Department of Mechanical Engineering
Faculty of Engineering

NUS National University of Singapore

Air Drag on a Stratospheric Balloon in Tropical Regions

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ACADEMIC HIGH-ALTITUDE CONFERENCE

NUS National University of Singapore

Temasek Laboratories

Motivation

- **Advantages of scientific stratospheric balloons relative to other high amplitude observation systems, such as, aircraft, rocket and satellite systems**

  Carry heavy payloads

  Work for a long duration

  Simpler and cheaper in assembling, launching and operating
- **Challenges of scientific stratospheric balloon in practical operation**

  Station keeping and trajectory control due to severe weather condition together with lack of active control methods in balloon systems
- **Preliminary research for station keeping of a scientific stratospheric balloon in a tropical region**

  Using practical weather data obtained from local meteorological agency

  Estimating balloon size based on the operational altitude and payload

  Numerical simulation studies using CFD software – Star CCM+

Local weather data in the tropical region

- **Local Meteorological Service releases a freely rising meteorological balloon twice a day, usually at 00 Coordinated Universal Time (UTC) (morning at the local time zone) and at 12 UTC (evening at the local time zone), respectively, which carries the observation instruments.**
- **2225 sets of data have been obtained for period from January 2012 to April 2015 given weather conditions and air traffic control**

  1205 sets of data were measured at 00 UTC

  1020 sets of data were measured at 12 UTC

  1006 sets of data among 2225 sets are suitable for us to study the air drag acting on the stratospheric balloon in which the atmospheric properties and wind information are available for the altitude up to or above 33.5 km

  706 sets were obtained at 00 UTC

  300 sets were obtained at 12 UTC

Local weather data in the tropical region

Data collected	**Relation with our project**
Wind speed (v)	Air drag, Reynolds number
Wind direction	Air drag
Pressure (p)	Air drag, film cover of balloon
Air density (ρ)	Buoyancy, air drag, Reynolds number, size of the balloon
Air temperature (T)	Viscosity

$$F_B = \rho g V_{\text{balloon}}$$

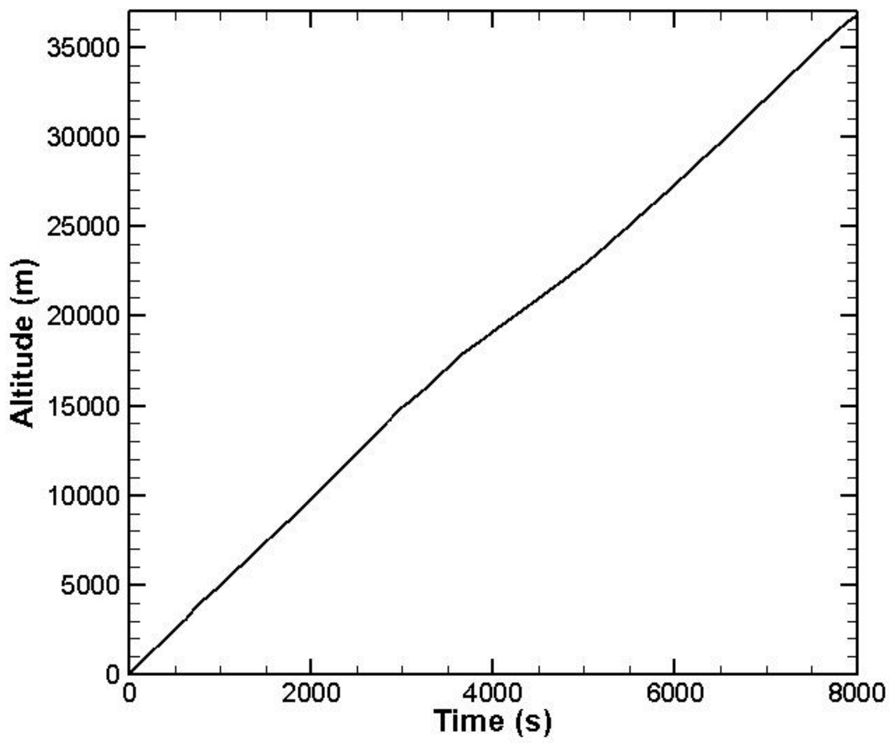
$$F_D = \frac{1}{2}\rho A(v)^2\, C_D(Re)$$

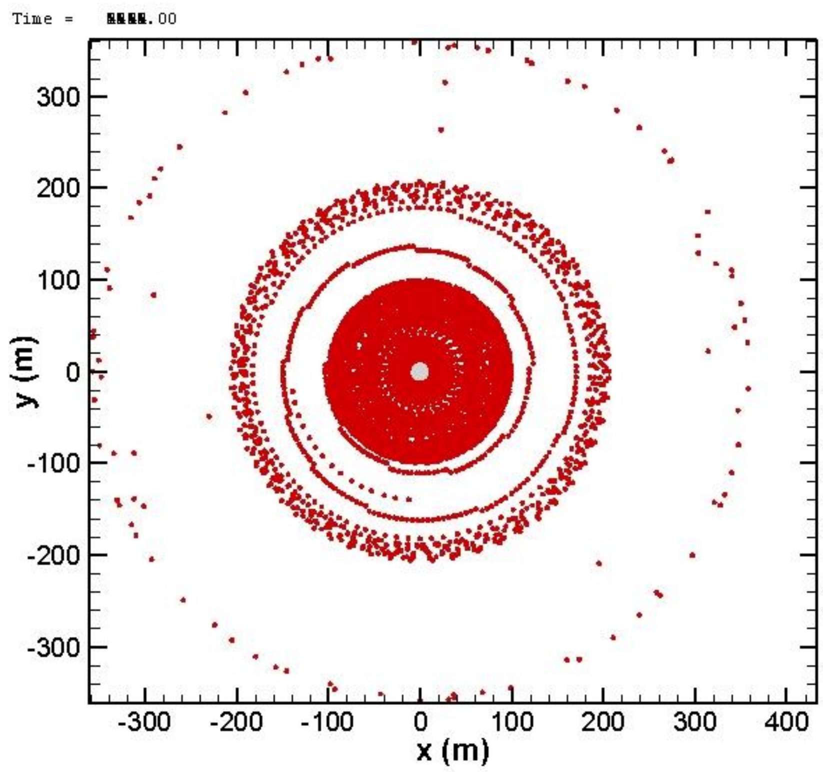
$$Re = \frac{\rho D v}{\mu}$$

$$\mu = 1.512 \times 10^{-6} \frac{(T + 273.15)^{1.5}}{T + 273.15 + 120.0}$$ (Sutherland's law)

Local weather data in the tropical region

A sample set of weather data obtained at 00 UTC on 02-Jan-2013





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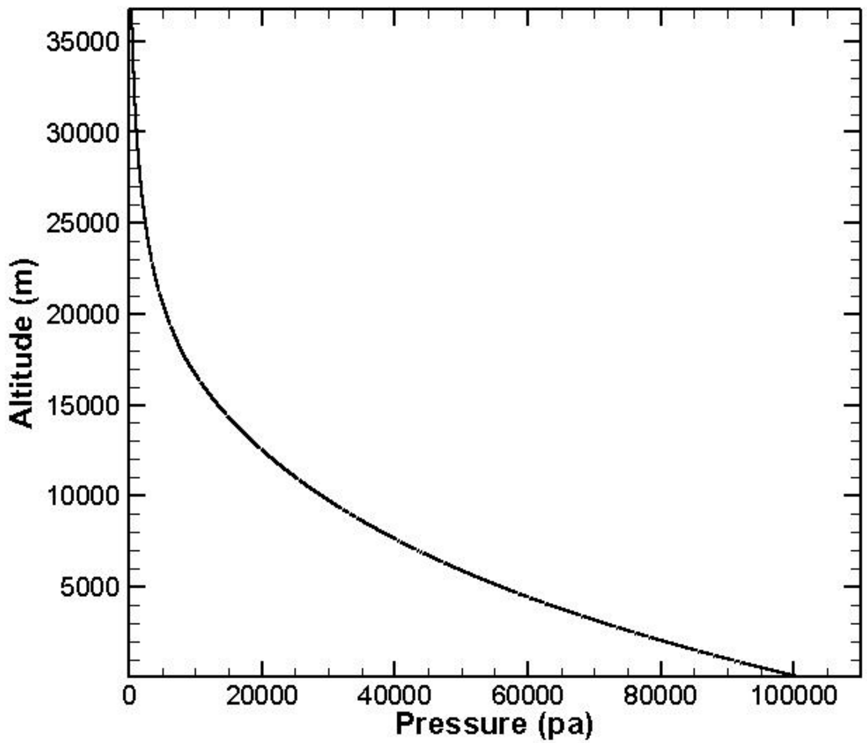

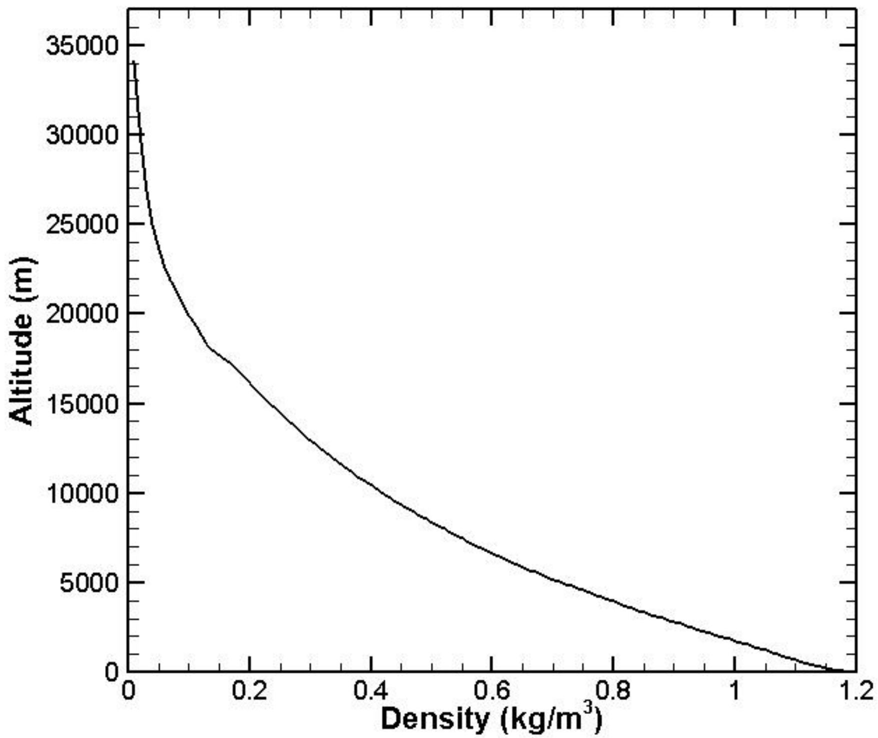

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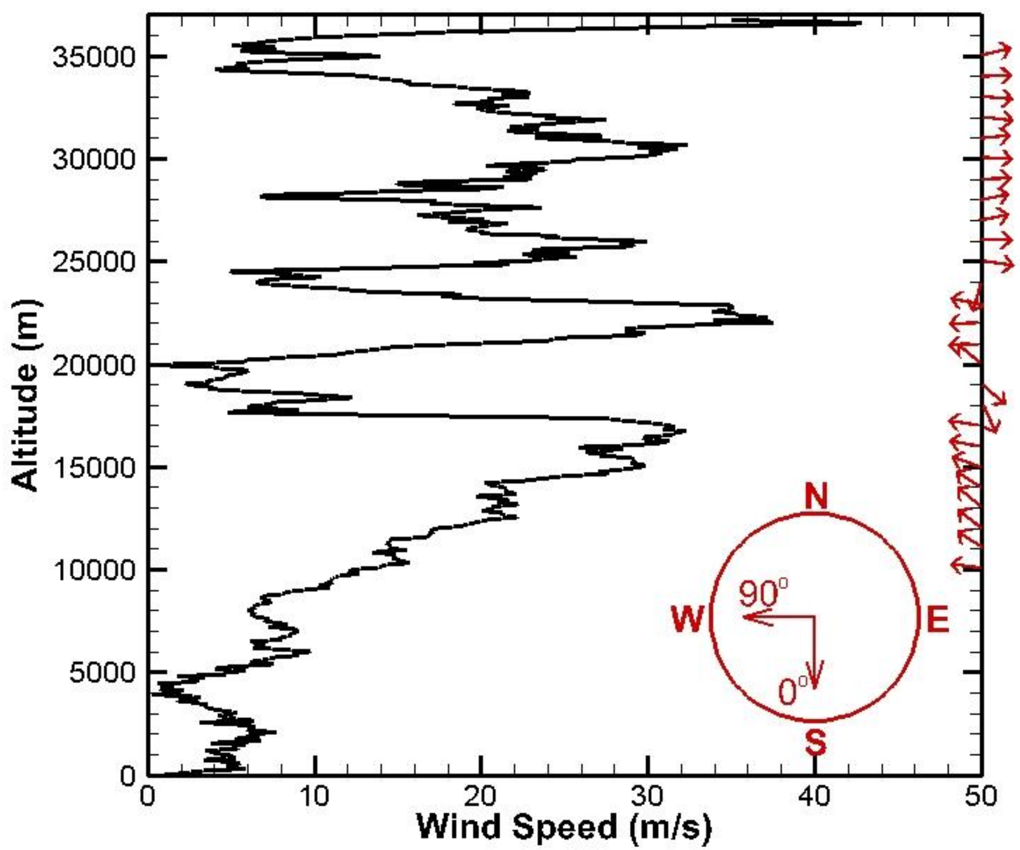
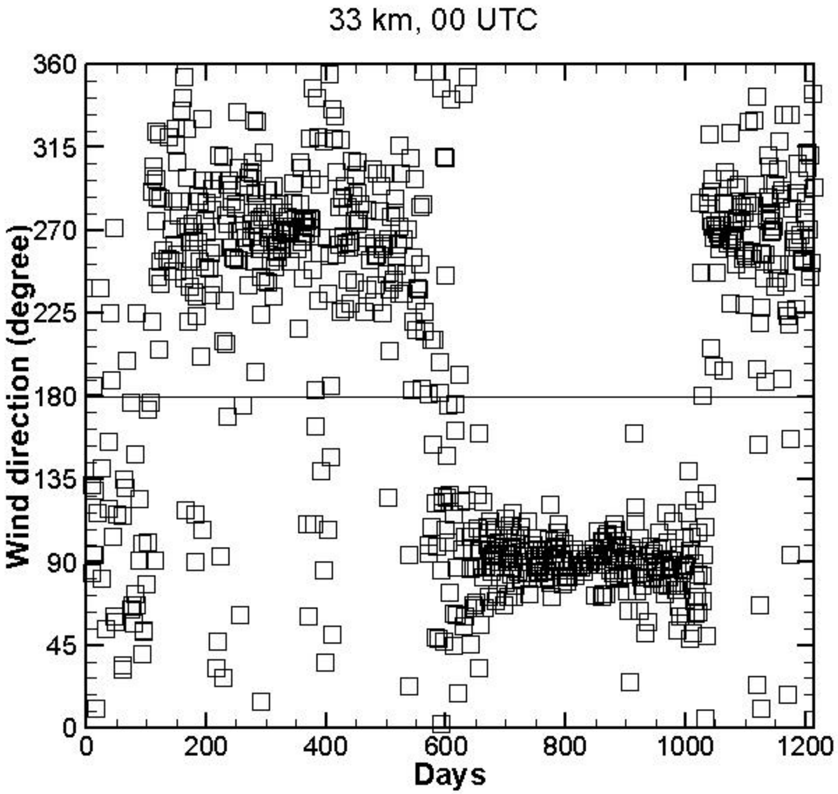
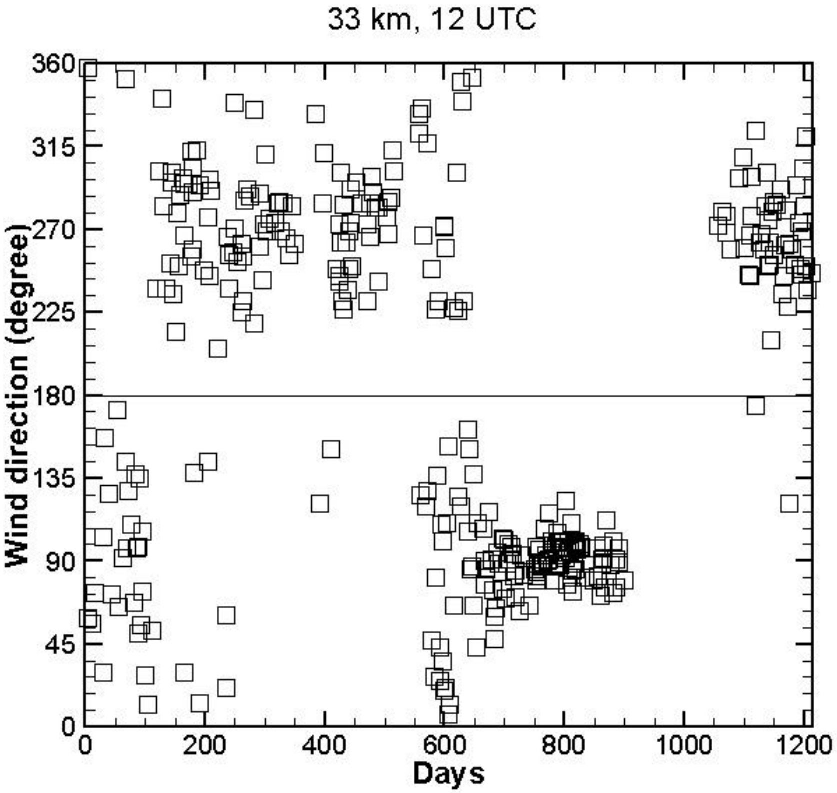


Local weather data in the tropical region

Wind condition at 33km – operational altitude of the balloon

Variation of wind direction at 33 km in our tropical region during the period from January 2012 to April 2015 – quasi-biennial oscillation (QBO) phenomenon





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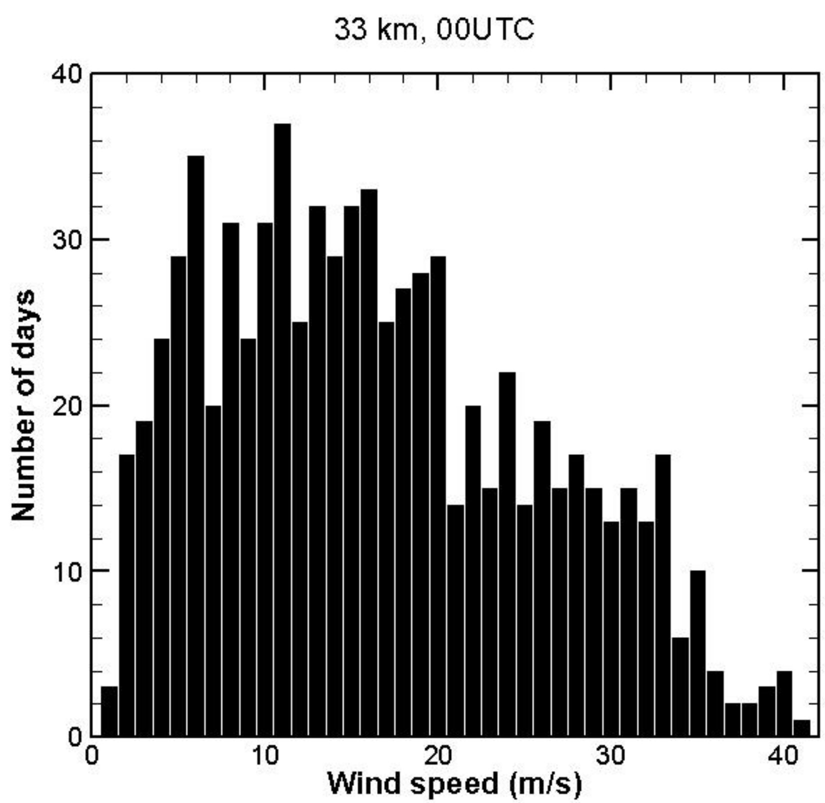
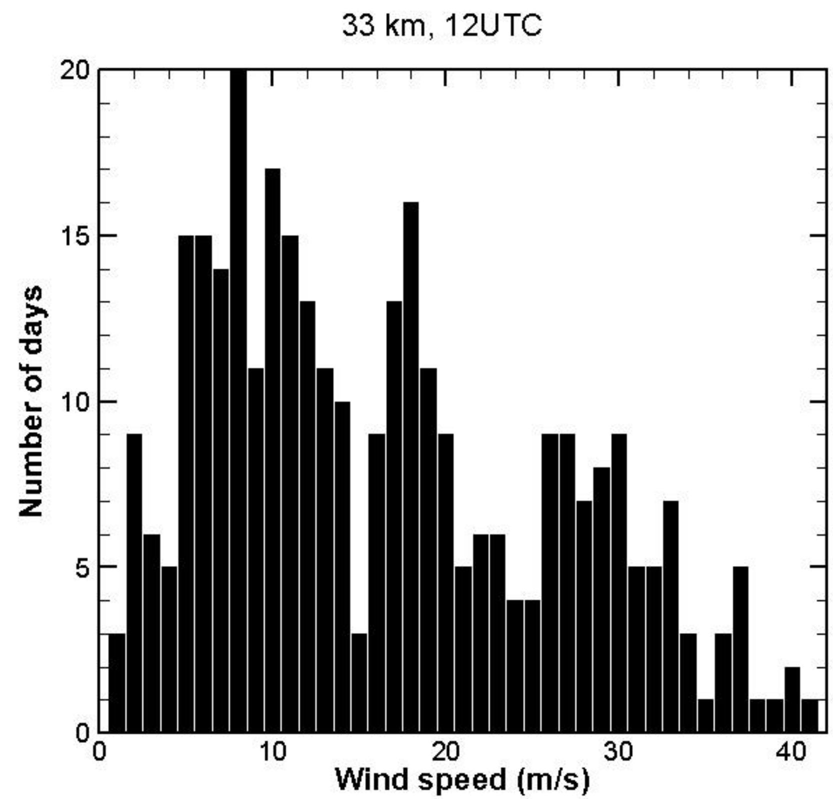
Local weather data in the tropical region

Wind condition at 33km – operational altitude of the balloon

Distribution of wind speed at 33 km in our tropical region during the period from January 2012 to April 2015





Local weather data in the tropical region

Weather condition at 33km – operational altitude of the balloon

Physical variable	Average value	Standard derivation
Wind speed	17 m/s	9 to10 m/s
Density	0.01 kg/m^3	6×10^{-4} kg/m^3
Pressure	765 pa	14 pa
Temperature	-39 ^oC	4 ^oC
Viscosity	1.53×10^{-5} pa·s	

Size of the stratospheric balloon

- **Operational altitude of balloon – 33km**
- **Super pressure balloon is chosen, not zero pressure balloon**

  Unaffected by sunset and stable in altitude
- **Target payload – 200 kg**
- **Total Mass of super pressure balloon system – 700 kg**

  Estimated based on reported super pressure balloon system through interpolation

Balloon name	Payload [kg]	Total mass of balloon system [kg]
PB60	100	430
Ours	200	700
586NT	295	900
PB300	490	1150
616NT	1815	3900
631NT	2270	4500

Size of the stratospheric balloon

Air density at 33km – ρ = 0.01 kg/m³

Shape of super pressure balloon – an oblate spheroid

$$\frac{x^2+y^2}{a^2}+\frac{z^2}{b^2}=0$$

a is equatorial radius of and b is polar radius

b/a = 0.6

Balance between weight of balloon system and buoyancy of balloon

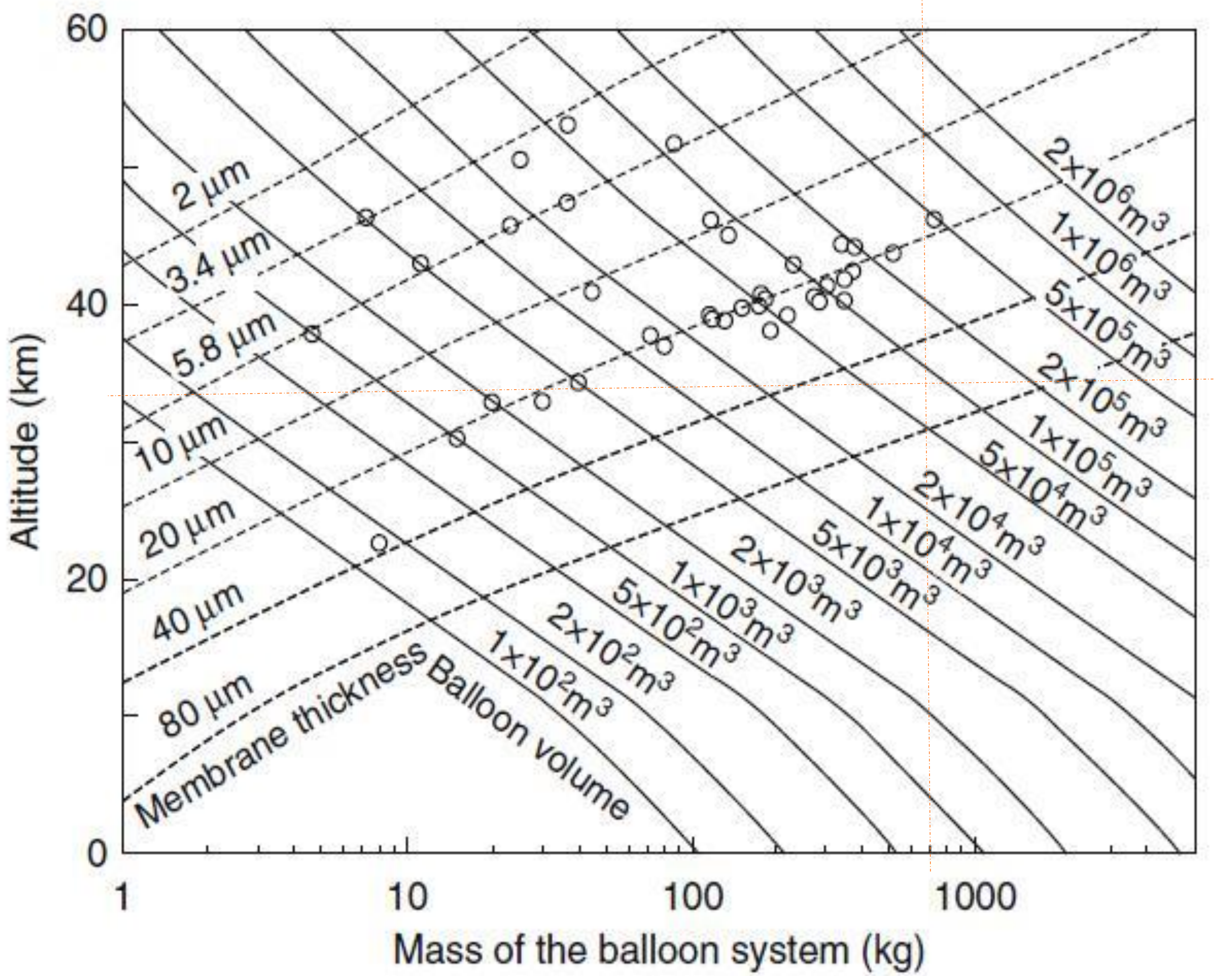
$$\rho\frac{3\pi a^2 b}{4}=700$$

a = 30 m and b = 18 m

$V_{Balloon}$ = 67858.4 m³

Reynolds number ($Re=\frac{\rho D v}{\mu}$) – 1×10^5 to 1.6×10^6 (D = 2a)

Size of the stratospheric balloon



$$V_{\text{balloon}} = 67{,}858.4\text{m}^3$$

Mass of the balloon system and attainable altitude*

* Yajima, N., Izutsu, N., Imamura, T., and Abe, T., "Scientific Ballooning-Technology and Applications of Exploration Balloons Floating in the Stratosphere and the Atmosphere of Other Planets", Springer, 2003

Air drag acting on the stratospheric balloon

- **Air drag acting has been calculated by the commercial Computational Fluid Dynamics (CFD) software, STAR CCM+**
- **Simulation geometry model of flow domain**

  Balloon center is located at the origin with its equator on *xy*-plane

  Rectangular wind tunnel with size as $40D\times16D\times16D$
- **Air is incompressible as March number is low**
- **Boundary conditions**

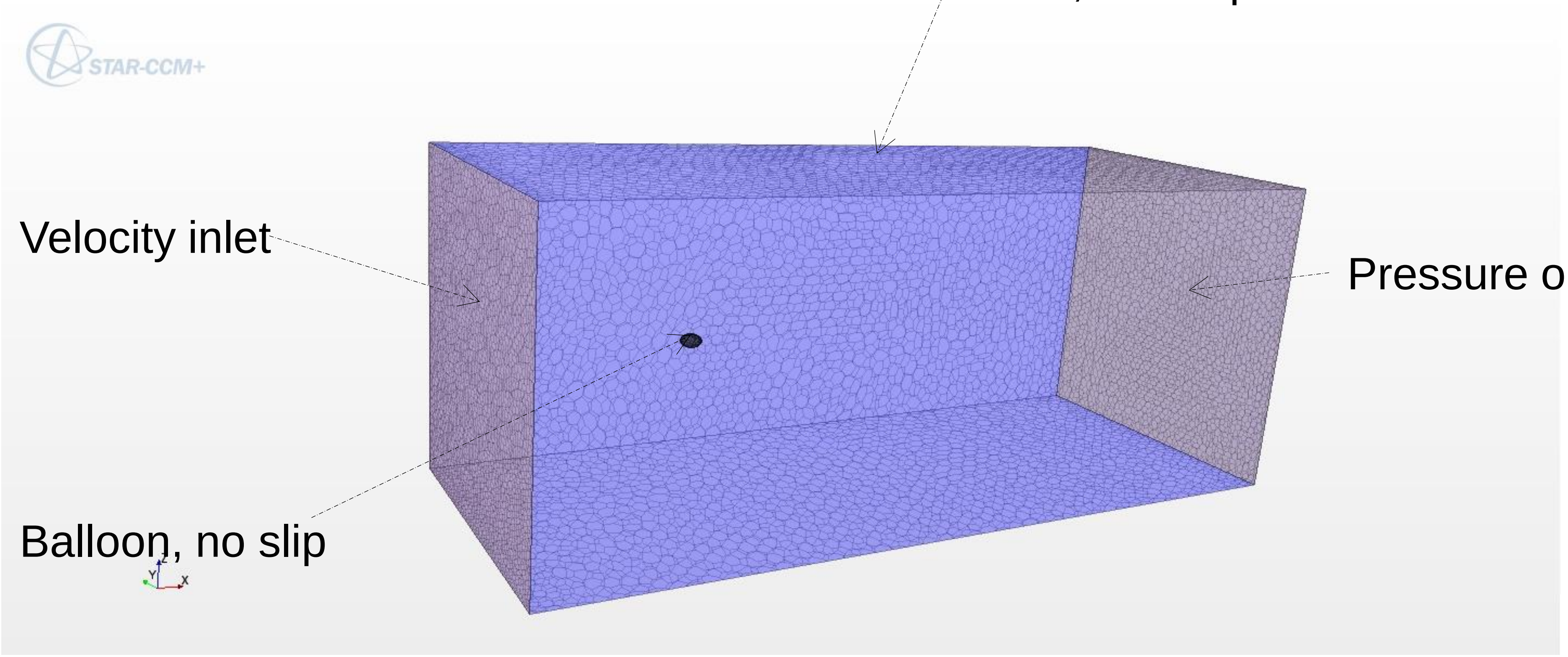
  Inlet condition – uniform wind speed normal to the boundary

  Outlet condition –pressure outlet

  balloon surface – no-slip

  Walls – free slip
- **k-ω SST flow model with high-Reynolds-number wall treatment has been chosen to deal with turbulent flow**

Air drag acting on the stratospheric balloon



Air drag acting on the stratospheric balloon

Velocity profile on *xy*-plane (a) and *xz*-plane (b) , and *Y*+ profile on balloon surface

$D = 60$ m

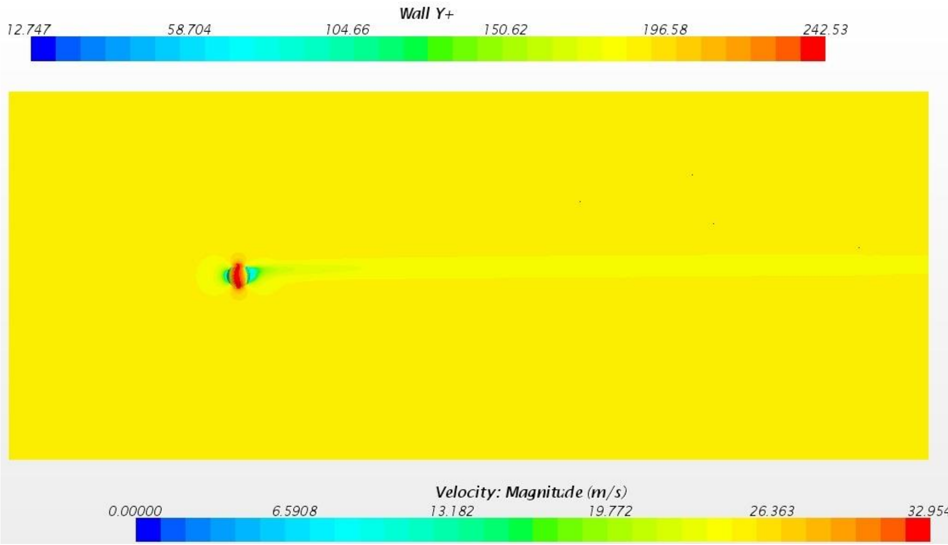
$\rho = 0.01\ kg/m^3$

$\mu = 1.5 \times 10^{-5}$ pa · s

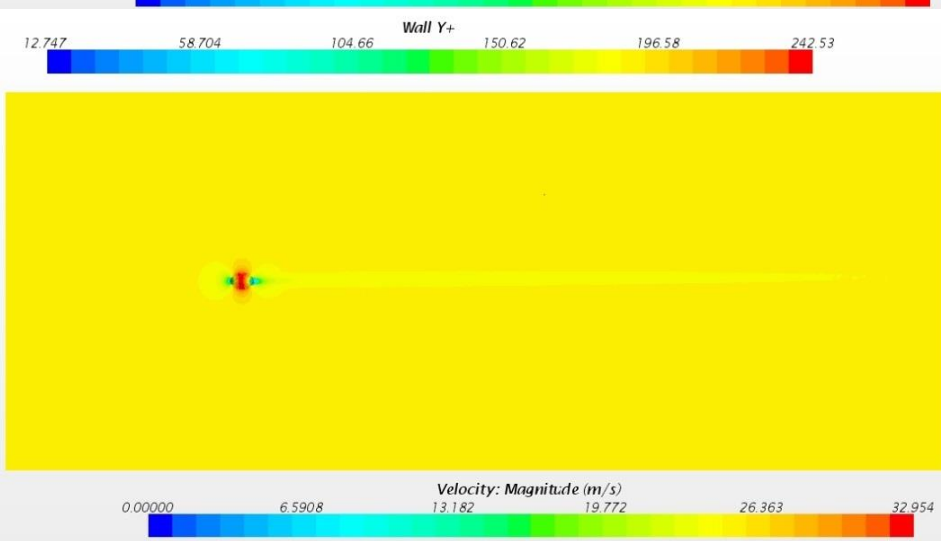
$v = 25$ m/s

$Re = 10^6$

1,402,736 polyhedral cells



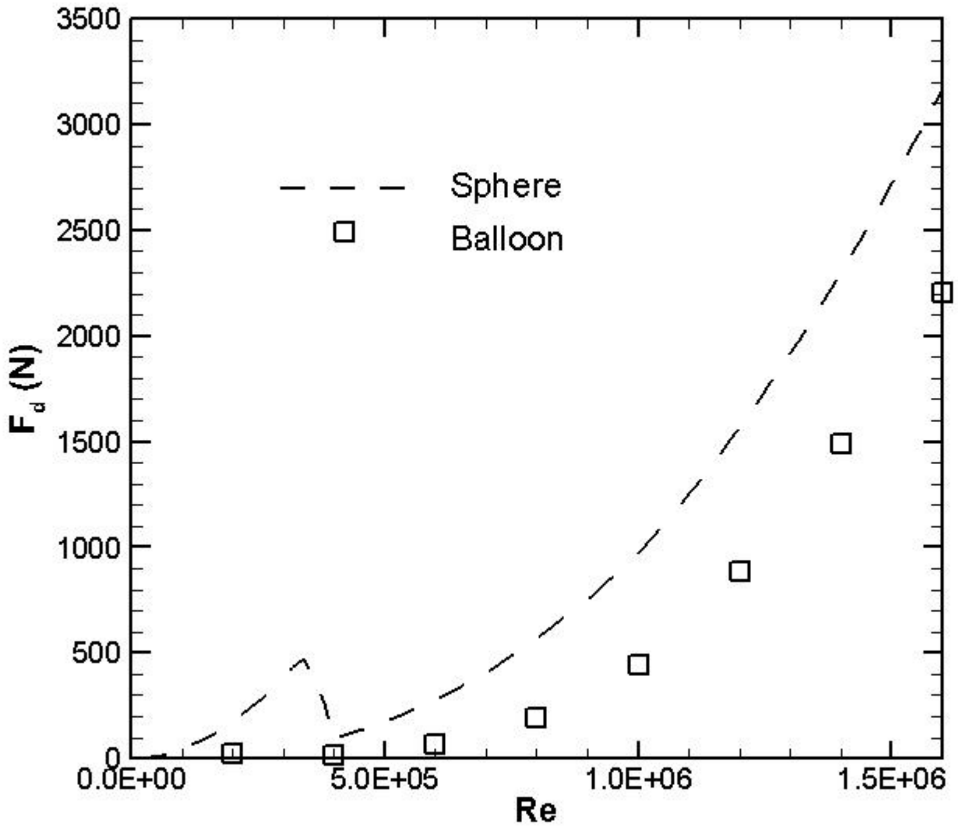
(a)



(b)

Air drag acting on stratospheric balloon

Drag force acting on the balloon under different Reynolds number



Dashed line – Clift, R., Grace, J. R., and Weber, M. E., Bubbles, Drops, and Particles, Academic Press, New York, 1978.

Summary

- Basic study and analysis have been carried out based on local weather data, and air flow conditions around the balloon at the operational altitude (33 km) have been obtained
- According to the target payload and flight altitude of the balloon, the total mass of the balloon system and the size of the balloon have been estimated
- Reynolds numbers have been obtained and numerical simulations by Star CCM+ have been carried out to calculate air drag acting on the balloon, which supplies us useful information for the station keeping of the balloon system.

Ongoing works

- Improve the accuracy of CFD simulations
- More elaborate statistical analysis on the weather data to represent the actual operational condition of the balloon system
- Size of the balloon will need to be be re-computed according to the additional mass of the control equipment.
- An iteration process will be developed to compute the desired balloon size and control ability to satisfy the station keeping goal of the whole balloon system

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Thank You

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