Description of the ARM Large-Scale Forcing Data from the Constrained Variational Analysis (VARANAL) – Version 2

Shuaiqi Tang, Cheng Tao and Shaocheng Xie
Lawrence Livermore National Laboratory

Minghua Zhang
Stony Brook University

May 2019

Contents

1. Introduction

1.1 General Description

This technical report represents an update of the previous technical report written by *Zhang et al.* (2001a) (available at http://www.arm.gov/publications/tech_reports/arm-tr-005.pdf), which described the Atmospheric Radiation Measurement (ARM) constrained variational analysis (VARANAL) that is used to develop the large-scale forcing data for driving Single-Column Models (SCMs), Cloud-Resolving Models (CRMs) and Large-Eddy Simulation Models (LESs). The VARANAL algorithm was originally developed by *Zhang and Lin* (1997) at the Stony Brook University and was migrated to the Lawrence Livermore National Laboratory (LLNL) as the ARM operational objective analysis system in May 1999. Since then, the algorithm has been evolved with time along with the availability of new observations and techniques to meet various modeling needs. Major updates include:

1) the method used to develop multi-year continuous forcing data (*Xie et al.*, 2004);

2) the incorporation of ECOR turbulent fluxes into the analysis (*Tang et al.*, 2019);

3) improving the workflow (e.g., implementing part of code into ADI) to increase efficiency.

We also extend the VARANAL algorithm into a three-dimensional constrained variational analysis (3DCVA) and designed an ensemble framework to address the forcing uncertainty. The 3D large-scale forcing data are released as another datastream varanal3d. Please refer to the varanal3d technical report for more information.

1.2 Data information

The current large-scale forcing data sets archived by ARM includes two major products:

1) the multi-year long-term continuous forcing data at SGP;

2) radiosonde- or NWP-based forcing data for short-term field campaigns (or IOPs) at different ARM fixed or mobile sites.

The details and workflow of the multi-year long-term continuous forcing data at SGP are shown in Section 4.1. A full list of IOP forcing data and more details are shown in Section 4.2.

All the forcing data share the same DOI number: doi:10.5439/1273323. They are available to the community from the ARM Archive (http://www.archive.arm.gov/discovery/). To cite the data, please refer to *Zhang and Lin* (1997) and *Zhang et al.* (2001b) for the VARANAL algorithm, *Xie et al.* (2004) for the NWP-based forcing data and *Tang et al.* (2019) for the version 2 of continuous forcing data. For major field campaigns, please also refer to the references shown in Section 4.2.

2. Contact

Shuaiqi Tang

Atmospheric, Earth, and Energy Division (L-103)

Lawrence Livermore National Laboratory

Livermore, CA 94550

tang32@llnl.gov

Cheng Tao

Atmospheric, Earth, and Energy Division (L-103)

Lawrence Livermore National Laboratory

Livermore, CA 94550

tao4@llnl.gov

Shaocheng Xie

Atmospheric, Earth, and Energy Division (L-103)

Lawrence Livermore National Laboratory

Livermore, CA 94550

xie2@llnl.gov

3. Algorithm

The constrained variational analysis method was developed by *Zhang and Lin* (1997) to derive large-scale vertical velocity and advective tendencies from sounding measurements of winds, temperature, and water vapor mixing ratio over a network of a small number of stations. Here, we will briefly review the algorithm of the constrained variational analysis that are introduced in *Zhang and Lin* (1997) and *Zhang et al.* (2001b).

3.1 Theoretical Formulation

From *Zhang and Lin* (1997), the vertical integration of the atmospheric mass, moisture, dry static energy and momentum equations in an atmospheric column (Figure 1) are:

$$\left\langle \nabla \cdot \vec{V} \right\rangle = -\frac{1}{g}\frac{dP_s}{dt} \tag{1}$$

$$\frac{\partial \langle q \rangle}{\partial t} + \left\langle \nabla \cdot \vec{V} q \right\rangle = E_s - P_{rec} - \frac{\partial \langle q_l \rangle}{\partial t} + \frac{\omega_s q_s}{g} \tag{2}$$

$$\frac{\partial \langle s \rangle}{\partial t} + \left\langle \nabla \cdot \vec{V} s \right\rangle = R_{TOA} - R_{SRF} + L_v P_{rec} + SH + L_v \frac{\partial \langle q_l \rangle}{\partial t} + \frac{\omega_s s_s}{g} \tag{3}$$

$$\frac{\partial \langle \vec{V} \rangle}{\partial t} + \left\langle \nabla \cdot \vec{V}\vec{V} \right\rangle + f\vec{k} \times \left\langle \vec{V} \right\rangle + \nabla \langle \phi \rangle = \vec{\tau_s} \tag{4}$$

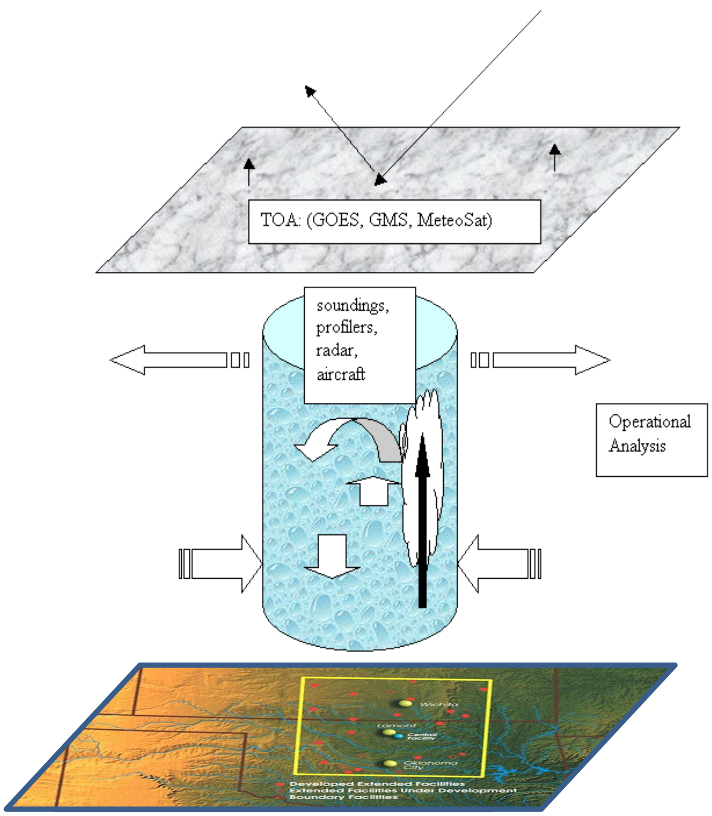

Figure 1: Schematic figure of an atmospheric column in VARANAL.

where the bracket <*> represents vertical integration from the surface to the top of atmosphere (TOA); $\vec{V}$ is wind vector in isobaric surface; g is gravitational constant; P_s is surface pressure, q is water vapor mixing ratio; $s = C_p T + gz$ is the dry static energy; E_s is surface evaporation; P_{rec}

is surface precipitation; L_v is the latent heat of vaporization; q_l is cloud liquid water content; R_{TOA} and R_{SRF} are net downward radiation at TOA and surface; ω_s, q_s and s_s are the pressure vertical velocity, water vapor mixing ratio and dry static energy at the surface, respectively; *SH* is surface sensible heat flux; *f* is the Coriolis parameter; $\vec{k}$ is the unit vector in vertical direction; ϕ is the geopotential, and $\vec{\tau_s}$ is the surface wind stress. Ice processes and advection of cloud hydrometeors are neglected. The terms related with the ω_s are from the vertical integration of the three-dimensional divergence terms. Physically, they represent the change of column moisture and column energy purely due to the change of column mass.

In the constrained variational analysis method, the atmospheric variables ($\vec{V}$, *s*, *q*) are forced to satisfy equations (1)-(4) with minimum adjustments to the first guess (either from radiosonde or from NWP analysis). The final analysis product is derived by minimizing the cost function:

$$I(t)=\iiint_{p,x,y}\left[\alpha_u(u-u_o)^2+\alpha_v(v-v_o)^2+\alpha_q(q-q_o)^2+\alpha_s(s-s_o)^2\right]dxdydp \quad (5)$$

with Equations (1)-(4) as strong constraints, where *u, v, q, s* denote the final analysis data, u_o, v_o q_o, s_o denote the first guess, and α is the weighting function related to the error estimates in the initial first guess.

3.2 Numerical implementation

For N stations in the sounding network, each with K layers, we use x_{ik} to denote a state variable at station *i* and layer *k*, and use column vector X to denote variables *u, v, q, s* at all grids:

$$X^T=[x_{11},x_{12},...,x_{1k},x_{21},...,x_{ik},...,x_{NK}]$$

(6)

Where superscript T means transpose of vector. The cost function (5) can be written as

$$I(t)=(u-u_o)^T W_u^{-1}(u-u_o)+(v-v_o)^T W_v^{-1}(v-v_o)+(q-q_o)^T W_q^{-1}(q-q_o)+(s-s_o)^T W_s^{-1}(s-s_o)$$

(7)

Where W is the weighting matrix related with the error covariance of a variable. The strong constraints of equations (1)-(4) can be written in the discrete form:

$$A_{mass}=\left\langle\left(\nabla\cdot\vec{V}\right)_m\right\rangle+\frac{1}{g}\left(\frac{dP_s}{dt}\right)_m=0 \quad (8)$$

$$A_{water}=\left\langle\left(\frac{\partial q}{\partial t}\right)_m\right\rangle+\left\langle\left(\nabla\cdot\vec{V}q\right)_m\right\rangle-E_s+P_{rec}+\left\langle\left(\frac{\partial q_l}{\partial t}\right)_m\right\rangle=0 \tag{9}$$

$$A_{heat}=\left\langle\left(\frac{\partial s}{\partial t}\right)_m\right\rangle+\left\langle\left(\nabla\cdot\vec{V}s\right)_m\right\rangle-R_{TOA}+R_{SRF}-L_vP_{rec}-SH-L_v\left\langle\left(\frac{\partial q_l}{\partial t}\right)_m\right\rangle=0 \tag{10}$$

$$A_{momentum}=\left\langle\left(\frac{\partial \vec{V}}{\partial t}\right)_m\right\rangle+\left\langle\left(\nabla\cdot\vec{V}\vec{V}\right)_m\right\rangle+f\vec{k}\times\left\langle\left(\vec{V}\right)_m\right\rangle+\left\langle\left(\nabla\phi\right)_m\right\rangle-\vec{\tau_s}=0 \tag{11}$$

Where

$$\left\langle X\right\rangle=\frac{1}{g}\sum_{k=1}^{k=K}\left(X_k\Delta P_k\right) \tag{12}$$

and subscript m represents average of the area covered by the N stations. The surface vertical velocity ω_s is assumed as 0. Geopotential height ϕ can be derived from the virtual temperature analysis using the hydrostatic balance

$$\frac{\partial\phi}{\partial p}=-\frac{RT_v}{P} \tag{13}$$

The variational equations for the analyzed variables are:

$$\frac{\partial I(t)}{\partial x_{ik}}+\lambda_1(t)\frac{\partial A_{mass}}{\partial x_{ik}}+\lambda_2(t)\frac{\partial A_{water}}{\partial x_{ik}}+\lambda_3(t)\frac{\partial A_{heat}}{\partial x_{ik}}+\lambda_{4,5}(t)\frac{\partial A_{momtentum}}{\partial x_{ik}}=0 \tag{14}$$

Where x_{ik} stands for variables of $u_{ik}, v_{ik}, q_{ik}, s_{ik}$. λ is the Lagrange multiplier. Note that $A_{momtentum}$ includes two equations for u and v, respectively. With a total of four variables and five Lagrange multipliers, the total number of variables to be calculated in any given time is $4\times N\times K+5$.

We assume measurement errors are uncorrelated at different locations and for different variables, so the covariance matrix W is diagonal. The diagonal elements are the reciprocal of error variances $\sigma_{x_{ik}}^2$. Thus, equation (14) becomes:

$$2\sigma_{x_{ik}}^{-2}\left(x_{ik}-x_{o,ik}\right)+\lambda_1(t)\frac{\partial A_{mass}}{\partial x_{ik}}+\lambda_2(t)\frac{\partial A_{water}}{\partial x_{ik}}+\lambda_3(t)\frac{\partial A_{heat}}{\partial x_{ik}}+\lambda_{4,5}(t)\frac{\partial A_{momtentum}}{\partial x_{ik}}=0 \tag{15}$$

Or

$$x_{ik}=x_{o,ik}-\frac{\sigma_{x_{ik}}^2}{2}\left[\lambda_1(t)\frac{\partial A_{mass}}{\partial x_{ik}}+\lambda_2(t)\frac{\partial A_{water}}{\partial x_{ik}}+\lambda_3(t)\frac{\partial A_{heat}}{\partial x_{ik}}+\lambda_{4,5}(t)\frac{\partial A_{momtentum}}{\partial x_{ik}}\right] \tag{16}$$

Numerical calculation of Eq. (16) and Eqs. (8)-(11) is carried out in an iterative mode. The iteration, when described to a single time level, contains three steps. The first step is that the previous estimate or original measurements are used to calculate each partial derivative to x_{ik} on the right-hand-side of Eq. (16) using the formation of Eqs. (8)-(11).

$$x_{ik}^{(l)} = x_{o,ik} - \frac{\sigma_{x_{ik}}^2}{2} \sum_{n=1}^{5} \lambda_n(t) B_{n,ik}^{(l-1)}$$

(17)

Where l denotes the iteration index, $B_{n,ik}^{(l-1)}$ are the partial derivatives of constraints A. Substitution of Eq. (17) to Eqs. (8)-(11) yields a linearized set of equations for λ_n . A general form of the equations is:

$$A_n\left(x_{o,ik} - \frac{\sigma_{x_{ik}}^2}{2} \sum_{n=1}^{5} \lambda_n(t) B_{n,ik}^{(l-1)} \right) = 0 \tag{18}$$

Because of the linearity of the operator, it can be further written as:

$$A_n\left(x_{o,ik}\right) - \sum_{n=1}^{5} \left[\frac{\sigma_{x_{ik}}^2}{2} \lambda_n(t) A_n\left(B_{n,ik}^{(l-1)}\right) \right] = 0 \tag{19}$$

This set of five equations for the five constraints is used to solve for λ_n at any given time. This constitutes the second step in the iteration.

In the third step, the adjustments are calculated by using the newly obtained λ_n in Eq. (17). After that, the next iteration is performed.

Because the constraints Eqs. (8)-(11) contain time derivatives, the actual iteration is carried out simultaneously for all time levels in the field experiment. For continuous forcing, it is carried out every month.

4. Forcing products

4.1 Continuous forcing at SGP

The long-term continuous forcing at SGP is a major VARANAL product developed from NWP analysis data and the long-term, high-density ARM observations measured at SGP. In this approach, the atmospheric state variables from NWP analyses are adjusted to balance the observed column budgets of mass, heat, moisture, and momentum, rather than the model-produced budgets (*Xie et al.*, 2004). The derived large-scale forcing and diagnostic variables can be used for statistically studying single-column models (SCM), cloud-resolving models (CRM) and large-eddy simulations (LES) results over long time periods.

4.1.1 Workflow

The structure of VARANAL for continuous forcing consists of four steps (Figure 2): (1) preparation of the required raw input data, (2) preprocessing, (3) variational analysis, and (4) postprocessing and output of final products. In step 1, all the required data are collected and reorganized from raw datasets to output in a standard format for further analysis. Step 2 includes major quality control of the raw data, averaging the data within the domain, filling in missing measurements, and interpolation to consistent observation times. In step 3, the large-scale variables (*u, v, T, q*) are adjusted by the constrained variational analysis method and the large-scale advective tendencies and vertical velocity are calculated. Step 4 calculates and outputs the variables that will be used to force and evaluate SCM/CRM/LES.

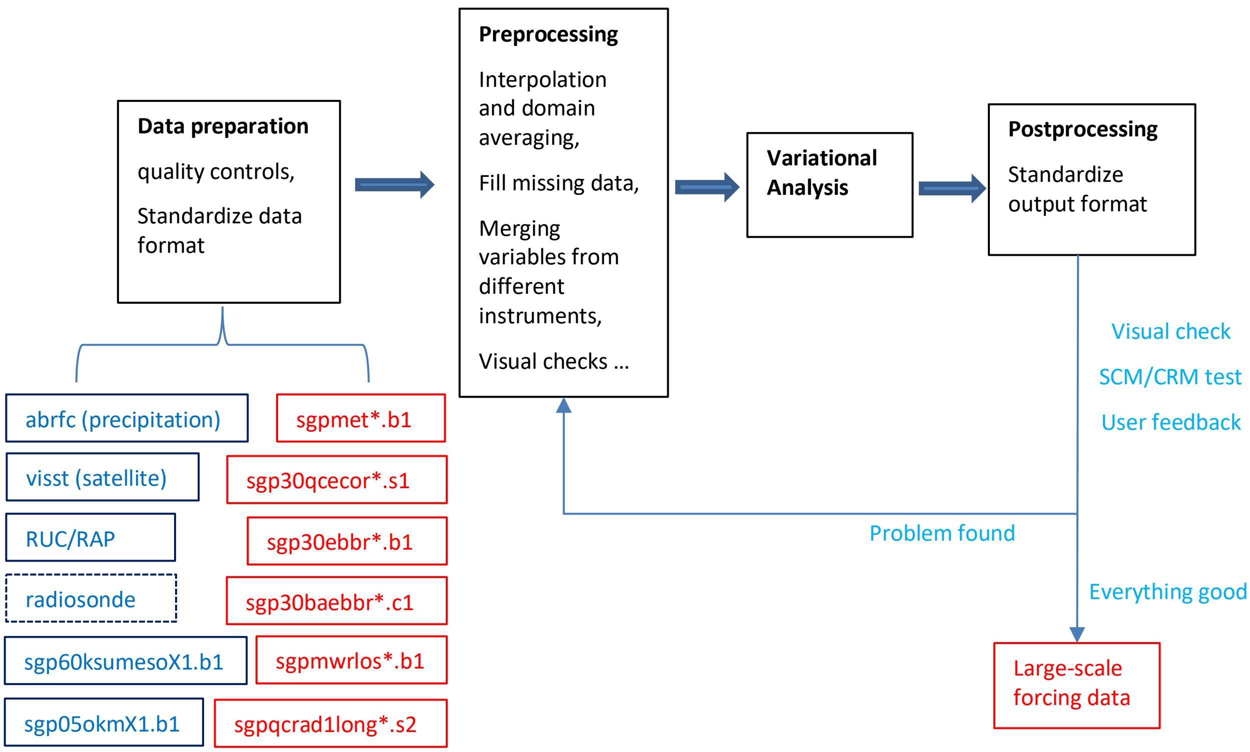

Figure 2. Illustration of the structure of the variational analysis system and the input datastreams for continuous forcing. The datastreams in red are ARM datastreams while those in blue (except radiosonde) represent datasets from external data centers and archived by ARM. Dashed box (radiosonde) means it is not used for continuous forcing but is used for some field campaigns.

To increase the efficiency of the workflow and reduce human effort during the process, a set of code optimizing efforts have been made. Step (1) has been implemented in the ARM Data

Integrator (ADI) in 2017 to directly prepare data from the ARM Archive. The visual checking part for suspicious data in step (2) is re-coded from interactive mode into offline iterative mode for more efficient human work. The workflow of step (3) and step (4) are optimized for less human interaction and standardizing output format. These efforts have greatly increased the automation of the framework and are more suitable for operational run with higher efficiency.

4.1.2 input data

The current continuous forcing data use the following datasets as input:

RUC/RAP (sgpruc20isobX1.c1/ sgprap20plevX1.c1): The National Oceanic and Atmospheric Administration (NOAA) rapid update cycle (RUC, before May 2012) analysis and Rapid Refresh (RAP, after May 2012) analysis.

- SMOS (sgpmet**.b1): Surface Meteorological Observation Stations measuring surface precipitation, surface pressure, surface winds, temperature, and relative humidity.
- EBBR (sgp30baebbr**.s1): Energy Budget Bowen Ratio stations measuring surface latent and sensible heat fluxes and surface broadband net radiative flux.
- ECOR (sgp30qcecor**.s1): Eddy Correlation Flux Measurement Systems measuring surface latent and sensible heat fluxes.
- OKM (sgp05okmX1.b1) and KAM (sgp60ksumesoX1.b1): Oklahoma and Kansas mesonet stations measuring surface precipitation, pressure, winds, and temperature.
- MWR (sgpmwrlos**.b1): Microwave Radiometer stations measuring the column precipitable water and total cloud liquid water.
- SIROS (sgpqcrad1long**.s2): Solar and Infrared Observing Systems measuring broadband longwave and shortwave radiative fluxes.
- GOES (sgpvisstgridg13v4minnisX1.c1): the Geostationary Operational Environment Satellite measuring radiative fluxes at TOA.
- ABRFC (sgpabrfcprecipX1.c1): the 4-km resolution gridded precipitation products from Arkansas-Red Basin River Forecast Center based on WSD-88 rain radar and gauge measurements.

The locations of these stations as of December 2015 are plotted in Figure 3. Along with time, there are some changes on the abbreviation or instrument (datastream) names. The datastream given above are obtained for the version 2 of continuous forcing (see section 3.4 for version information) for December 2015. Datastream names may change for other time and versions. Station numbers and locations may also change in time (e.g., no KAM stations in Figure 3 because the data is only available before September 2013).

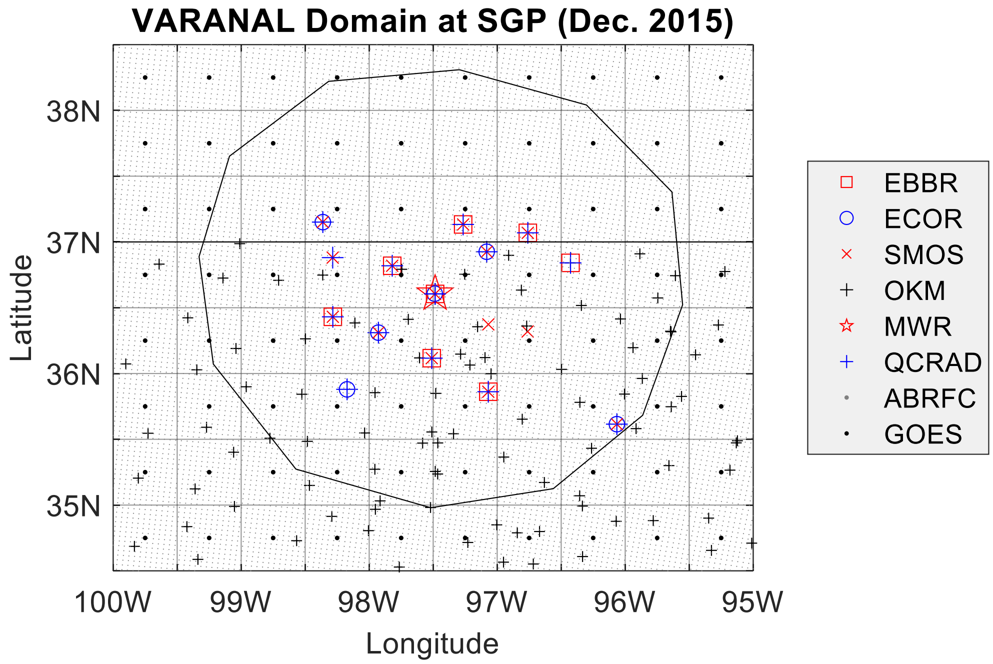

Figure 3: ARM surface stations, GOES TOA measurements and ABRFC gridded precipitation data at the SGP domain as of December. Gray lines show 0.5°× 0.5° s grids of GOES satellite products (black dots). The black circle is the domain of VARANAL. Black line at 37°N indicates the boundary between Oklahoma (below) and Kansas (above). (revised from *Tang et al.* (2016a))

To avoid overweighting problem due to the spatial distribution of surface stations, the surface stational measurements are firstly interpolated into the GOES grids of 0.5°×0.5° horizontal resolution in the domain in Figure 3. If there are actual measurements within the 0.5°×0.5° grid box, simple arithmetic averaging is used to obtain the value for that grid box. Under circumstances that multiple instruments observe the same quantities, their measurements are merged in the arithmetic averaging process with a weighting function depending on their quality. If there is no actual measurement in the grid box, the Barnes scheme (*Barnes*, 1964) is used with the length scale of L_x=50km, L_y=50km, and L_t=6hr to fill the missing grid box. Then, the constraint variables are calculated by averaging the interpolated fields within the VARANAL domain (the dodecagon in Figure 3).

Note that there are periods when RUC/RAP data are missing. The missing RUC/RAP data with gap > 6hr, listed in Table 1, are filled with RUC/RAP data at another time periods of the month. Missing periods < 6hr are filled by linear interpolation. Please be careful when using continuous forcing data during these periods.

Table 1. Time periods of missing RUC/RAP data with gap > 6hr.

Data source	Year	Missing period
RAP	2014	Dec. 19 15Z to Dec. 19 23Z
RAP	2014	Dec. 20 20Z to Dec. 21 19Z
RAP	2014	Dec. 25 20Z to Dec. 26 19Z
RAP	2016	May 16 14Z to May 17 23Z
RAP	2018	Feb. 18 00Z to Feb. 18 23Z
RAP	2018	Apr. 10 01Z to Apr. 10 23Z
RAP	2018	May 2 04Z to May 2 23Z
RAP	2018	May 7 03Z to May 7 23Z

4.1.3 output data

The final outputs from the variational analysis for the single-level time series and multi-layer data include forcing data for SCM/CRM/LES and evaluation data. All the output variables are listed in the Appendix 1.

4.1.4 version updates

There are two versions of continuous forcing currently at the ARM Archive: version 1 available from 1999 to 2011, version 2 (*Tang et al.*, 2019) available from 2004 to October 2018. The major version update is that version 1 only uses EBBR measured surface turbulence fluxes while version 2 uses merged fluxes from EBBR and ECOR to better represent various surface types within the analysis domain. There are some other updates such as fixing bugs, updating input data version and applying ADI for data preparation.

ECOR and EBBR are two instruments measuring surface turbulence fluxes in different ways. EBBR is firstly deployed at SGP while ECOR is deployed later (reliable ECOR data at SGP are from September 2003). Details about the two instruments can be found in the ECOR and EBBR handbooks (*Cook*, 2018a; b). Although for both instruments there are value-added products (VAP), the Quality-Controlled ECOR (QCECOR) and Bulk Aerodynamic Technique EBBR (BAEBBR), available to correct the systematic instrumental biases or fill the missing gaps when the method is invalid, the turbulence fluxes measured from ECOR and EBBR still have quite significant differences. Overall, BAEBBR has larger LH and smaller SH compared to QCECOR during summer. These differences are partly due to the different surface vegetation types the instruments are looking at, and partly due to the instrument difference itself. As a result, the derived large-scale forcing has quite considerable uncertainty (climatologically ~20% for vertical velocity) in magnitude (Figure 4) due to the difference of ECOR and EBBR. More details can be found in *Tang et al.* (2019).

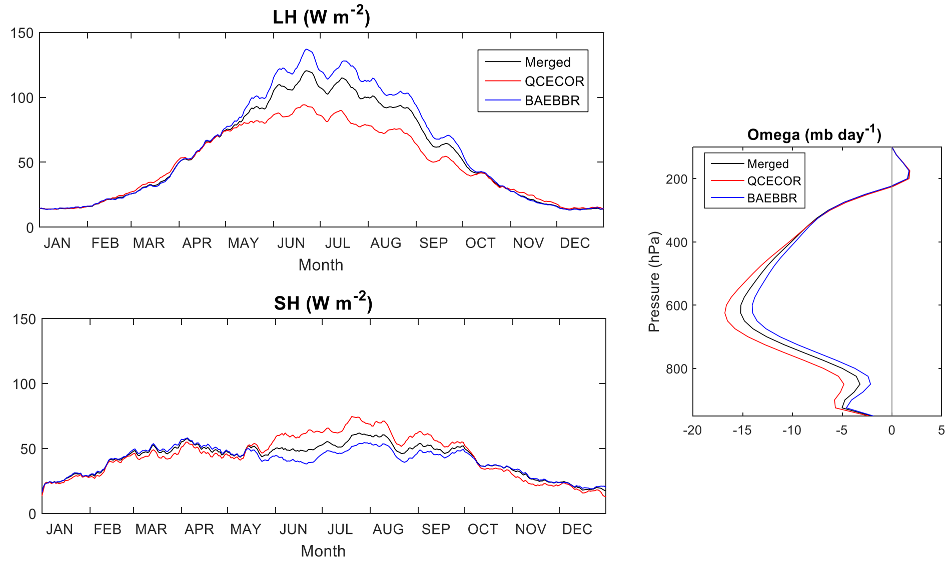

Figure 4. The seasonal cycle of SGP domain-averaged latent heat (LH) and sensible heat (SH) fluxes by using QCECOR-only (QCECOR), BAEBBR-only (BAEBBR) and both QCECOR and BAEBBR data (Merged) averaged from 2004-2015, and the impact to the derived large-scale vertical velocity (Omega). Revised from *Tang et al.* (2019).

4.2 IOP-Based Forcing

Different field campaigns have different instrument availabilities. Some incorporated radiosonde and surface measurements while some used NWP analysis or reanalysis for initial guess and/or for some of the constraint variables. Therefore, the step 1 and 2 in Figure 2 generally need specific treatments for different field campaigns. Table 2 lists the available field campaigns and the data sources used to derive these forcings. All the forcing data, as well as readme files including the field campaign background, VARANAL settings, input data sources, and version information, can be downloaded from https://iop.archive.arm.gov/arm-iop/0eval-data/xie/scm-forcing/.

Table 2. Information of large-scale forcing for field campaigns.

Field campaigns	**Site**	**time**	**Data sources**	**references**
9704	SGP	Apr. 1997	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	
9706	SGP	Jun. 1997	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	

9709	SGP	Sep. 1997	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	
9804	SGP	Apr. 1998	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	
9901	SGP	Jan. 1999	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	
9903	SGP	Mar. 1999	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	
9907	SGP	Jul. 1999	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	
0003	SGP	Mar. 2000	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	(*Xie et al.*, 2005)
0009	SGP	Sep. 2000	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	
0011	SGP	Nov. 2000	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	
0205	SGP	May. 2002	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	
0211	SGP	Nov. 2002	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	
0305	SGP	May. 2003	Radiosonde supplemented with RUC and wind profiler, ARM surface measurements, GOES TOA fluxes	
Long-term at Darwin	TWP	Wet seasons 2004-2007	Radiosonde with ERA-Interim reanalysis as background, radar precipitation, ARM MWR LWP. surface and TOA heat and radiative fluxes from ERA-Interim.	
M-PACE	NSA	5-22 Oct 2004	Radiosonde with ERA-Interim reanalysis as background, satellite TOA fluxes, surface stations for precipitation, LWP and radiative fluxes, turbulence fluxes come from bulk calculation for land and ERA-Interim reanalysis for ocean.	(*Xie et al.*, 2006)
TWP-ICE	TWP	Jan-Feb 2006	Radiosonde, satellite TOA fluxes, radar precipitation, surface fluxes measured from ship and land stations. ERA-Interim data are used as background and fill to missing gaps.	(*Xie et al.*, 2010)

CLASIC	SGP	June 2007	Radiosonde with RUC as background. ARM surface measurements, GOES TOA fluxes	
ISDAC	NSA	Apr 2008	Purely based on ERA-Interim	
AMFCHINA	HFE	Nov 2008	MERRA reanalysis, TRMM precipitation, satellite TOA fluxes, surface stations for meteorology variables and surface fluxes.	
MC3E	SGP	Apr-Jun 2011	Radiosonde with RUC as background. ARM surface measurements, GOES TOA fluxes	(*Xie et al.*, 2014)
AMIE-GAN	GAN	Oct 2011 - Mar 2012	ECMWF analysis (state variables, turbulence and radiative fluxes), SMART-R, S-POL, and TRMM radar precipitation.	
DYNAMO-Revelle	REV	Oct-Dec 2011	ECMWF analysis (state variables, turbulence and radiative fluxes), CSU TOGA radar and TRMM precipitation.	
DYNAMO-North Sounding Array		Oct-Dec 2011	Gridded sounding data from CSU, TRMM precipitation, ECMWF analysis for surface and TOA heat and radiative fluxes.	
GOAmazon	MAO	Jan 2014 - Dec 2015	ERA-Interim reanalysis, SIPAM radar precipitation, TRMM precipitation, GOES TOA fluxes, ARM and Brazilian surface stations for radiative and turbulent fluxes.	(*Tang et al.*, 2016b)
PECAN	SGP	Jun-Jul 2017	Radiosonde with RUC as background. ARM and PECAN surface measurements, GOES TOA fluxes.	

References:

Barnes, S. L. (1964), A Technique for Maximizing Details in Numerical Weather Map Analysis, Journal of Applied Meteorology, 3(4), 396-409, doi: 10.1175/1520-0450(1964)003<0396:ATFMDI>2.0.CO;2.

Cook, D. R. (2018a), Eddy Correlation Flux Measurement System (ECOR) Instrument Handbook, *Technical Report Rep. DOE/SC-ARM/TR-052*, U.S. Department of Energy.

Cook, D. R. (2018b), Energy Balance Bowen Ratio (EBBR) Instrument Handbook, *Technical Report Rep. DOE/SC-ARM/TR-037*, U.S. Department of Energy.

Tang, S., M. Zhang, and S. Xie (2016a), An ensemble constrained variational analysis of atmospheric forcing data and its application to evaluate clouds in CAM5, Journal of Geophysical Research: Atmospheres, 121(1), 33-48, doi: 10.1002/2015JD024167.

Tang, S., S. Xie, M. Zhang, Q. Tang, Y. Zhang, S. A. Klein, et al. (2019), Differences in Eddy-Correlation and Energy-Balance Surface Turbulent Heat Flux Measurements and Their Impacts on the Large-Scale Forcing Fields at the ARM SGP Site, Journal of Geophysical Research: Atmospheres, 124(6), 3301-3318, doi: 10.1029/2018jd029689.

Tang, S., S. Xie, Y. Zhang, M. Zhang, C. Schumacher, H. Upton, et al. (2016b), Large-scale vertical velocity, diabatic heating and drying profiles associated with seasonal and diurnal variations of convective systems observed in the GoAmazon2014/5 experiment, Atmos. Chem. Phys., 16(22), 14249-14264, doi: 10.5194/acp-16-14249-2016.

Xie, S., R. T. Cederwall, and M. Zhang (2004), Developing long-term single-column model/cloud system–resolving model forcing data using numerical weather prediction products constrained by surface and top of the atmosphere observations, Journal of Geophysical Research, 109(D1), doi: 10.1029/2003jd004045.

Xie, S., S. A. Klein, M. Zhang, J. J. Yio, R. T. Cederwall, and R. McCoy (2006), Developing large-scale forcing data for single-column and cloud-resolving models from the Mixed-Phase Arctic Cloud Experiment, Journal of Geophysical Research, 111(D19), doi: 10.1029/2005jd006950.

Xie, S., T. Hume, C. Jakob, S. A. Klein, R. B. McCoy, and M. Zhang (2010), Observed Large-Scale Structures and Diabatic Heating and Drying Profiles during TWP-ICE, Journal of Climate, 23(1), 57-79, doi: 10.1175/2009jcli3071.1.

Xie, S., Y. Zhang, S. E. Giangrande, M. P. Jensen, R. McCoy, and M. Zhang (2014), Interactions between Cumulus Convection and Its Environment as Revealed by the MC3E Sounding Array, Journal of Geophysical Research: Atmospheres, 2014JD022011, doi: 10.1002/2014JD022011.

Xie, S., M. Zhang, M. Branson, R. T. Cederwall, A. D. Del Genio, Z. A. Eitzen, et al. (2005), Simulations of midlatitude frontal clouds by single-column and cloud-resolving models during the Atmospheric Radiation Measurement March 2000 cloud intensive operational period, Journal of Geophysical Research: Atmospheres, 110(D15), D15S03, doi: 10.1029/2004JD005119.

Zhang, M., and J. Lin (1997), Constrained Variational Analysis of Sounding Data Based on Column-Integrated Budgets of Mass, Heat, Moisture, and Momentum: Approach and Application to ARM Measurements, Journal of the Atmospheric Sciences, 54(11), 1503-1524, doi: 10.1175/1520-0469(1997)054<1503:CVAOSD>2.0.CO;2.

Zhang, M., S. Xie, R. T. Cederwall, and J. J. Yio (2001a), Description of the ARM Operational Objective Analysis System, ARM Technical Reports ARM-TR-005.

Zhang, M., J. Lin, R. T. Cederwall, J. J. Yio, and S. C. Xie (2001b), Objective Analysis of ARM IOP Data: Method and Sensitivity, Monthly Weather Review, 129(2), 295-311, doi: 10.1175/1520-0493(2001)129<0295:OAOAID>2.0.CO;2.

Appendix 1: Filehead of continuous forcing data

```
netcdf sgp60varanarapC1.c1.20151201.000000 {
dimensions:
	time = UNLIMITED ; // (744 currently)
	lev = 37 ;
variables:
	double base_time ;
		base_time:units = "seconds since 1970-1-1 0:00:00 0:00" ;
		base_time:long_name = "Base time in Epoch" ;
		base_time:string = "2015-12-1 0:00:00 0:00 GMT" ;
	double time(time) ;
		time:units = "days since 2014-12-31" ;
		time:long_name = "calendar day fraction of the year 2015" ;
		time:calendar = "gregorian" ;
		time:axis = "T" ;
	double time_offset(time) ;
		time_offset:units = "seconds since 2015-12-1 0:00:00
0:00" ;
		time_offset:long_name = "Time offset from base_time" ;
		time_offset:missing_value = 1.e+20f ;
	int year(time) ;
		year:units = " " ;
		year:long_name = "Year" ;
		year:missing_value = -9999s ;
	int month(time) ;
		month:units = " " ;
		month:long_name = "Month" ;
		month:missing_value = -9999s ;
	int day(time) ;
		day:units = " " ;
		day:long_name = "Day" ;
		day:missing_value = -9999s ;
	int hour(time) ;
		hour:units = " " ;
		hour:long_name = "Hour" ;
		hour:missing_value = -9999s ;
	int minute(time) ;
		minute:units = "Minute" ;
		minute:long_name = " " ;
		minute:missing_value = -9999s ;
	float lat ;
		lat:units = "degrees_north" ;
		lat:long_name = "latitude" ;
	float lon ;
		lon:units = "degrees_west" ;
		lon:long_name = "longitude " ;
	float alt ;
		alt:units = "m" ;
		alt:long_name = "altitude, height above mean sea level" ;
	float phis ;
		phis:units = "m2/s2" ;
```

```
            phis:long_name = "surface geopential height" ;
      float lev(lev) ;
            lev:units = "mb" ;
            lev:long_name = "pressure levels" ;
      float T(time, lev) ;
            T:units = "K" ;
            T:long_name = "Temperature" ;
            T:standard_name = "air_temperature" ;
            T:version = "v2" ;
            T:source = "RAP Analysis" ;
            T:missing_value = -9999.f ;
      float q(time, lev) ;
            q:units = "g/kg" ;
            q:long_name = "Water vapor mixing ratio" ;
            q:standard_name = "humidity_mixing_ratio" ;
            q:version = "v2" ;
            q:source = "RAP Analysis" ;
            q:missing_value = -9999.f ;
      float u(time, lev) ;
            u:units = "m/s" ;
            u:long_name = "Horizontal wind U component" ;
            u:standard_name = "eastward_wind" ;
            u:version = "v2" ;
            u:source = "RAP Analysis" ;
            u:missing_value = -9999.f ;
      float v(time, lev) ;
            v:units = "m/s" ;
            v:long_name = "Horizontal wind V component" ;
            v:standard_name = "northward_wind" ;
            v:version = "v2" ;
            v:source = "RAP Analysis" ;
            v:missing_value = -9999.f ;
      float omega(time, lev) ;
            omega:units = "mb/hour" ;
            omega:long_name = "vertical velocity" ;
            omega:standard_name =
"lagrangian_tendency_of_air_pressure" ;
            omega:version = "v2" ;
            omega:source = "Derived from RAP Analysis" ;
            omega:missing_value = -9999.f ;
      float div(time, lev) ;
            div:units = "1/s" ;
            div:long_name = "Horizontal wind divergence" ;
            div:standard_name = "divergence_of_wind" ;
            div:version = "v2" ;
            div:source = "Derived from RAP Analysis" ;
            div:missing_value = -9999.f ;
      float T_adv_h(time, lev) ;
            T_adv_h:units = "K/hour" ;
            T_adv_h:long_name = "Horizontal Temp advection" ;
            T_adv_h:standard_name =
"tendency_of_air_temperature_due_to_advection horizontal" ;
```

```
            T_adv_h:version = "v2" ;
            T_adv_h:source = "Derived from RAP Analysis" ;
            T_adv_h:missing_value = -9999.f ;
      float T_adv_v(time, lev) ;
            T_adv_v:units = "K/hour" ;
            T_adv_v:long_name = "Vertical Temp advection" ;
            T_adv_v:standard_name =
"tendency_of_air_temperature_due_to_advection vertical" ;
            T_adv_v:version = "v2" ;
            T_adv_v:source = "Derived from RAP Analysis" ;
            T_adv_v:missing_value = -9999.f ;
      float q_adv_h(time, lev) ;
            q_adv_h:units = "g/kg/hour" ;
            q_adv_h:long_name = "Horizontal q advection" ;
            q_adv_h:standard_name =
"tendency_of_humidity_mixing_ratio_due_to_advection horizontal" ;
            q_adv_h:version = "v2" ;
            q_adv_h:source = "Derived from RAP Analysis" ;
            q_adv_h:missing_value = -9999.f ;
      float q_adv_v(time, lev) ;
            q_adv_v:units = "g/kg/hour" ;
            q_adv_v:long_name = "Vertical q advection" ;
            q_adv_v:standard_name =
"tendency_of_humidity_mixing_ratio_due_to_advection vertical" ;
            q_adv_v:version = "v2" ;
            q_adv_v:source = "Derived from RAP Analysis" ;
            q_adv_v:missing_value = -9999.f ;
      float s(time, lev) ;
            s:units = "K" ;
            s:long_name = "Dry satic energy/Cp" ;
            s:standard_name =
"dry_static_energy_content_of_atmosphere_layer" ;
            s:version = "v2" ;
            s:source = "RAP Analysis" ;
            s:missing_value = -9999.f ;
      float s_adv_h(time, lev) ;
            s_adv_h:units = "K/hour" ;
            s_adv_h:long_name = "Hori. dry static energy adv./Cp" ;
            s_adv_h:standard_name =
"tendency_of_dry_static_energy_due_to_advection horizontal" ;
            s_adv_h:version = "v2" ;
            s_adv_h:source = "Derived from RAP Analysis" ;
            s_adv_h:missing_value = -9999.f ;
      float s_adv_v(time, lev) ;
            s_adv_v:units = "K/hour" ;
            s_adv_v:long_name = "Vert. dry static energy adv./Cp" ;
            s_adv_v:standard_name =
"tendency_of_dry_static_energy_due_to_advection vertical" ;
            s_adv_v:version = "v2" ;
            s_adv_v:source = "Derived from RAP Analysis" ;
            s_adv_v:missing_value = -9999.f ;
      float dsdt(time, lev) ;
```

```
            dsdt:units = "K/hour" ;
            dsdt:long_name = "d(dry static energy)/dt/Cp" ;
            dsdt:standard_name =
"tendency_of_dry_static_energy_content_of_atmosphere_layer" ;
            dsdt:version = "v2" ;
            dsdt:source = "RAP Analysis" ;
            dsdt:missing_value = -9999.f ;
      float dTdt(time, lev) ;
            dTdt:units = "K/hour" ;
            dTdt:long_name = "d(temperature)/dt" ;
            dTdt:standard_name = "tendency_of_air_temperature" ;
            dTdt:version = "v2" ;
            dTdt:source = "RAP Analysis" ;
            dTdt:missing_value = -9999.f ;
      float dqdt(time, lev) ;
            dqdt:units = "g/kg/hour" ;
            dqdt:long_name = "d(water vapor mixing ratio)/dt" ;
            dqdt:standard_name = "tendency_of_humidity_mixing_ratio" ;
            dqdt:version = "v2" ;
            dqdt:source = "RAP Analysis" ;
            dqdt:missing_value = -9999.f ;
      float q1(time, lev) ;
            q1:units = "K/hour" ;
            q1:long_name = "Apparent heat sources Yanai (1973)" ;
            q1:standard_name = "Q1" ;
            q1:version = "v2" ;
            q1:source = "Derived from RAP Analysis" ;
            q1:missing_value = -9999.f ;
      float q2(time, lev) ;
            q2:units = "K/hour" ;
            q2:long_name = "Apparent moisture sinks Yanai (1973)" ;
            q2:standard_name = "Q2" ;
            q2:version = "v2" ;
            q2:source = "Derived from RAP Analysis" ;
            q2:missing_value = -9999.f ;
      float prec_srf(time) ;
            prec_srf:units = "mm/hour" ;
            prec_srf:long_name = "Surface precipitation" ;
            prec_srf:standard_name = "lwe_precipitation_rate" ;
            prec_srf:version = "v2" ;
            prec_srf:source = "Rain gauge adjusted WSR-88D radar
precipitation - ABRFC" ;
            prec_srf:missing_value = -9999.f ;
      float LH(time) ;
            LH:units = "W/m2" ;
            LH:long_name = "Surf. latent heat flux, upward positive" ;
            LH:standard_name = "surface_upward_latent_heat_flux" ;
            LH:version = "v2" ;
            LH:source = "Merged from BAEBBR and QCECOR" ;
            LH:missing_value = -9999.f ;
      float SH(time) ;
            SH:units = "W/m2" ;
```

```
		SH:long_name = "Surf. sensible heat flux,upward positive" ;
		SH:standard_name = "surface_upward_sensible_heat_flux" ;
		SH:version = "v2" ;
		SH:source = "Merged from BAEBBR and QCECOR" ;
		SH:missing_value = -9999.f ;
	float p_srf_aver(time) ;
		p_srf_aver:units = "mb" ;
		p_srf_aver:long_name = "Surf. pressure averaged over the
domain" ;
		p_srf_aver:standard_name = "surface_air_pressure domain
average" ;
		p_srf_aver:version = "v2" ;
		p_srf_aver:source = "Merged products from surface
measurements - SMOS, OKM, KAS mesonet" ;
		p_srf_aver:missing_value = -9999.f ;
	float p_srf_center(time) ;
		p_srf_center:units = "mb" ;
		p_srf_center:long_name = "Surf. pressure at center of the
domain" ;
		p_srf_center:standard_name = "surface_air_pressure domain
center" ;
		p_srf_center:version = "v2" ;
		p_srf_center:source = "Merged products from surface
measurements - SMOS, OKM, KAS mesonet" ;
		p_srf_center:missing_value = -9999.f ;
	float T_srf(time) ;
		T_srf:units = "C" ;
		T_srf:long_name = "Surf. air temperature" ;
		T_srf:standard_name = "air_temperature at 2m" ;
		T_srf:version = "v2" ;
		T_srf:source = "Merged products from surface measurements -
SMOS, OKM, KAS mesonet" ;
		T_srf:missing_value = -9999.f ;
	float T_soil(time) ;
		T_soil:units = "C" ;
		T_soil:long_name = "Soil temperature" ;
		T_soil:standard_name = "soil_temperature" ;
		T_soil:version = "v2" ;
		T_soil:source = "BAEBBR" ;
		T_soil:missing_value = -9999.f ;
	float RH_srf(time) ;
		RH_srf:units = "%" ;
		RH_srf:long_name = "Surf. air relative humidity" ;
		RH_srf:standard_name = "relative_humidity at 2m" ;
		RH_srf:version = "v2" ;
		RH_srf:source = "Merged products from surface measurements
- SMOS, OKM, KAS mesonet" ;
		RH_srf:missing_value = -9999.f ;
	float wspd_srf(time) ;
		wspd_srf:units = "m/s" ;
		wspd_srf:long_name = "Surf. wind speed" ;
		wspd_srf:standard_name = "wind_speed at 10m" ;
```

```
            wspd_srf:version = "v2" ;
            wspd_srf:source = "Merged products from surface
measurements - SMOS, OKM, KAS mesonet" ;
            wspd_srf:missing_value = -9999.f ;
      float u_srf(time) ;
            u_srf:units = "m/s" ;
            u_srf:long_name = "Surf. U component" ;
            u_srf:standard_name = "eastward_wind at 10m" ;
            u_srf:version = "v2" ;
            u_srf:source = "Merged products from surface measurements -
SMOS, OKM, KAS mesonet" ;
            u_srf:missing_value = -9999.f ;
      float v_srf(time) ;
            v_srf:units = "m/s" ;
            v_srf:long_name = "Surf. V component" ;
            v_srf:standard_name = "northward_wind at 10m" ;
            v_srf:version = "v2" ;
            v_srf:source = "Merged products from surface measurements -
SMOS, OKM, KAS mesonet" ;
            v_srf:missing_value = -9999.f ;
      float rad_net_srf(time) ;
            rad_net_srf:units = "W/m2" ;
            rad_net_srf:long_name = "Surf. net rad., Downward" ;
            rad_net_srf:standard_name = "Surf. net rad., Downward" ;
            rad_net_srf:version = "v2" ;
            rad_net_srf:source = "SIRS - qcrad" ;
            rad_net_srf:missing_value = -9999.f ;
      float lw_net_toa(time) ;
            lw_net_toa:units = "W/m2" ;
            lw_net_toa:long_name = "TOA LW flux, upward positive" ;
            lw_net_toa:standard_name = "toa_net_upward_longwave_flux" ;
            lw_net_toa:version = "v2" ;
            lw_net_toa:source = "GOES VISST" ;
            lw_net_toa:missing_value = -9999.f ;
      float sw_net_toa(time) ;
            sw_net_toa:units = "W/m2" ;
            sw_net_toa:long_name = "TOA net SW flux, downward
positive" ;
            sw_net_toa:standard_name =
"toa_net_downward_shortwave_flux" ;
            sw_net_toa:version = "v2" ;
            sw_net_toa:source = "GOES VISST" ;
            sw_net_toa:missing_value = -9999.f ;
      float sw_dn_toa(time) ;
            sw_dn_toa:units = "W/m2" ;
            sw_dn_toa:long_name = "TOA solar insolation" ;
            sw_dn_toa:standard_name = "TOA solar insolation" ;
            sw_dn_toa:version = "v2" ;
            sw_dn_toa:source = "GOES VISST" ;
            sw_dn_toa:missing_value = -9999.f ;
      float cld_low(time) ;
            cld_low:units = "%" ;
```

```
            cld_low:long_name = "Satellite-measured low level cloud" ;
            cld_low:standard_name = " " ;
            cld_low:version = "v2" ;
            cld_low:source = "GOES VISST" ;
            cld_low:missing_value = -9999.f ;
      float cld_mid(time) ;
            cld_mid:units = "%" ;
            cld_mid:long_name = "Satellite-measured middle level
cloud" ;
            cld_mid:standard_name = " " ;
            cld_mid:version = "v2" ;
            cld_mid:source = "GOES VISST" ;
            cld_mid:missing_value = -9999.f ;
      float cld_high(time) ;
            cld_high:units = "%" ;
            cld_high:long_name = "Satellite-measured high level
cloud" ;
            cld_high:standard_name = " " ;
            cld_high:version = "v2" ;
            cld_high:source = "GOES VISST" ;
            cld_high:missing_value = -9999.f ;
      float cld_tot(time) ;
            cld_tot:units = "%" ;
            cld_tot:long_name = "Satellite-measured total cloud" ;
            cld_tot:standard_name = " " ;
            cld_tot:version = "v2" ;
            cld_tot:source = "GOES VISST" ;
            cld_tot:missing_value = -9999.f ;
      float cld_thick(time) ;
            cld_thick:units = "km" ;
            cld_thick:long_name = "Satellite-measured cloud
thickness" ;
            cld_thick:standard_name = " " ;
            cld_thick:version = "v2" ;
            cld_thick:source = "GOES VISST" ;
            cld_thick:missing_value = -9999.f ;
      float cld_top(time) ;
            cld_top:units = "km" ;
            cld_top:long_name = "Satellite-measured cloud top" ;
            cld_top:standard_name = "cloud_top_altitude" ;
            cld_top:version = "v2" ;
            cld_top:source = "GOES VISST" ;
            cld_top:missing_value = -9999.f ;
      float LWP(time) ;
            LWP:units = "cm" ;
            LWP:long_name = "cloud liquid water path" ;
            LWP:standard_name =
"atmosphere_cloud_liquid_water_content" ;
            LWP:version = "v2" ;
            LWP:source = "MWR" ;
            LWP:missing_value = -9999.f ;
      float dh2odt_col(time) ;
```

```
          dh2odt_col:units = "mm/hour" ;
          dh2odt_col:long_name = "Column-integrated dH2O/dt" ;
          dh2odt_col:standard_name = " " ;
          dh2odt_col:version = "v2" ;
          dh2odt_col:source = "RAP Analysis" ;
          dh2odt_col:missing_value = -9999.f ;
     float h2o_adv_col(time) ;
          h2o_adv_col:units = "mm/hour" ;
          h2o_adv_col:long_name = "Column-integrated H2O adv." ;
          h2o_adv_col:standard_name = " " ;
          h2o_adv_col:version = "v2" ;
          h2o_adv_col:source = "RAP Analysis" ;
          h2o_adv_col:missing_value = -9999.f ;
     float evap_srf(time) ;
          evap_srf:units = "mm/hour" ;
          evap_srf:long_name = "Surface evaporation" ;
          evap_srf:standard_name = "lwe_water_evaporation_rate at
surface" ;
          evap_srf:version = "v2" ;
          evap_srf:source = "Derived from LH" ;
          evap_srf:missing_value = -9999.f ;
     float dsdt_col(time) ;
          dsdt_col:units = "W/m2" ;
          dsdt_col:long_name = "Column d(dry static energy)/dt" ;
          dsdt_col:standard_name = " " ;
          dsdt_col:version = "v2" ;
          dsdt_col:source = "RAP Analysis" ;
          dsdt_col:missing_value = -9999.f ;
     float s_adv_col(time) ;
          s_adv_col:units = "W/m2" ;
          s_adv_col:long_name = "Column dry static energy adv." ;
          s_adv_col:standard_name = " " ;
          s_adv_col:version = "v2" ;
          s_adv_col:source = "RAP Analysis" ;
          s_adv_col:missing_value = -9999.f ;
     float rad_heat_col(time) ;
          rad_heat_col:units = "W/m2" ;
          rad_heat_col:long_name = "Column radiative heating" ;
          rad_heat_col:standard_name = " " ;
          rad_heat_col:version = "v2" ;
          rad_heat_col:source = "Surface and TOA radiation
measurements" ;
          rad_heat_col:missing_value = -9999.f ;
     float LH_col(time) ;
          LH_col:units = "W/m2" ;
          LH_col:long_name = "Column latent heating" ;
          LH_col:standard_name = " " ;
          LH_col:version = "v2" ;
          LH_col:source = "Derived from surface precipitation" ;
          LH_col:missing_value = -9999.f ;
     float omega_srf(time) ;
          omega_srf:units = "mb/hr" ;
```

```
            omega_srf:long_name = "Surface omega" ;
            omega_srf:standard_name =
"lagrangian_tendency_of_air_pressure at surface" ;
            omega_srf:version = "v2" ;
            omega_srf:source = "set to zero" ;
            omega_srf:missing_value = -9999.f ;
      float q_srf(time) ;
            q_srf:units = "kg/kg" ;
            q_srf:long_name = "water vapor mixing ratio" ;
            q_srf:standard_name = "humidity_mixing_ratio at 2m" ;
            q_srf:version = "v2" ;
            q_srf:source = "Merged products from surface measurements -
SMOS, OKM, KAS mesonet" ;
            q_srf:missing_value = -9999.f ;
      float s_srf(time) ;
            s_srf:units = "K" ;
            s_srf:long_name = "dry static energy/Cp" ;
            s_srf:standard_name = "dry_static_energy at 2m" ;
            s_srf:version = "v2" ;
            s_srf:source = "Merged products from surface measurements -
SMOS, OKM, KAS mesonet" ;
            s_srf:missing_value = -9999.f ;
      float PW(time) ;
            PW:units = "cm" ;
            PW:long_name = "column precip_water" ;
            PW:standard_name =
"tendency_of_atmosphere_water_vapor_content" ;
            PW:version = "v2" ;
            PW:source = "MWR" ;
            PW:missing_value = -9999.f ;
      float lw_up_srf(time) ;
            lw_up_srf:units = "W/m2" ;
            lw_up_srf:long_name = "Surf. upwelling LW" ;
            lw_up_srf:standard_name =
"surface_upwelling_longwave_flux_in_air" ;
            lw_up_srf:version = "v2" ;
            lw_up_srf:source = "SIRS - qcrad" ;
            lw_up_srf:missing_value = -9999.f ;
      float lw_dn_srf(time) ;
            lw_dn_srf:units = "W/m2" ;
            lw_dn_srf:long_name = "Surf. downwelling LW" ;
            lw_dn_srf:standard_name =
"surface_downwelling_longwave_flux_in_air" ;
            lw_dn_srf:version = "v2" ;
            lw_dn_srf:source = "SIRS - qcrad" ;
            lw_dn_srf:missing_value = -9999.f ;
      float sw_up_srf(time) ;
            sw_up_srf:units = "W/m2" ;
            sw_up_srf:long_name = "Surf. upwelling SW" ;
            sw_up_srf:standard_name =
"surface_upwelling_shortwave_flux_in_air" ;
            sw_up_srf:version = "v2" ;
```

```
            sw_up_srf:source = "SIRS - qcrad" ;
            sw_up_srf:missing_value = -9999.f ;
      float sw_dn_srf(time) ;
            sw_dn_srf:units = "W/m2" ;
            sw_dn_srf:long_name = "Surf. downwelling SW" ;
            sw_dn_srf:standard_name =
"surface_downwelling_shortwave_flux_in_air" ;
            sw_dn_srf:version = "v2" ;
            sw_dn_srf:source = "SIRS - qcrad" ;
            sw_dn_srf:missing_value = -9999.f ;
      float T_skin(time) ;
            T_skin:units = "C" ;
            T_skin:long_name = "Surf. skin temperature" ;
            T_skin:standard_name = "surface_temperature" ;
            T_skin:version = "v2" ;
            T_skin:source = "derived from srface LW with emissivisity
0.98" ;
            T_skin:missing_value = -9999.f ;

// global attributes:
            :Conventions = "CF-1.7" ;
            :title = "VarAna 1hr RAP_Based v2: SGP 2015-12" ;
            :history = "Version: v2" ;
            :update = "surface LH and SH are merged from ECOR and EBBR
instruments" ;
            :date_created = "Fri Apr 14 06:02:44 2017" ;
            :contact = "Shuaiqi Tang: tang32@llnl.gov, Qi Tang:
tang30@llnl.gov, Yunyan Zhang: zhang25@llnl.gov and Shaocheng Xie:
xie2@llnl.gov" ;
            :program_name = "proc_output_nwp.pro" ;
            :institution = "Lawrence Livermore National Laboratory, CA,
USA" ;
            :references = "https://www.arm.gov/data/data-
sources/varanal-29" ;
            :note = "Data below the surface are set to lowest available
level data" ;
}
```