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The surface layer observed by a high-resolution sodar at DOME C, Antarctica

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Abstract

A one-year field experiment started on December 2011 at the French - Italian station of Concordia at Dome C, East Antarctic Plateau. The objective of the experiment was the study of the surface layer turbulent processes under stable/very stable stratifications, and the mechanisms leading to the formation of the warming events. A sodar was improved to achieve the vertical/temporal resolution needed to study these processes. The system, named surface layer sodar (SL-sodar), may operate both in high vertical resolution (low range) and low vertical resolution (high range) modes. SL-sodar observations were complemented with in situ turbulence and radiation measurements. A few preliminary results, concerning the standard summer diurnal cycle, a summer warming event, and unusually high frequency boundary layer atmospheric gravity waves are presented.

I. INTRODUCTION

At Dome C, light wind and clear sky favor weak turbulence and mixing, and strong temperature gradients near the surface. The boundary layer height varies depending on the relative contribution of the mechanical and thermal generation of turbulence.

Because of the extremely low temperature and humidity, and the high elevation, Dome C is a potentially ideal site for astronomical observations. For this reason, the optical turbulence over the Antarctic plateau has been a subject of studies by astronomers [Lawrence et al. 2004, Aristidi et al. 2005, Agabi et al. 2006, Lascaux et al. 2009].

At Dome C, Ricaud et al. [2012] made an experiment to monitor the vertical evolution of the planetary boundary layer (PBL) temperature and humidity in the transition from winter to summer, by using a microwave radiometer operating at 60 GHz and 183 GHz. Due to the instrument low vertical resolution, the fine structure of the thermal turbulence could not be evidenced.

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Ghenton et al. [2010] analyzed the Dome C 45 m meteo tower measurements (temperature, humidity, wind speed and direction measurements) for a three-week period in summer 2008. The main task of their work was to compare these measurements with the 6-hourly European Center for Medium-Range Forecasts (ECMWF) analyses and the daily radiosoundings.

Pietroni et al. [2012], using the temperature profiles measured with a passive microwave radiometer [Kadygrov and Pick 1998, Argentini et al. 2004], characterized the behavior of the surface-based temperature inversions over the course of a year. They found that during the winter and the summer "nights" strong temperature inversions allow for a mixing depth of a few tens of meters with a quiescent layer above, decoupled from the surface layer. During the summer, despite the low surface temperatures, weak convection generates the development of a mixed layer characterized by a maximum depth of 200-400 m [Argentini et al. 2005]. The diurnal behavior of this mixed layer, monitored with a sodar, was described by Mastrantonio et al. [1999], Argentini et al. [2005], and King et al. [2006]. The sodar measurements, because of the membrane ringing just after the tone burst emission, allowed for a first echo recording starting at 20-30 m, depending on the membrane ringing time. Because of this limitation, those measurements did not allow to study the surface turbulent layer under stable conditions, neither in summer nor in winter.

An advanced high-resolution sodar named surface-layer sodar (hereafter SL-sodar), allowing for the lowest observation height at ≈ 2 m and a vertical resolution of ≈ 2 m, was developed by the ISAC-CNR [Argentini et al. 2011]. The SL-sodar was deployed at Concordia station after a preliminary test period at the ISAC-CNR research centre of Rome [Argentini et al. 2011]. In this paper, a few preliminary results from the summer season are shown.

II. SITE AND INSTRUMENTATION

Concordia is a permanent station located at Dome C (75.1° S, 123.3° E, 3233 m a.s.l.), on the East Antarctic plateau, at approximately 1000 km from the nearest coast. One-year in situ turbulence and radiation measurements, as well as SL-sodar observations, were carried out at Concordia station from December 2011 up to December 2012.

Table 1. *SL-sodar setting parameters.*

	Mode 1	Mode 2
Carrier Frequency	2000 Hz	4850 Hz
Pulse duration	50 ms	10 ms
Repetition rate	3 s	2 s
Maximum range	430 m	280 m
Lowest height	8 m	2 m
Vertical resolution	8 m	2 m

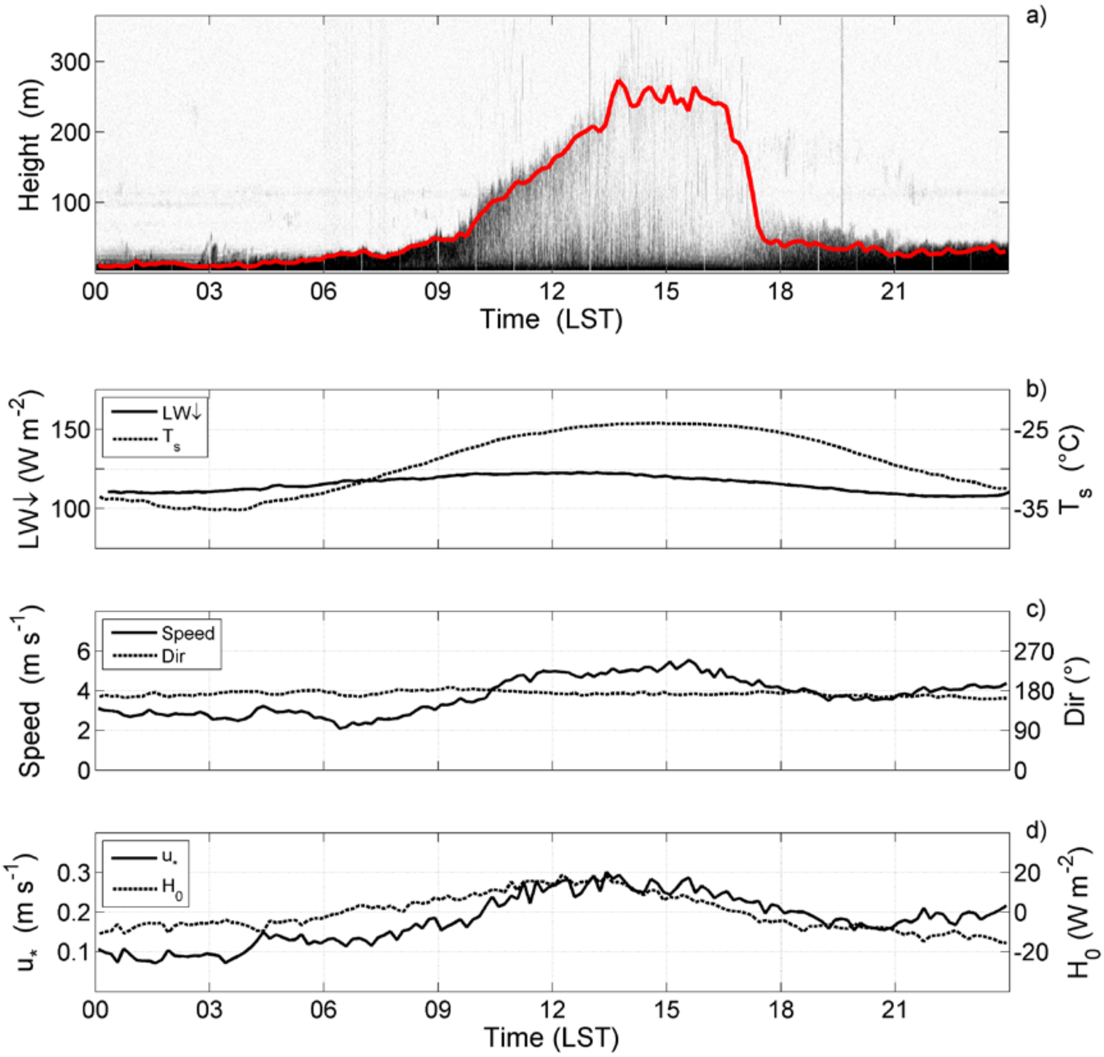

Figure 1. Sodargram for 28 December 2011 with mixing height estimate (straight line) (a), downwelling longwave radiation ($LW\downarrow$) and sonic temperature (T_s) (b), wind speed and direction (c), momentum (u_*) and heat fluxes (H_0) (d).

The SL-sodar [Argentini et al. 2011] is an improved version of the sodar described by Mastrantonio et al. [1999] and Argentini and Pietroni [2010], with the possibility of zooming in the atmospheric surface-layer thermal turbulent structure. The SL-sodar consists of 3 horn-type antennas, placed symmetrically around a 1.2 m diameter parabolic receiving antenna, emitting simultaneously acoustic pulses at the same frequency. The receiving antenna is noise-protected by a shielding structure of 1.5 m L x 1.5 m W x 2.0 m H in size. The transmitting and receiving circuits are kept separated to minimize the "cross-talk" between channels. The carrier frequency, the pulse duration, and the pulse repetition rate

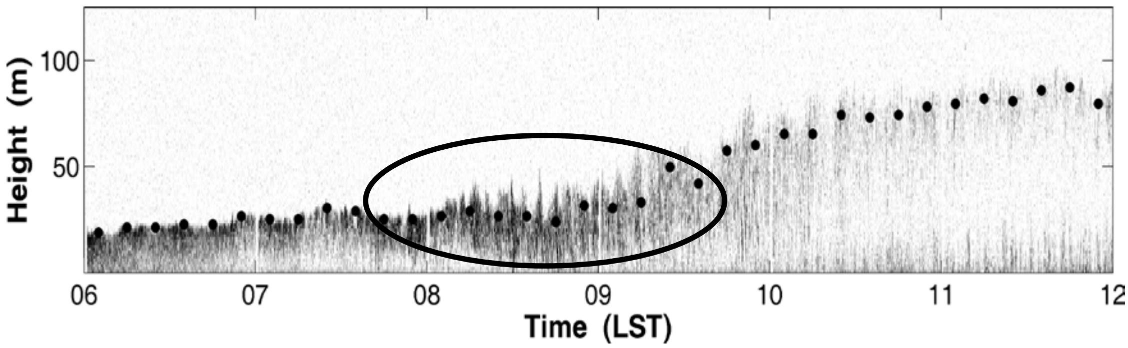

Figure 2. Sodargram for 5 February 2012, the full dots represent the mixing height estimate. High amplitude waves are observed between 0800–0930 LST.

can change according to the two modes listed in Table 1. "Mode 1" allows to monitor the convective mixed layer, while "Mode 2", with higher vertical resolution, is used to investigate the near-surface stable layer.

Measurements of turbulence were made with a Metek USA-1, a three-axes sonic thermo-anemometer (sampling frequency of 10 Hz) installed on a 3.5 m mast. The heat and momentum fluxes are estimated using the eddy covariance method [Lee et al. 2004]. The longwave and shortwave radiation components (up and down) are measured using Kipp & Zonen CNR1 pyrgeometers and pyranometers, installed at 1.5 m above the snow surface.

In this paper, unless told otherwise, the local standard time (LST) is used.

III. Results

Summertime ABL diurnal behavior

The facsimile recording of the vertical/temporal variation of the acoustic backscattering (sodargram) "depicts" the thermal structure of the atmosphere. The scattering elements producing the change of echo intensity are the small-scale temperature inhomogeneities due to thermal turbulence. Temperature fluctuations are usually associated with the convective plumes originating from the surface, or with potential temperature gradients and wind shear usually occurring in the inversion layers. During the summer, the boundary layer at Dome C can reach a depth of 200-400 m. Therefore, the "Mode 1" setting (see Table 1) was used to catch the whole vertical evolution during the daily cycle.

Figure 1a shows the typical boundary layer sodargram during a clear summer day (28 December 2011), with the superimposed estimate of the mixing height (MH, straight line). A stable boundary layer occurs between 0000 and 0900 LST; from 0900 to 1630 LST the MH increases because of the convective activity, and then it drops to 50 m because of the surface radiative cooling.

The *MH* was estimated using a method originally proposed by Beyrich and Weill [1993], which uses the backscattered range corrected signal (RCS). Under stable nocturnal stratification, the *MH* was determined either from the minimum of the first derivative or from the maximum curvature of the RCS, depending on the stage of the planetary boundary layer evolution, and on the shape of the sodar profile. Under convective conditions, the *MH* was es-

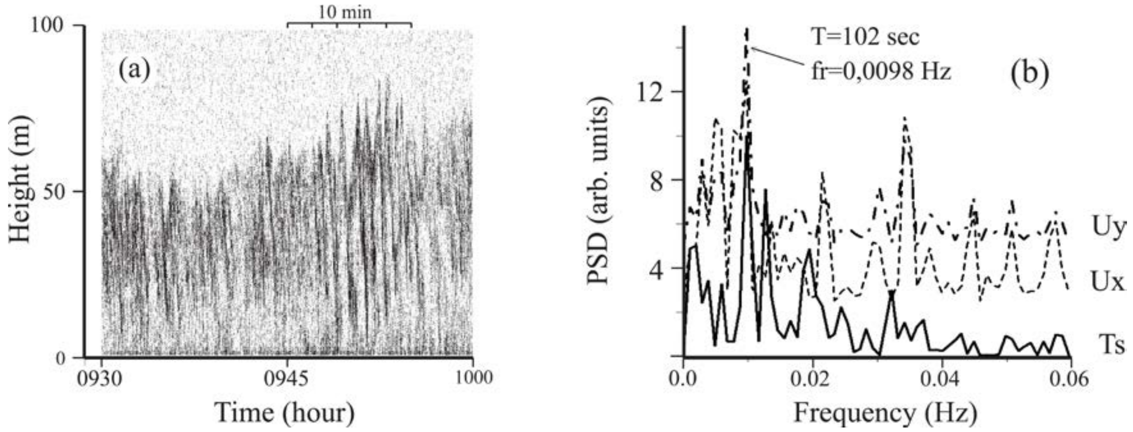

Figure 3. Sodar echogram for February 5, 2012 (0930 to 1000 LST) (a); Power Spectral Density (PSD) of the horizontal wind components (Ux, Uy) and sonic temperature (T_s) at 39 m (b) for the indicated 10-minutes interval (the scale is given in arbitrary units).

timated as the height at which an elevated secondary maximum occurs (i.e. the height of the turbulent zone characterizing the top of the mixing layer). For the same day, Figure 1b shows the downward longwave radiation $LW\downarrow$ and the sonic temperature T_s, Figure 1c the wind speed and direction. The heat turbulent flux H_0 and friction velocity u_* are plotted in Figure 1d. $LW\downarrow$ ranges between 100 and 150 W m^{-2}, while T_s reaches its minimum (-35°C) at 0300 LST, and its maximum (-25°C) between 1200 and 1500 LST. The direction indicates a wind from the continent persisting the whole day. The maximum wind speed (6 ms^{-1}) occurs because of the momentum transfer from the free atmosphere to the surface layer, as a consequence of the turbulent mixing (confirmed by the positive and increasing values for H_0 and u_*) during convective hours.

Gravity waves in the ABL

Between 2 and 5 February 2012, waves with periods of a few minutes are observed under stable stratification for more than 35% of the time. The resolution achieved by the SL-sodar with the "Mode2" setting (Table 1) allowed to visualize the fine structure of these wave patterns. At the transition time from the stable to the unstable boundary layer (between 0800 and 1000 LST) the capping inversion layer oscillates with an amplitude that reaches 70 m (Figure 2). The apparent period of these oscillating structures was estimated through the spectral analysis of the sonic temperature and the wind components of the sonic anemometers, installed at 3 different levels (7.0, 22.8, and 37.5 m) on a 45-m meteorological tower [Genthon et al. 2009] located at ≈ 1 km from the SL-sodar.

In Figures 3a and 3b, the sodargram and the power spectral density of the temperature and horizontal wind components measured at 37.5 m (between 0945 and 1000 LST on 5 February) are shown. A peak occurs simultaneously in the temperature and wind components Power Spectral Density (PSD) at 0.0098 Hz, corresponding to a period of 102 s. The analysis of the sonic anemometers measurements at the three levels, limited to the time interval 0800-

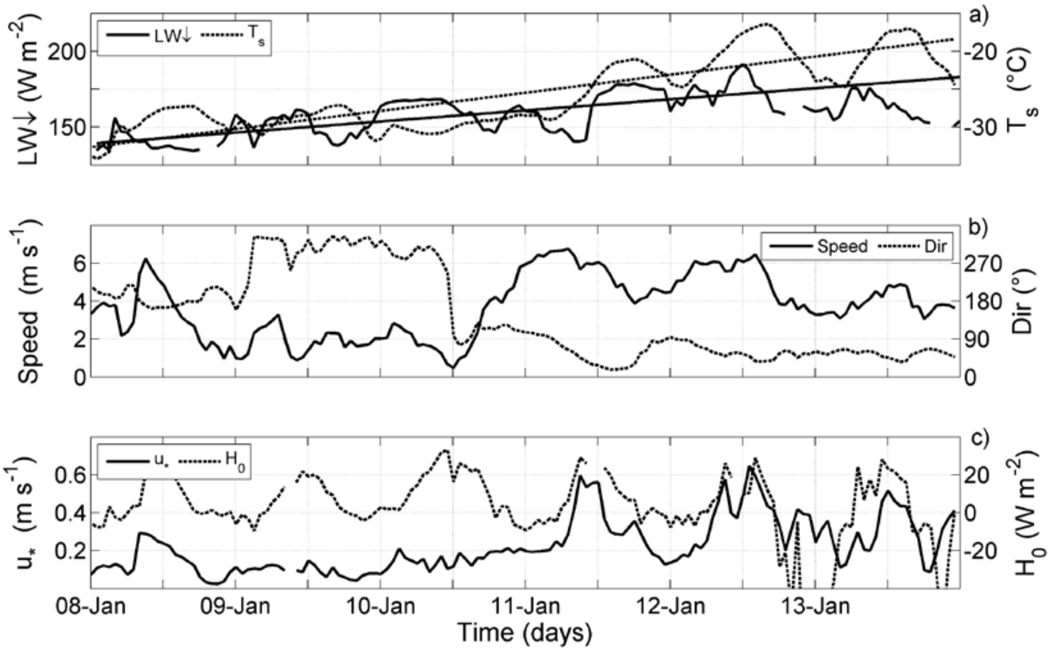

Figure 4. Downwelling longwave radiation ($LW \downarrow$) and sonic temperature (T_s) with superimposed the linear trends (a), the wind speed and direction (b), the heat (H_0) and momentum (u_*) fluxes (c) for days 8-14 January 2012.

0930 LST, gives an apparent period ranging between 90 and 120 s. The apparent period remains approximately the same also when the inversion strength and height change. This behavior indicates that the origin of these waves might be a disturbance (probably the wind shear) originating between the inversion layer and the free atmosphere. A similar behavior was observed during other days.

A summer warming event

Warming events of particular intensity were regularly observed at Dome C during the winter [Argentini et al. 2001, Petenko et al. 2007, Ghenton et al. 2013]. During these events the surface temperature sometimes has a sharp increase of 20-40 °C [Argentini et al. 2001], reaching then the typical summer values.

Studies carried out at South Pole [Carroll 1982, Stone et al. 1990, Stone and Kahl 1991, Stone 1993] have evidenced that these warming events are generally observed in presence of clouds. Neff [1999], analyzing the particles trajectories across Antarctica, found that these warming processes are mostly due to warm and moist air intrusion and to the condensation of nuclei originating from the Weddell Sea, producing a wide variety of cloud types. Carroll [1982] suggested two possible mechanisms of this phenomenon: the advection of warm air, and/or the vertical mixing of air from different layers. Schwerdtfeger and Weller [1977] related the surface warming to the variation of long-wave radiation emitted by the clouds associated to the moist air in the upper part of the atmosphere.

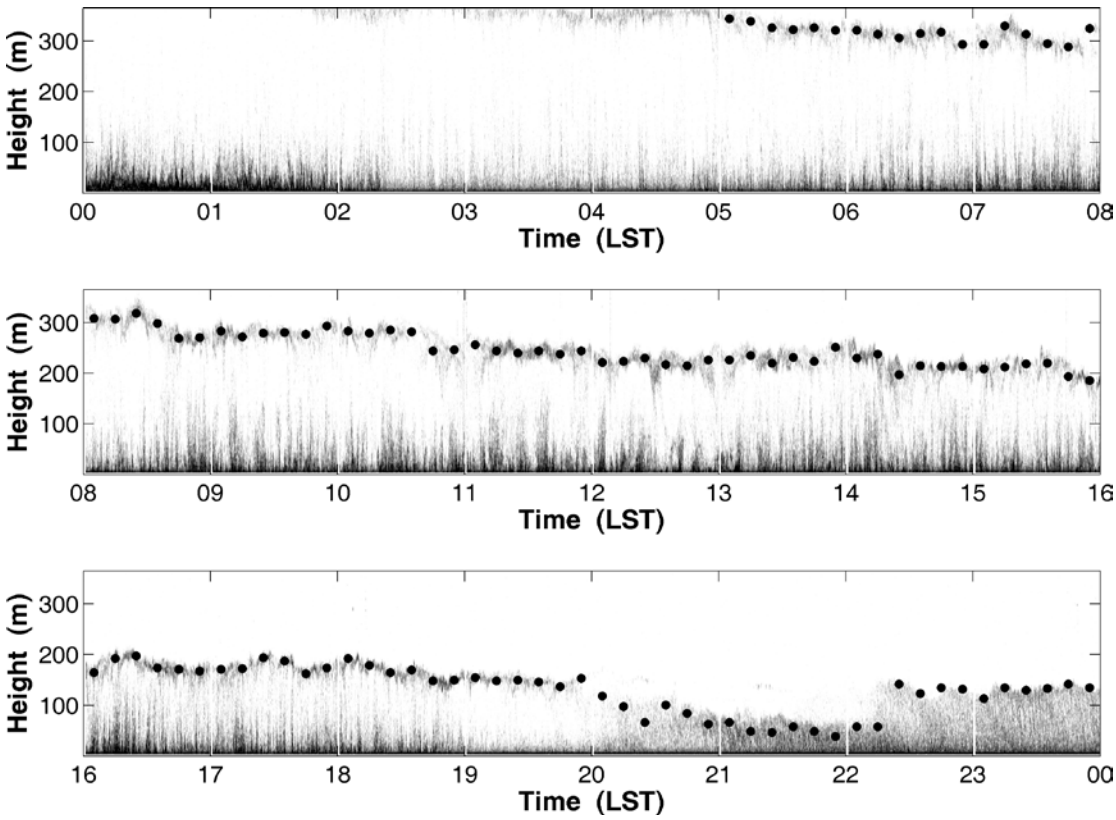

Figure 5. Sodargram for 10 January 2012 with the mixing height estimate (dots).

The measurements collected during a summer warming event observed between 8 and 17 January 2012 have been analyzed. Figure 4 shows the time series of the downwelling longwave radiation $LW\downarrow$ and the sonic temperature T_s (Figure 4a), the wind speed and direction (Figure 4b), the heat flux H_0 and the friction velocity u_* (Figure 4c) during the selected period.

Starting from 9 January 2012, wet and warm coastal air masses are advected from the coast toward the Dome C area. Until the end of January 10 the $LW\downarrow$ and T_s (Figure 4a) do not show the typical diurnal behavior observed during the previous and the following days. An increasing trend is evident starting on 9 January. The wind direction changes, rotating from S to NE-NW, and the wind speed is low up to 1200 LST of 10 January. Due to the presence of the clouds, the downwelling long wave radiation and the surface temperature increase, initiating the convective activity shown in the sodargram of Figure 5. The vertical mixing reduces the decoupling between the boundary layer and the free atmosphere. As a consequence, the wind speed increases: at 2400 LST of 11 January the wind speed is ≈ 6 m s^{-1} (Figure 4b). H_0 and u_* (Figure 4c) confirm this anomalous behavior. At the end of 11 January

the behavior is again the typical summer one, with a peak in the wind speed at 1200 LST.
The sodargram for 10 January, with the mixing height estimate superimposed (dots), confirms this hypothesis. A clear and intense convective activity is observed during the whole day even in the nighttime between 9 and 10 January.

IV. Summary

The main results of this observational study can be summarized as follows:
• during the summer, under steady weather conditions, the atmospheric boundary layer thermal structure is characterized by the alternation of a stable stratified layer with a convective boundary layer, following a behavior similar to that observed at mid-latitudes.
• A regular wave activity was observed within the inversion layer. The time period of these waves ranges between 90 s and 120 s, and their origin can be attributed to the wind shear across the inversion layer.
• The summer warming events take origin from the presence of clouds advected from the coast toward the Dome C area. Clouds modify the surface radiation budget by increasing the downward longwave radiation, which in turn produces an increase of surface temperature, leading to convection. Due to the decrease of the temperature inversion strength, the vertical mixing, combined with the wind shear, allows the transport of warm air from the upper parts of the atmosphere towards the surface, further contributing to the surface warming.

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