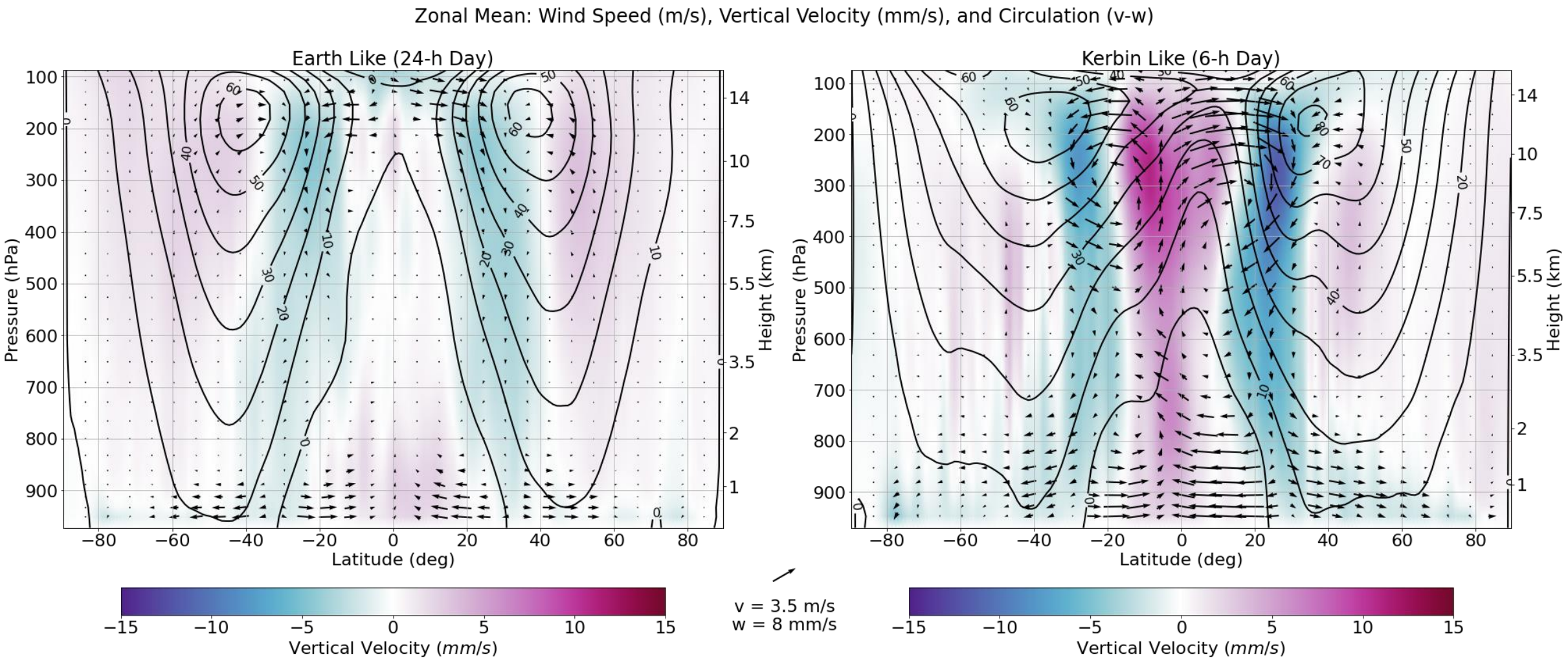
Comparison of the dependence of the maximum in the latitude of the maximum of zonal wind speed between *Komacek and Abbot (2019;* black*)* and *Kaspi and Showman (2015;* pink*).*

(Kaspi and Showman, 2015)



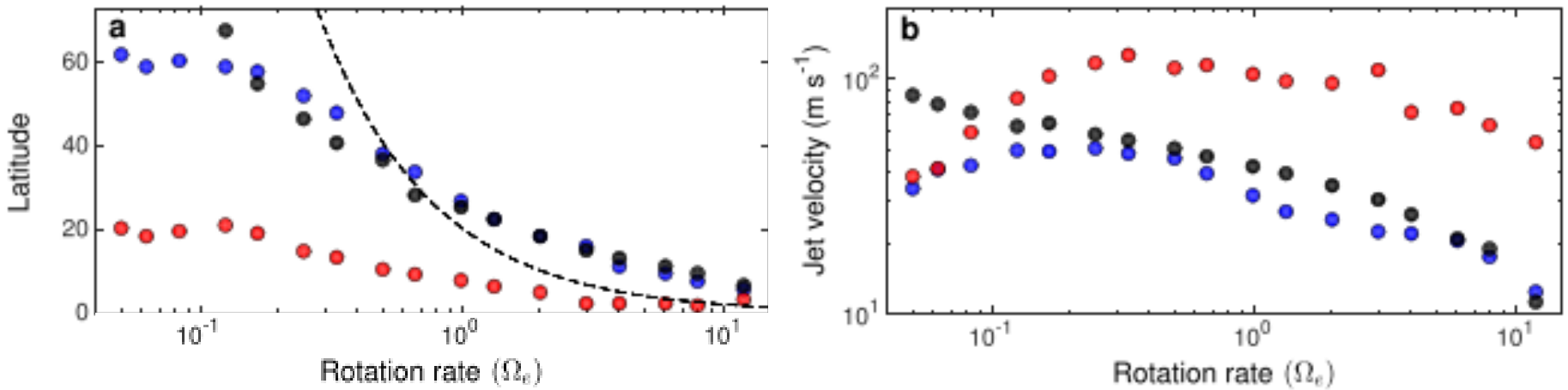
Left: zonal-mean zonal wind (grey) and zero-wind contour (black)
Right: zonal mean temperature and zonal-mean meridional eddy-momentum flux.

Climate of the Troposphere



Climate of the Troposphere

(Kaspi and Showman, 2015)



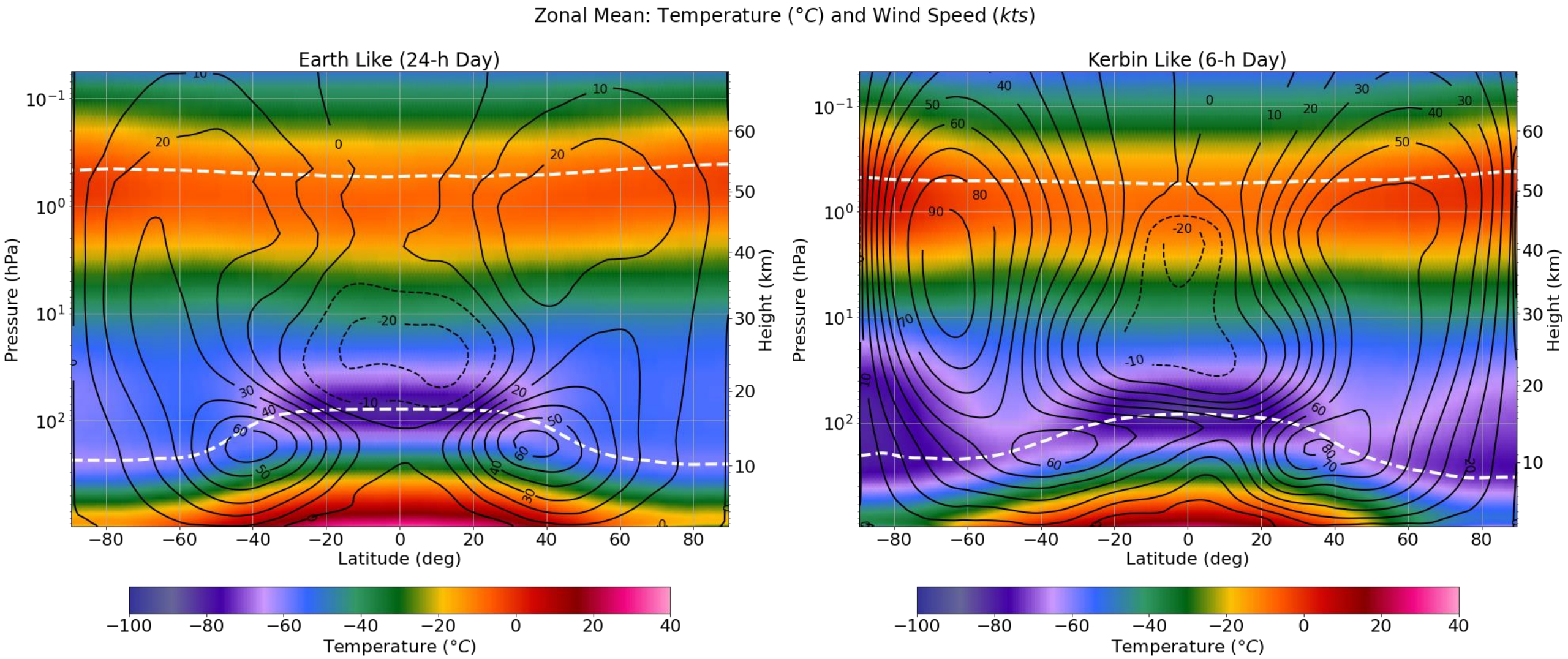
(a) Latitude of the Hadley cell maximum (red), Hadley cell width (black), and the latitudinal location of the maximum jet (blue)

(b) Magnitude of the subtropical jet (blue), the magnitude of an angular momentum conserving wind at the latitude of the maximum jet (red), and the strength of the Hadley cell stream function (black) to the power of 2/5.

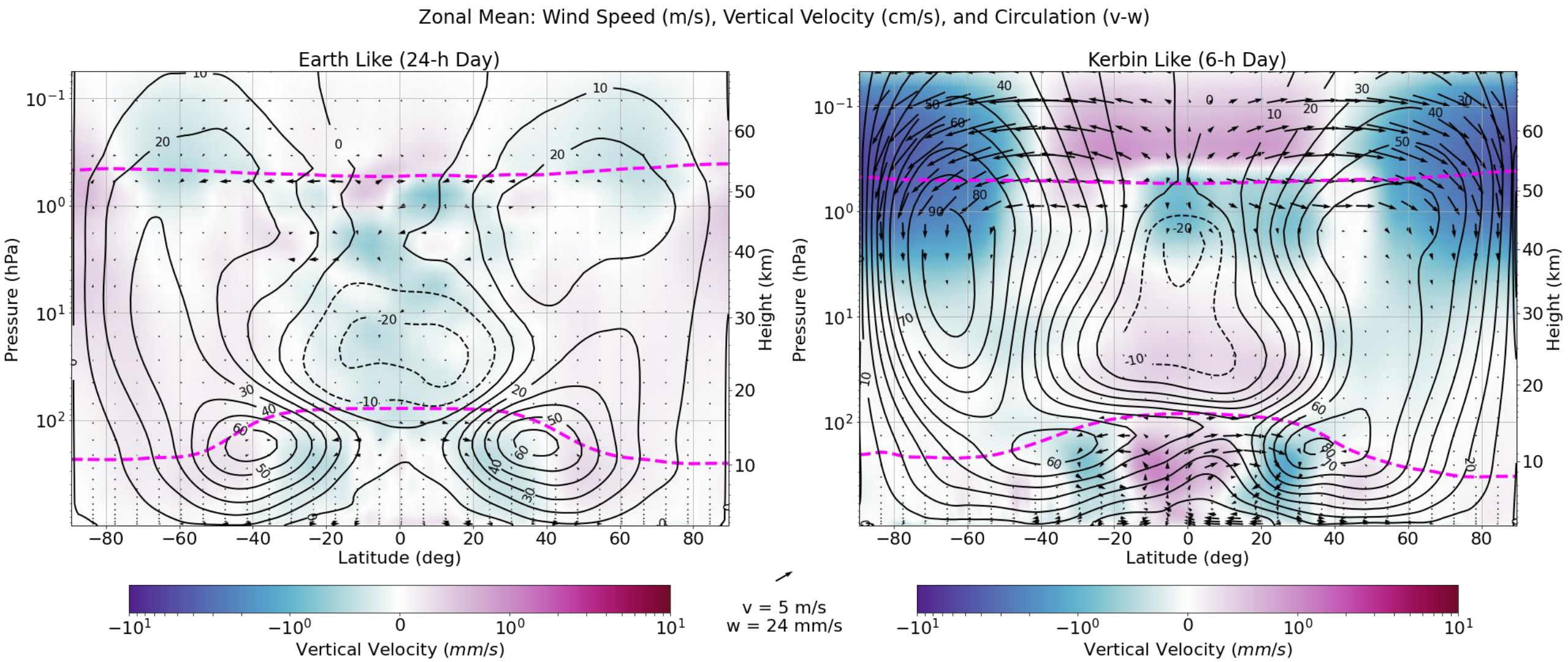
Nonmonotonic trend in subtropical jet speed with rotation period (*Komacek and Abbot, 2019*)

- Trade-off between the increase in rotation rate leading to an increase in angular momentum of poleward-moving air in the Hadley cell and the narrowing of the Hadley cell causing the jet to acquire less mean angular momentum

Climate of the Stratosphere and Mesosphere



Climate of the Stratosphere and Mesosphere



Climate of the Stratosphere and Mesosphere

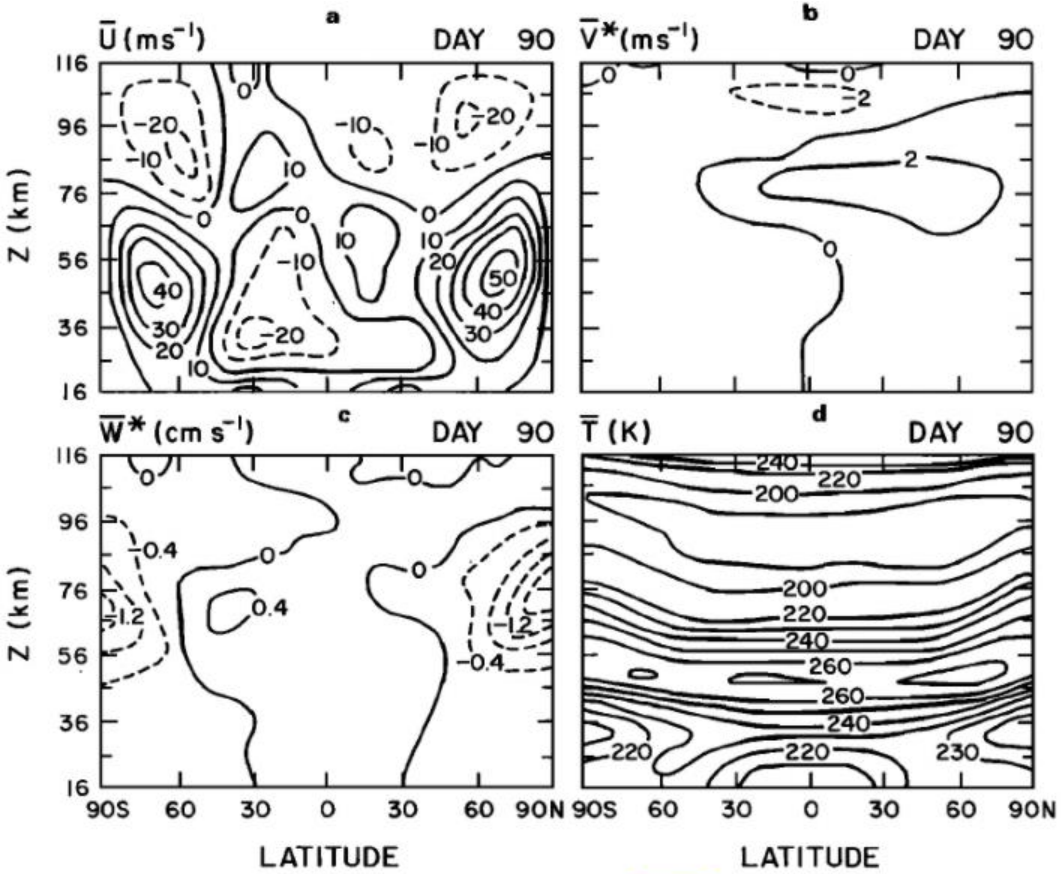
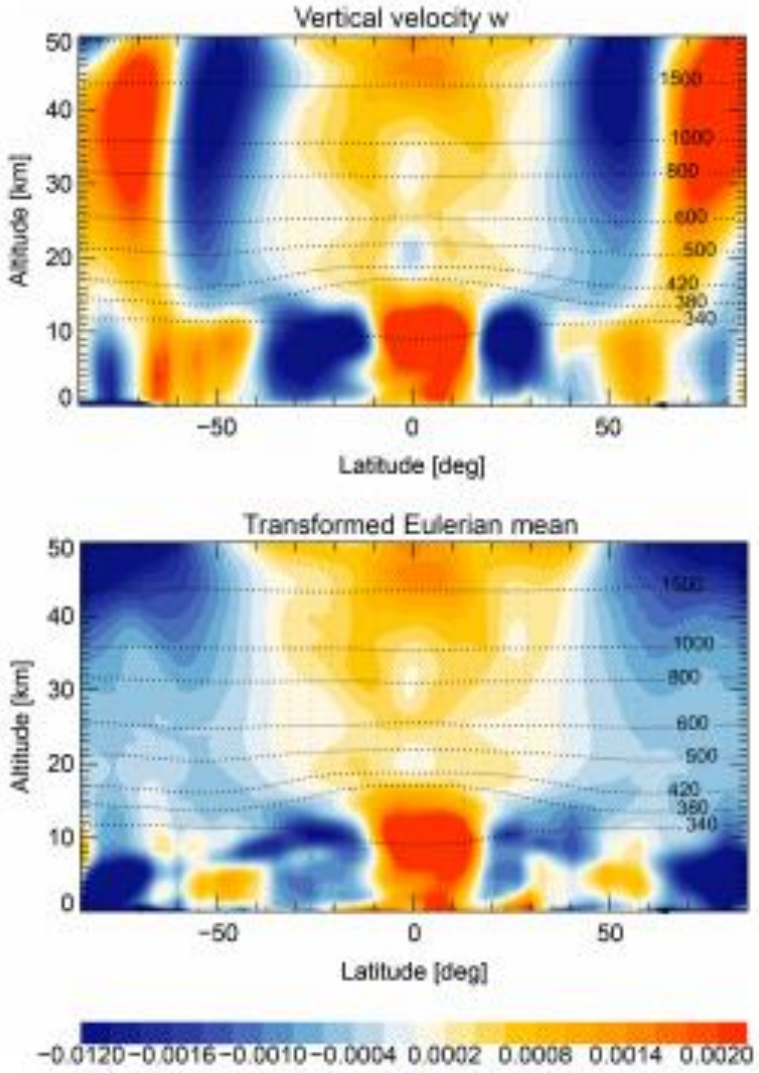


Fig. 2. As in Figure 1, but for equinox

Zonally Averaged circulation and temperature for model equinox (*Garcia and Soloman, 1987*)

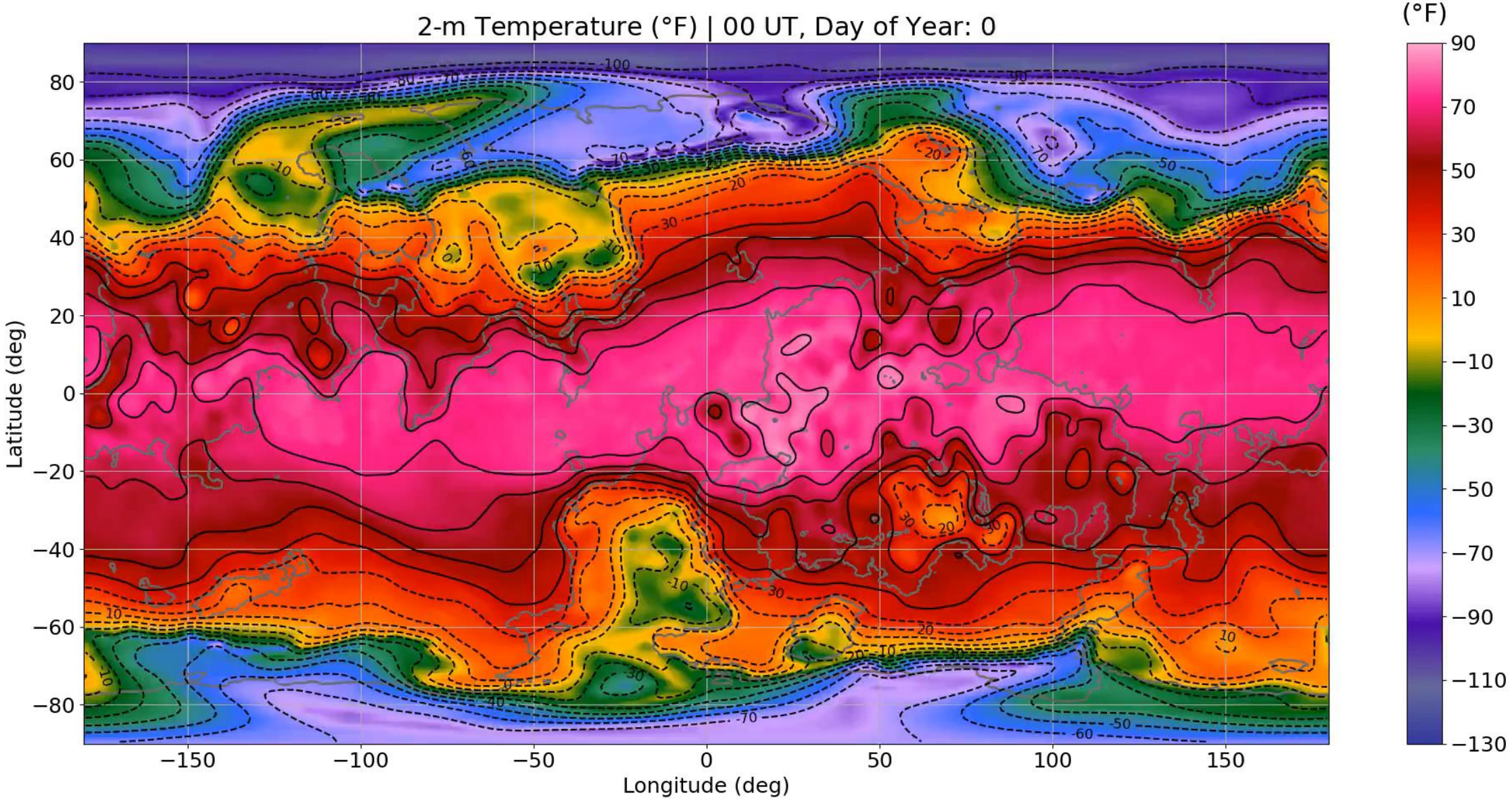


Annual, zonal mean vertical velocity (top) and transformed Eulerian mean (TEM) vertical velocity (bottom) from EMAC for the year 2005. Dotted lines display potential temperature levels (K). The vertical axis displays log-pressure-height (km).

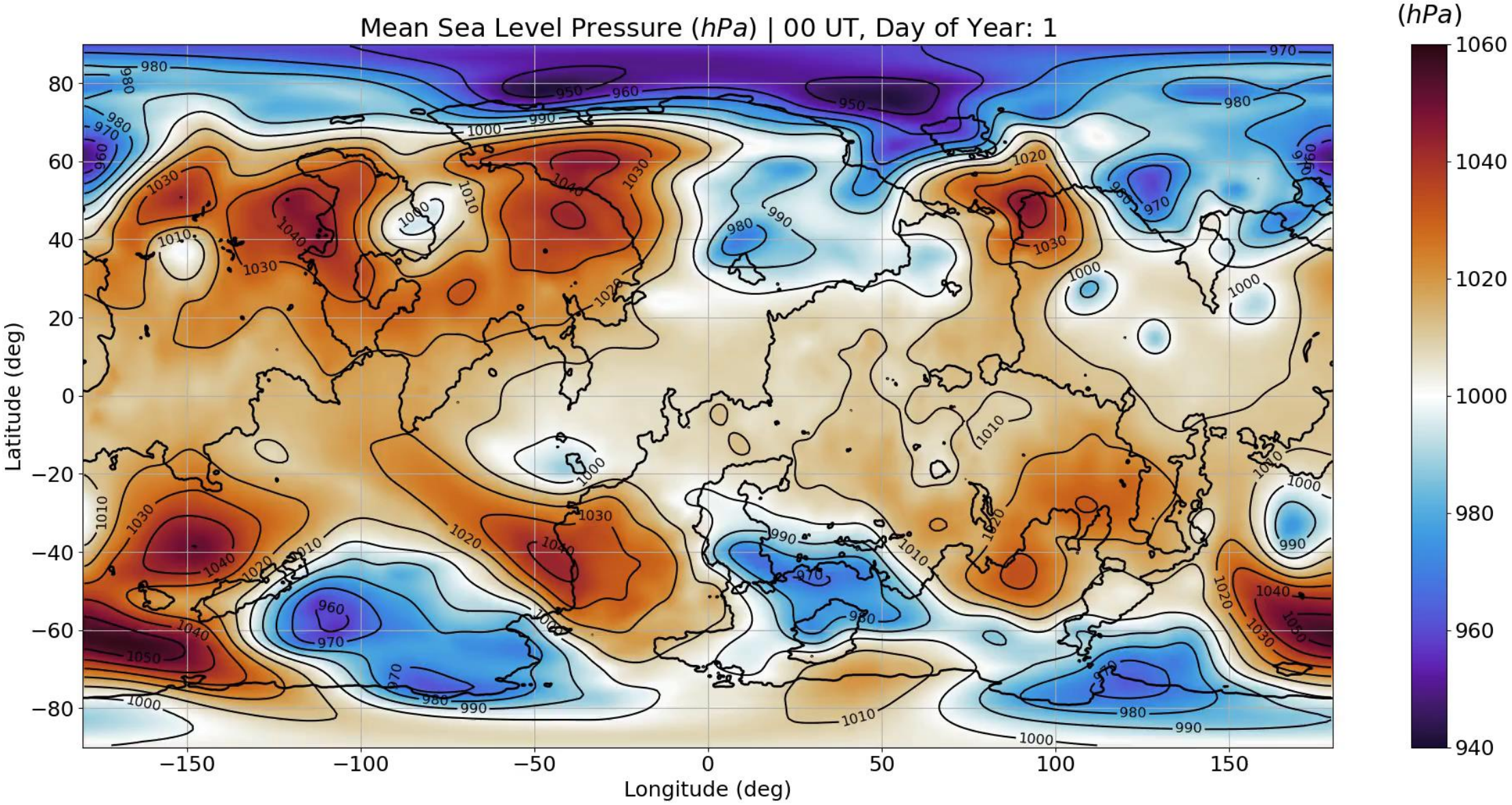
(*Garcia and Soloman, 1987*)

MPAS Animations

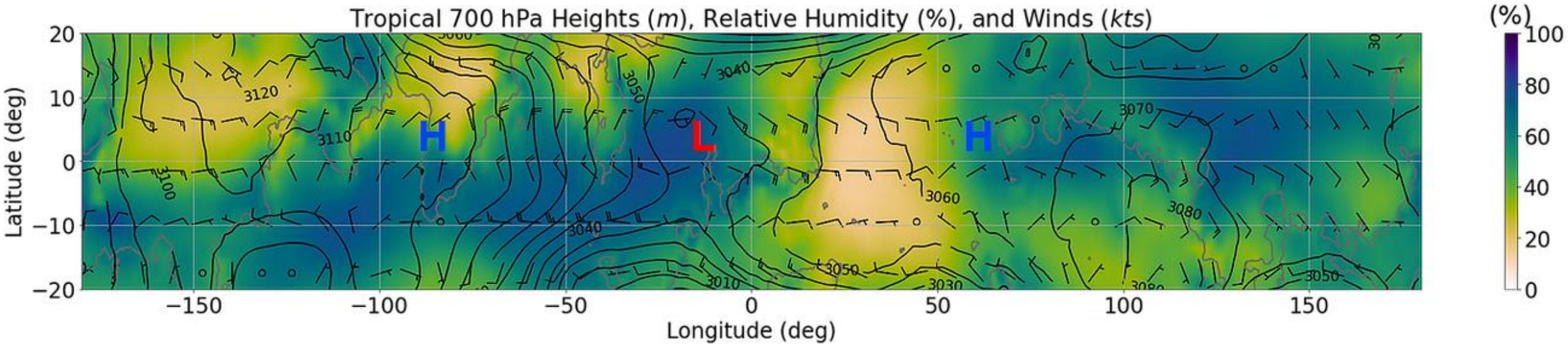
2-m Temperature



Sea Level Pressure

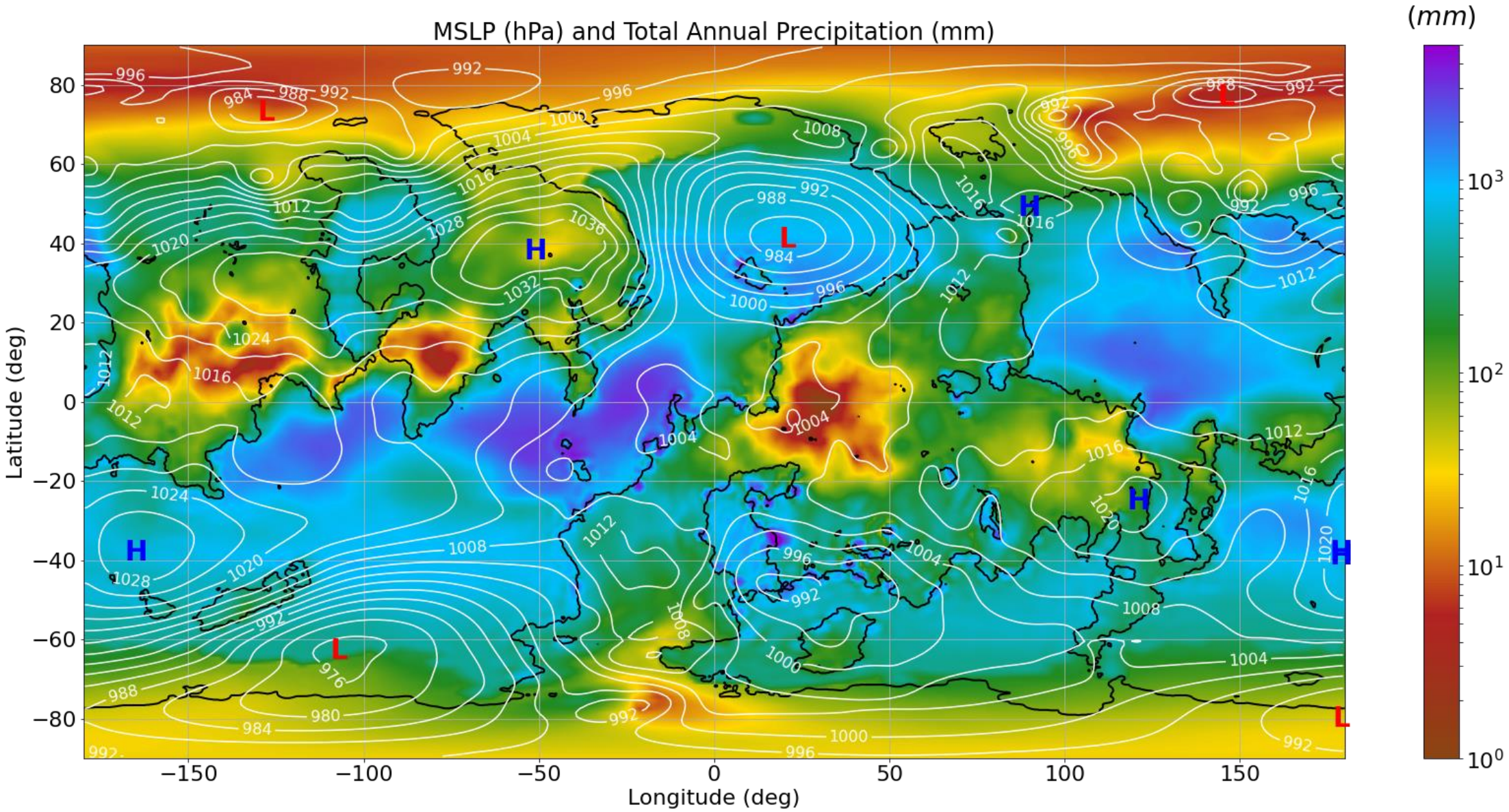


Spatial Climatology



- Gradient in 700 hPa heights between the continents and ocean.
- 700 hPa heights are relatively high (3100 m) over the KSC (Africa like) continent. Over the ocean to the east 700 hPa fall and reach a local minimum (3010 m). Further east, 700 hPa heights over the continent rise again. This High-Low-High pattern is characteristic of a type of a Kelvin wave.
- Kelvin waves influence patterns of rainfall in the tropics (Frierson, 2007) and can aid, or suppress, the development of tropical cyclones (Schreck, 2015).
- On Kerbin, precipitation is enhanced west of the wave minima (L) over the ocean east of the KSC.

Spatial Climatology



Summary of Results

- Increasing the planetary rotation rate enhanced equator to pole-contrasts and contributed to a bifurcation of the jet stream, reproducing the results of confirmed the results of Kaspi and Showman (2015) and Komacek and Abbot (2019) who used a more simplistic atmospheric model without terrain or moist physics.

- Decreasing the day-length from 24-h to 6-h had a significant impact on diurnal temperature variations. This was most notably in the tropics, where zonally averaged (near-surface) temperatures decreased.

- A lack of seasons resulted in a significantly less hospitable climate producing extreme cold at the poles and a largely stationary Hadley Cell and ITCZ. The Hadley cell was more asymmetric on a faster rotating planet with no seasonal cycle.

- In the middle-atmosphere, the absence of seasonality produced a robust polar vortex in both hemispheres year-round.

Kerbal Weather Project

Flying through the Jet Stream

Tropical Re-entry

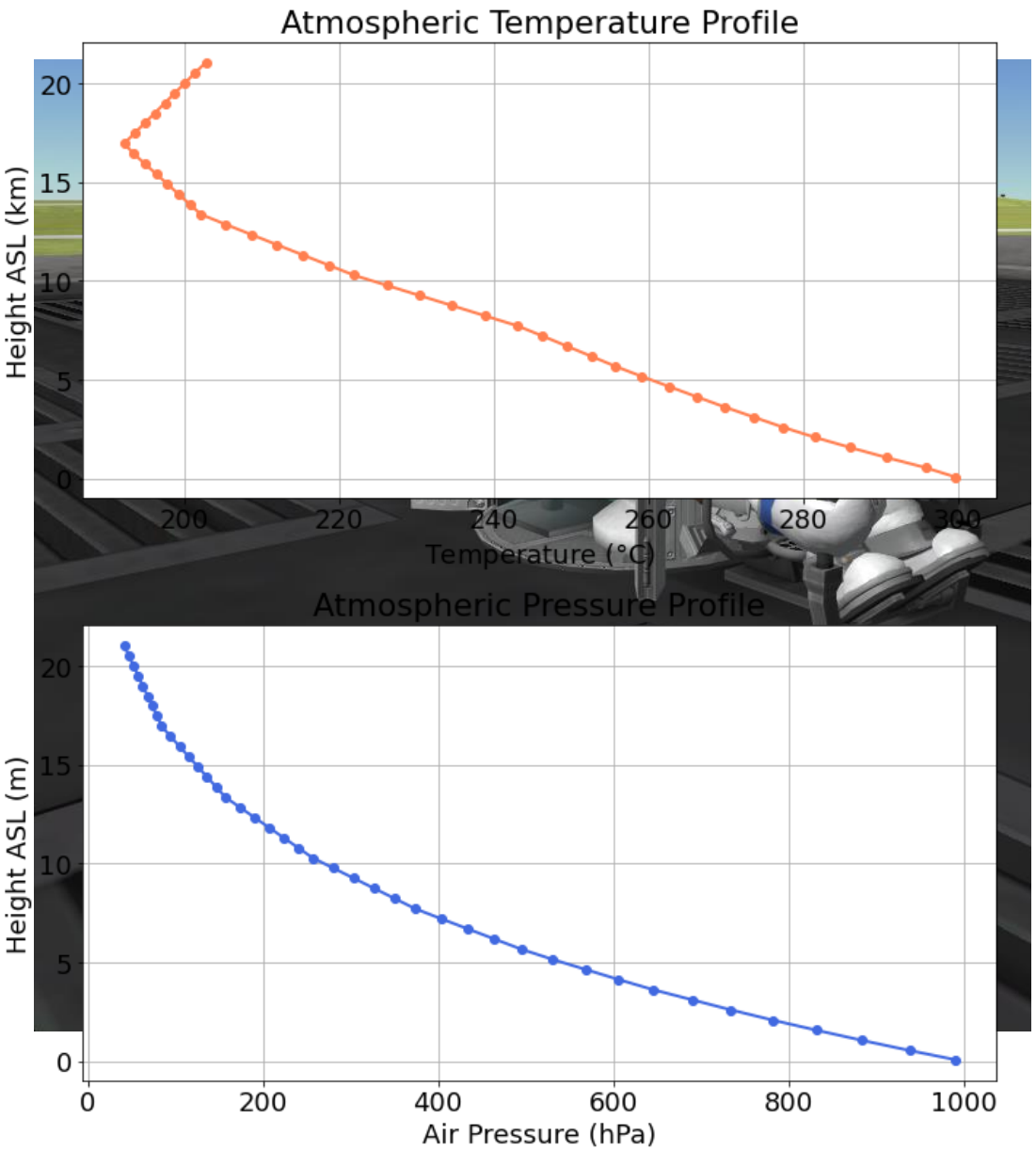
- Depending on the phase of the QBO winds in the tropical stratosphere may be easterly or westerly.
- Easterly Headwinds on re-entry contribute to an increase in atmospheric drag
- Increased atmospheric pressure/density, relative to the stock atmosphere, density results in increased dynamic pressure (Q).

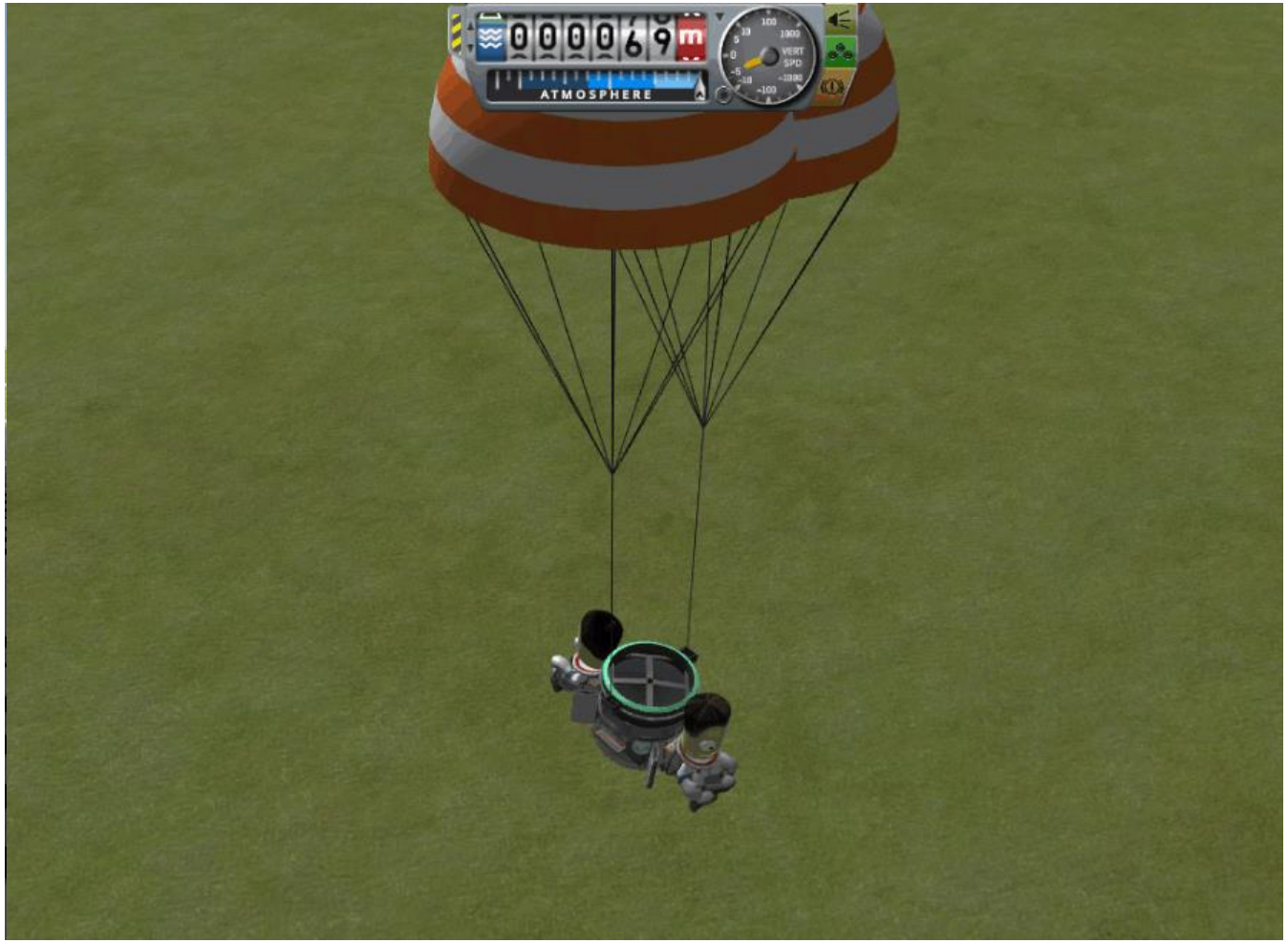
Satellite Science

East of the KSC continent the satellite orbits open ocean and adjacent coastline at mid latitudes.

- Over the ocean KWP reports SSTs which are relatively warm (285 K)
- Along the mountain coast, temperatures dip as low as 246 K.
- Oceanic precipitable water is five times tat over land highlighting how the moisture capacity of the air increases non-linearly with increasing temperature.
- Differences in temperature and moisture content account for the difference in precipitation rate between land and sea.

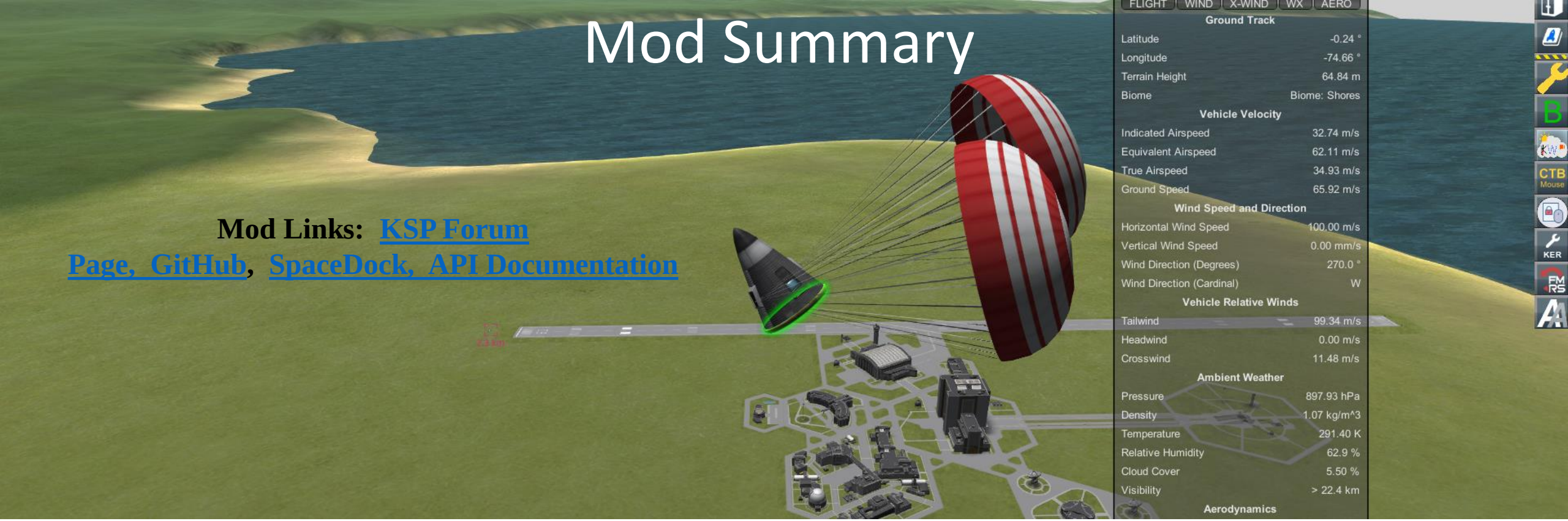
Kerbal Space Center (KSC) - Crewed Balloon Sounding





Mod Summary

Mod Links: [KSP Forum Page, GitHub, SpaceDock, API Documentation]



- Model output can be incorporated into a STEM video game by reducing data size through averaging in space or time.

- Examples from KSP highlight how climate/weather model data could be brought to life to teach students about basic concepts in atmospheric science in an interactive way.

KWP Links

- [KSP Forum Page]
- [GitHub]
- [SpaceDock]
- [API Documentation]

KerbalWeatherProject

latest

Search docs

Tutorial

API Documentation

Climate API

Weather API

License

Need Help

Retrieve column (3D) atmospheric variables

`climate_api.pressure`*(latitude, longitude, altitude, ut)*

Parameters

- latitude (double) - decimal degrees
- longitude (double) - decimal degrees
- altitude (double) - meters above sea level
- ut (double) - universal time in seconds (time since game began)

Returns (double): air pressure (Pa)

`climate_api.temperature`*(latitude, longitude, altitude, ut)*

Parameters

- latitude (double) - decimal degrees
- longitude (double) - decimal degrees
- altitude (double) - meters above sea level
- ut (double) - universal time in seconds (time since game began)

Returns (double): air temperature (K)

`climate_api.relative_humidity`*(latitude, longitude, altitude, ut)*

Parameters

- latitude (double) - decimal degrees
- longitude (double) - decimal degrees
- altitude (double) - meters above sea level
- ut (double) - universal time in seconds (time since game began)

Returns (double): relative_humidity (%)

References

Chandra, A. S., Zhang, C., Klein, S. A., & Ma, H.-Y. (2015). Low-cloud characteristics over the tropical western Pacific from ARM observations and CAM5 simulations. Journal of Geophysical Research: Atmospheres, 120, 8953–8970. https://doi.org/10.1002/2015JD023369

Garcia, R. R., and Solomon, S. (1985), The effect of breaking gravity waves on the dynamics and chemical composition of the mesosphere and lower thermosphere, J. Geophys. Res., 90(D2), 3850– 3868, https://doi.org/10.1029/JD090iD02p03850.

Hoppe, C. M., Ploeger, F., Konopka, P., and Müller, R.: Kinematic and diabatic vertical velocity climatologies from a chemistry climate model, Atmos. Chem. Phys., 16, 6223–6239, https://doi.org/10.5194/acp-16-6223-2016.

Kaspi, Y., Showman A. P., 2015: Atmospheric Dynamics of Terrestrial Exoplanets Over a Wide Range of Orbital and Atmospheric Parameters. The Astrophysical Journal, 804, http://dx.doi.org/10.1088/0004-637X/804/1/60

Kay, J. E., and Coauthors, 2012: Exposing Global Cloud Biases in the Community Atmosphere Model (CAM) Using Satellite Observations and Their Corresponding Instrument Simulators. J. Climate, 25, 5190–5207, https://doi.org/10.1175/JCLI-D-11-00469.1.

Komacek, D., Abbot S. D., 2019: The Atmospheric Circulation and Climate of Terrestrial Planets Orbiting Sun-like and M Dwarf Stars over a Broad Range of Planetary Parameters. The Astrophysical Journal, 871, https://doi.org/10.3847/1538-4357/aafb33

Kong, X., A. Wang, X. Bi, X. Li, and H. Zhang, 2020: Effects of Horizontal Resolution on Hourly Precipitation in AGCM Simulations. J. Hydrometeor., 21, 643–670, https://doi.org/10.1175/JHM-D-19-0148.1.

Stengel, M., Schlundt, C., Stapelberg, S., Sus, O., Eliasson, S., Willén, U., and Meirink, J. F., 2018: Comparing ERA-Interim clouds with satellite observations using a simplified satellite simulator, Atmos. Chem. Phys., 18, 17601–17614, https://doi.org/10.5194/acp-18-17601-2018

Trenberth, K., Y. Zhang, and M. Gehne, 2017: Intermittency in precipitation: Duration, frequency, intensity, and amounts using hourly data. J. Hydrometeor., 18, 1393–1412, https://doi.org/10.1175/JHM-D-16-0263.1.

Zhang, Y., Xie, S., Lin, W., Klein, S. A., Zelinka, M., Ma, P.-L., Rasch, P. J., Qian, Y., Tang, Q., & Ma, H.-Y. (2019). Evaluation of clouds in version 1 of the E3SM atmosphere model with satellite simulators. Journal of Advances in Modeling Earth Systems, 11, 1253–1268. https://doi.org/10.1029/2018MS001562