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Development of the ARM Lagrangian Large-Scale Forcing Data (ARMLAGTRAJ) Value-Added Product Based on the lagtraj Framework

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ARM

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Acronyms and Abbreviations

ARM	Atmospheric Radiation Measurement
ARMBE	ARM Best Estimate data products
CRM	cloud-resolving model
DOE	U.S. Department of Energy
ECMWF	European Center for Medium-Range Weather Forecasts
ERA5	5th generation of ECMWF Reanalysis 5
GCSS	GEWEX Cloud Systems Study
GEWEX	Global Energy and Water Cycle Experiment
GPCI	GCSS Pacific Cross-section Intercomparison, a working group of GCSS
LES	large-eddy simulation
LLNL	Lawrence Livermore National Laboratory
MAGIC	Marine ARM GPCI Investigation of Clouds
MBL	marine boundary layer
MOSAiC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate
netCDF	Network Common Data Form
SCM	single-column model
VARANAL	large-scale forcing data developed based on the constrained variational analysis

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1.0 Introduction

The Atmospheric Radiation Measurement (ARM) large-scale forcing data developed based on the constrained variational analysis (VARANAL) value-added product (VAP) (Zhang and Lin 1997, Zhang et al. 2001, Xie et al. 2004, Tang et al. 2019) has been widely used for single-column models (SCMs), cloud-resolving models (CRMs), and large-eddy simulation models (LESs) to understand and improve physical processes in models. Recently, the U.S. Department of Energy (DOE) ARM user facility conducted several major field campaigns using ship-based moving observational platforms. For example, the Marine ARM GPCI Investigation of Clouds (MAGIC) field campaign focused on the role of subtropical marine-boundary layer (MBL) clouds, and the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) field campaign aimed to improve understanding of the coupled climate systems in the Arctic.

Observations from moving platforms are critical to provide a comprehensive characterization of coupled-system processes associated with all stages of the cloud and/or sea-ice life cycle. Traditional ARM large-scale forcing data have been developed at fixed locations. They need to be extended to include these moving platforms to address data needs for ship-based field campaigns or to support LES modeling in a Lagrangian framework.

With these considerations in mind, we develop ARM-type Lagrangian large-scale forcing data sets based on the *lagtraj* framework[1] (Boeing et al. 2020) with notable enhancements in generating forcings that are more suitable for ARM field campaigns. The *lagtraj* is a novel tool that generates forcings for LES and SCM simulation in both Lagrangian and Eulerian perspective. This technical report focuses on the major changes we performed on the *lagtraj* algorithm and provides an overview of the ARM Lagrangian Large-Scale Forcing Data (ARMLAGTRAJ) value-added products.

2.0 Algorithm

The *lagtraj* (https://github.com/EUREC4A-UK/lagtraj) is an open-source, Python-based tool that develops forcings for SCM/CRM/LES model simulations using a fully automated framework. While we focus on the Lagrangian forcing development in this technical report, the *lagtraj* can be applied to derive forcings in both Eulerian and Lagrangian. The workflow for creating Lagrangian forcings using the *lagtraj* is shown in Figure 1 and includes three major steps:

1. Download the fifth generation of European Center for Medium-range Weather Forecasts (ECMWF) Reanalysis 5 (ERA5; Hersbach et al. 2020) for the domain and time periods of interest.
2. Produce the trajectory file using the winds at either a single height or pressure level or using a weighted average between two levels.
3. Extract forcing profiles along the trajectory with the flexibility to select the output levels, the averaging width for mean calculations and gradients, and whether to apply any masking (land or ocean) or not.

[1] Copyright (c) 2021 Leif Denby and Steven Boeing, University of Leeds: https://github.com/EUREC4A-UK/lagtraj/blob/master/LICENSE

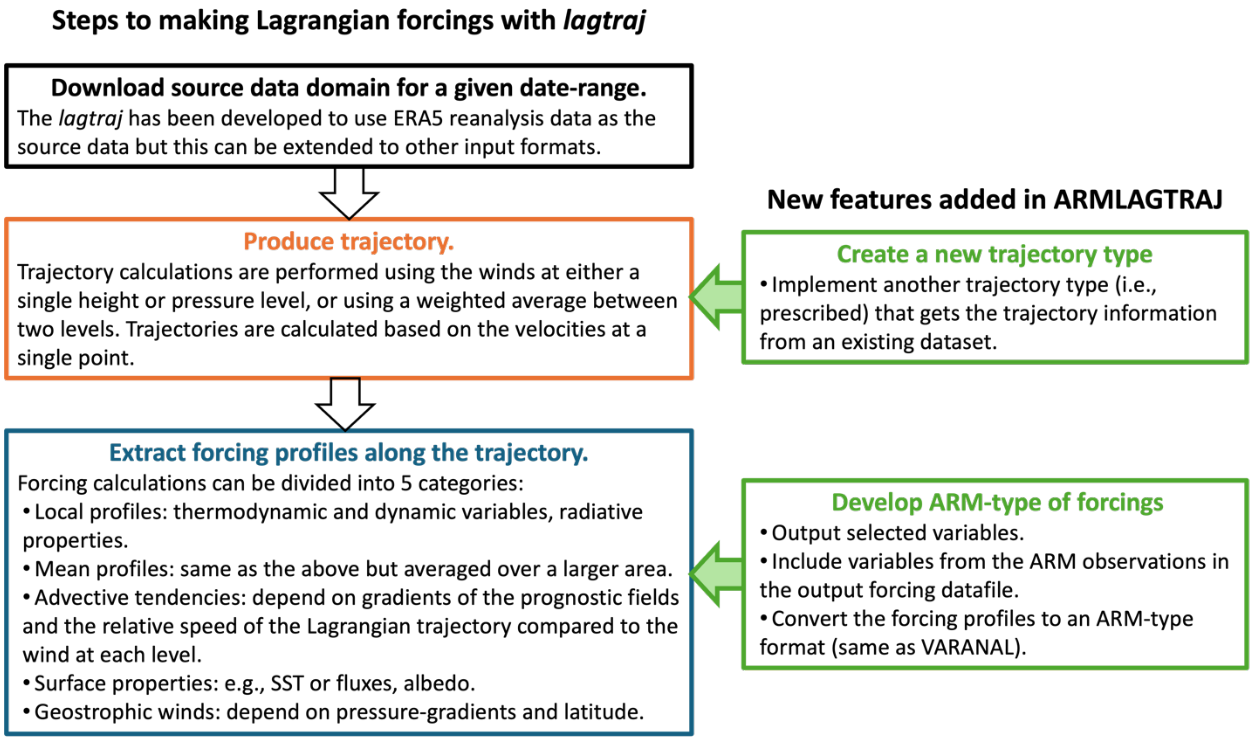

Figure 1. The workflow for creating Lagrangian forcings using the *lagtraj* framework. New features added in the ARMLAGTRAJ are shown in green boxes.

New features we added in the ARMLAGTRAJ include:

1. A new trajectory type has been created and implemented to allow the use of trajectory information from an existing trajectory data set. For example, the trajectory used in the ARMLAGTRAJ for the MOSAiC field campaign follows the ship locations.
2. The final outputs from the ARMLAGTRAJ for the single-level time series and multi-layer data include forcing data for SCM/CRM/LES and evaluation data.
3. Variables from the available ARM observations are also included in the output files.
4. The derived forcing profiles are converted to an ARM-type format, similar to that of VARANAL.

3.0 Output Data

A unique feature of the ARMLAGTRAJ is the inclusion of the variables from the available ARM measurements, which allows direct comparison between the ERA5 and ARM observations. As an example, Figure 2 shows the time series of column precipitable water and surface downward longwave radiation for the MOSAiC campaign during November 2019. The observed values for these two quantities are from the ARM Best Estimate data sets (ARMBE; Xie et al. 2010). We note that ERA5 broadly captured the observed distributions in both column precipitable water and surface downward longwave radiation. Both the ERA5 and ARM observations can be used to compare with model simulations when they are driven by the large-scale forcing data set.

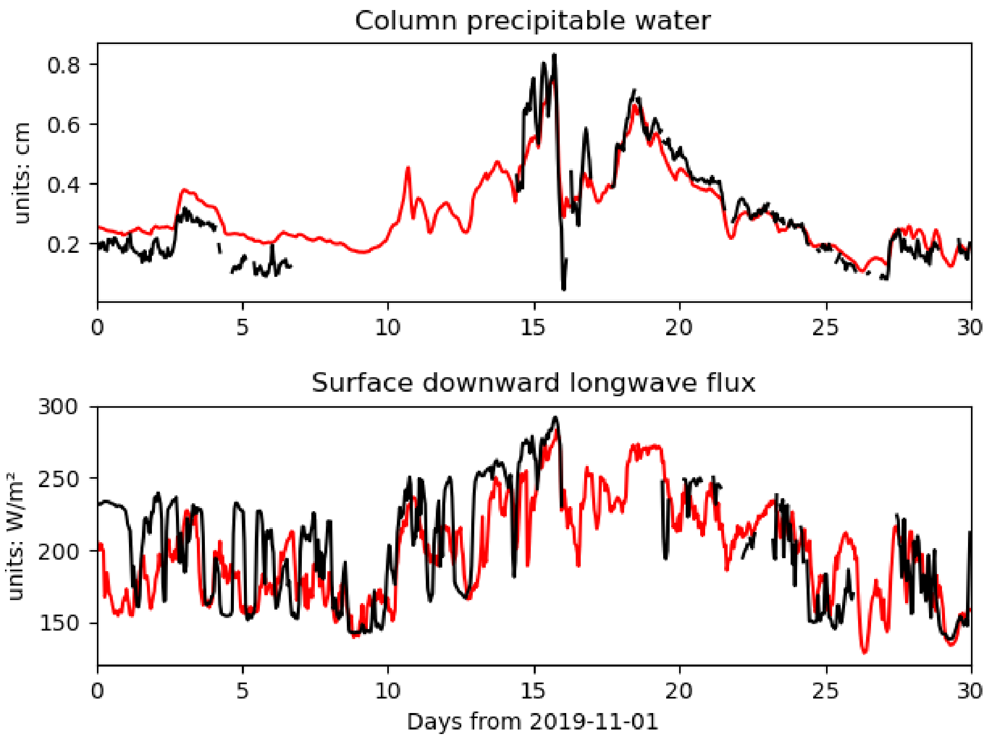

Figure 2. Time series of column precipitable water and surface downward longwave radiation for the MOSAiC field campaign during November 2019. The black and red line represents the ARM observations and ERA5 reanalysis, respectively.

A detailed list of the output variables in the ARMLAGTRAJ is given in Appendix A. The VAP produces a single output file per month, named with the following convention:

XXX60armlagtrajecmwfFF.c1.YYYYMMDD.hhmmss.cdf

where:

XXX = the location of the instrument (e.g., mos)
60armlagtrajecmwf = identifies that this is ARMLAGTRAJ VAP developed based on the ERA5 data with 60-min time resolution
FF = facility (e.g., M1)
c1 = identifies the data level
YYYYMMDD = year, month, and day
hhmmss = hour, minute, second

4.0 References

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Appendix A

Example of File Head of ARMLAGTRAJ

```
netcdf mos60armlagtrajecmwfM1.c1.20191101.000000 {
dimensions:
    time = UNLIMITED ; // (720 currently)
    lev = 211 ;
variables:
    double base_time ;
        base_time:string = "2019-11-01 0:00:00 0:00 GMT" ;
        base_time:long_name = "Base time in Epoch" ;
        base_time:units = "seconds since 1970-1-1 0:00:00 0:00" ;
        base_time:ancillary_variables = "time_offset" ;
        base_time:missing_value = 1.e+20 ;
        base_time:_FillValue = 1.e+20 ;
    double time(time) ;
        time:long_name = "Time offset from midnight" ;
        time:units = "seconds since 2019-11-01" ;
        time:axis = "T" ;
        time:calendar = "gregorian" ;
        time:standard_name = "time" ;
    double time_offset(time) ;
        time_offset:long_name = "Time offset from base_time" ;
        time_offset:units = "seconds since 2019-11-01 0:00:00 0:00" ;
        time_offset:ancillary_variables = "base_time" ;
        time_offset:missing_value = 1.e+20 ;
        time_offset:_FillValue = 1.e+20 ;
    int lev(lev) ;
        lev:long_name = "Pressure levels" ;
        lev:units = "mb" ;
        lev:axis = "Z" ;
    double T(time, lev) ;
        T:long_name = "Domain-mean temperature" ;
        T:units = "K" ;
        T:standard_name = "air_temperature" ;
        T:variable_source = "t_mean (interpolated)" ;
        T:missing_value = -9999. ;
        T:_FillValue = -9999. ;
    double T_local(time, lev) ;
        T_local:long_name = "Trajectory-centered temperature" ;
        T_local:units = "K" ;
```

```
        T_local:standard_name = "air_temperature" ;
        T_local:variable_source = "t_local (interpolated)" ;
        T_local:missing_value = -9999. ;
        T_local:_FillValue = -9999. ;
    double q(time, lev) ;
        q:long_name = "Domain-mean water vapor mixing ratio" ;
        q:units = "g/kg" ;
        q:standard_name = "humidity_mixing_ratio" ;
        q:variable_source = "r_v_mean (interpolated)" ;
        q:missing_value = -9999. ;
        q:_FillValue = -9999. ;
    double u(time, lev) ;
        u:long_name = "Domain-mean horizontal wind U component" ;
        u:units = "m/s" ;
        u:standard_name = "eastward_wind" ;
        u:variable_source = "u_mean (interpolated)" ;
        u:missing_value = -9999. ;
        u:_FillValue = -9999. ;
    double v(time, lev) ;
        v:long_name = "Domain-mean horizontal wind V component" ;
        v:units = "m/s" ;
        v:standard_name = "northward_wind" ;
        v:variable_source = "v_mean (interpolated)" ;
        v:missing_value = -9999. ;
        v:_FillValue = -9999. ;
    double omega(time, lev) ;
        omega:long_name = "Domain-mean vertical velocity" ;
        omega:units = "mb/hr" ;
        omega:standard_name = "lagrangian_tendency_of_air_pressure" ;
        omega:variable_source = "w_pressure_corr_mean (interpolated)"
;
        omega:missing_value = -9999. ;
        omega:_FillValue = -9999. ;
    double div(time, lev) ;
        div:long_name = "Domain-mean horizontal wind divergence" ;
        div:units = "1/s" ;
        div:standard_name = "divergence_of_wind" ;
        div:variable_source = "dudx+dvdy (interpolated)" ;
        div:missing_value = -9999. ;
        div:_FillValue = -9999. ;
    double T_adv_h(time, lev) ;
        T_adv_h:long_name = "Domain-mean horizontal Temperature
advection" ;
        T_adv_h:units = "K/hr" ;
        T_adv_h:standard_name =
"tendency_of_air_temperature_due_to_advection" ;
        T_adv_h:variable_source = "u_mean*dtdx+v_mean*dtdy
(interpolated)" ;
        T_adv_h:missing_value = -9999. ;
        T_adv_h:_FillValue = -9999. ;
    double q_adv_h(time, lev) ;
        q_adv_h:long_name = "Domain-mean horizontal q advection" ;
```

```
        q_adv_h:units = "g/kg/hr" ;
        q_adv_h:variable_source = "u_mean*dr_vdx+v_mean*dr_vdy
(interpolated)" ;
        q_adv_h:missing_value = -9999. ;
        q_adv_h:_FillValue = -9999. ;
    double dTdt(time, lev) ;
        dTdt:long_name = "Domain-mean derivative of air temperature
with respect to time" ;
        dTdt:units = "K/hr" ;
        dTdt:standard_name = "tendency_of_air_temperature" ;
        dTdt:variable_source = "dtdt_adv (interpolated)" ;
        dTdt:missing_value = -9999. ;
        dTdt:_FillValue = -9999. ;
    double dqdt(time, lev) ;
        dqdt:long_name = "Domain-mean derivative of water vapor mixing
ratio with respect to time" ;
        dqdt:units = "g/kg/hr" ;
        dqdt:variable_source = "dr_vdt_adv (interpolated)" ;
        dqdt:missing_value = -9999. ;
        dqdt:_FillValue = -9999. ;
    double LH(time) ;
        LH:long_name = "Domain-mean surface latent heat flux, upward
positive" ;
        LH:units = "W/m2" ;
        LH:standard_name = "surface_upward_latent_heat_flux" ;
        LH:variable_source = "mslhf_mean" ;
        LH:missing_value = -9999. ;
        LH:_FillValue = -9999. ;
    double SH(time) ;
        SH:long_name = "Domain-mean surface sensible heat flux, upward
positive" ;
        SH:units = "W/m2" ;
        SH:standard_name = "surface_upward_sensible_heat_flux" ;
        SH:variable_source = "msshf_mean" ;
        SH:missing_value = -9999. ;
        SH:_FillValue = -9999. ;
    double p_srf_aver(time) ;
        p_srf_aver:long_name = "Domain-mean surface pressure averaged
over the domain" ;
        p_srf_aver:units = "mb" ;
        p_srf_aver:variable_source = "sp_mean" ;
        p_srf_aver:missing_value = -9999. ;
        p_srf_aver:_FillValue = -9999. ;
    double p_srf_center(time) ;
        p_srf_center:long_name = "Domain-mean surface pressure at
center of the domain" ;
        p_srf_center:units = "mb" ;
        p_srf_center:variable_source = "sp_local" ;
        p_srf_center:missing_value = -9999. ;
        p_srf_center:_FillValue = -9999. ;
    double u_srf(time) ;
        u_srf:long_name = "Surface U component" ;
```

```
        u_srf:units = "m/s" ;
        u_srf:standard_name = "eastward_wind" ;
        u_srf:variable_source = "u10_mean" ;
        u_srf:missing_value = -9999. ;
        u_srf:_FillValue = -9999. ;
    double v_srf(time) ;
        v_srf:long_name = "Surface V component" ;
        v_srf:units = "m/s" ;
        v_srf:standard_name = "northward_wind" ;
        v_srf:variable_source = "v10_mean" ;
        v_srf:missing_value = -9999. ;
        v_srf:_FillValue = -9999. ;
    double lw_net_toa(time) ;
        lw_net_toa:long_name = "Domain-mean TOA LW flux, upward
positive" ;
        lw_net_toa:units = "W/m2" ;
        lw_net_toa:standard_name = "toa_net_upward_longwave_flux" ;
        lw_net_toa:variable_source = "mtnlwrf_mean" ;
        lw_net_toa:missing_value = -9999. ;
        lw_net_toa:_FillValue = -9999. ;
    double sw_net_toa(time) ;
        sw_net_toa:long_name = "Domain-mean TOA net SW flux, downward
positive" ;
        sw_net_toa:units = "W/m2" ;
        sw_net_toa:standard_name = "toa_net_downward_shortwave_flux" ;
        sw_net_toa:variable_source = "mtnswrf_mean" ;
        sw_net_toa:missing_value = -9999. ;
        sw_net_toa:_FillValue = -9999. ;
    double sw_dn_toa(time) ;
        sw_dn_toa:long_name = "Domain-mean TOA solar insolation" ;
        sw_dn_toa:units = "W/m2" ;
        sw_dn_toa:variable_source = "mtdwswrf_mean" ;
        sw_dn_toa:missing_value = -9999. ;
        sw_dn_toa:_FillValue = -9999. ;
    double cld_tot(time) ;
        cld_tot:long_name = "Domain-mean total cloud" ;
        cld_tot:units = "%" ;
        cld_tot:variable_source = "tcc_mean" ;
        cld_tot:missing_value = -9999. ;
        cld_tot:_FillValue = -9999. ;
    double LWP(time) ;
        LWP:long_name = "Liquid water path" ;
        LWP:units = "g/m2" ;
        LWP:variable_source = "crwc_mean + clwc_mean" ;
        LWP:missing_value = -9999. ;
        LWP:_FillValue = -9999. ;
    double PW(time) ;
        PW:long_name = "Domain-mean column precipitable water" ;
        PW:units = "cm" ;
        PW:variable_source = "tcw" ;
        PW:missing_value = -9999. ;
        PW:_FillValue = -9999. ;
```

```
    double lw_net_srf(time) ;
        lw_net_srf:long_name = "Domain-mean surface net longwave
(downward)" ;
        lw_net_srf:units = "W/m2" ;
        lw_net_srf:variable_source = "msnlwrf_mean" ;
        lw_net_srf:missing_value = -9999. ;
        lw_net_srf:_FillValue = -9999. ;
    double lw_dn_srf(time) ;
        lw_dn_srf:long_name = "Domain-mean surface downwelling
longwave" ;
        lw_dn_srf:units = "W/m2" ;
        lw_dn_srf:variable_source = "msdwlwrf_mean" ;
        lw_dn_srf:missing_value = -9999. ;
        lw_dn_srf:_FillValue = -9999. ;
    double sw_net_srf(time) ;
        sw_net_srf:long_name = "Domain-mean surface net shortwave
(downward)" ;
        sw_net_srf:units = "W/m2" ;
        sw_net_srf:variable_source = "msnswrf_mean" ;
        sw_net_srf:missing_value = -9999. ;
        sw_net_srf:_FillValue = -9999. ;
    double sw_dn_srf(time) ;
        sw_dn_srf:long_name = "Domain-mean surface downwelling
shortwave" ;
        sw_dn_srf:units = "W/m2" ;
        sw_dn_srf:variable_source = "msdwswrf_mean" ;
        sw_dn_srf:missing_value = -9999. ;
        sw_dn_srf:_FillValue = -9999. ;
    double T_skin(time) ;
        T_skin:long_name = "Domain-mean surface skin temperature" ;
        T_skin:units = "degC" ;
        T_skin:missing_value = -9999. ;
        T_skin:_FillValue = -9999. ;
    double cld_tot_local(time) ;
        cld_tot_local:long_name = "Trajectory-centered total cloud" ;
        cld_tot_local:units = "%" ;
        cld_tot_local:variable_source = "tcc_local" ;
        cld_tot_local:missing_value = -9999. ;
        cld_tot_local:_FillValue = -9999. ;
    double PW_local(time) ;
        PW_local:long_name = "Trajectory-centered total column
precipitable water" ;
        PW_local:units = "cm" ;
        PW_local:variable_source = "tcw_local" ;
        PW_local:missing_value = -9999. ;
        PW_local:_FillValue = -9999. ;
    double lw_dn_srf_local(time) ;
        lw_dn_srf_local:long_name = "Trajectory-centered surface
downwelling longwave" ;
        lw_dn_srf_local:units = "W/m2" ;
        lw_dn_srf_local:variable_source = "msdwlwrf_local" ;
        lw_dn_srf_local:missing_value = -9999. ;
```

```
        lw_dn_srf_local:_FillValue = -9999. ;
    double sw_dn_srf_local(time) ;
        sw_dn_srf_local:long_name = "Trajectory-centered surface
downwelling shortwave" ;
        sw_dn_srf_local:units = "W/m2" ;
        sw_dn_srf_local:variable_source = "msdwswrf_local" ;
        sw_dn_srf_local:missing_value = -9999. ;
        sw_dn_srf_local:_FillValue = -9999. ;
    double lw_net_srf_local(time) ;
        lw_net_srf_local:long_name = "Trajectory-centered surface net
longwave (downward)" ;
        lw_net_srf_local:units = "W/m2" ;
        lw_net_srf_local:variable_source = "msnlwrf_local" ;
        lw_net_srf_local:missing_value = -9999. ;
        lw_net_srf_local:_FillValue = -9999. ;
    double sw_net_srf_local(time) ;
        sw_net_srf_local:long_name = "Trajectory-centered surface net
shortwave (downward)" ;
        sw_net_srf_local:units = "W/m2" ;
        sw_net_srf_local:variable_source = "msnswrf_mean" ;
        sw_net_srf_local:missing_value = -9999. ;
        sw_net_srf_local:_FillValue = -9999. ;
    double arm_cld_tot(time) ;
        arm_cld_tot:long_name = "ARM observed total cloud" ;
        arm_cld_tot:units = "%" ;
        arm_cld_tot:variable_source = "tot_cld from mosarmbecldradM1"
;
        arm_cld_tot:missing_value = -9999. ;
        arm_cld_tot:_FillValue = -9999. ;
    double arm_PW(time) ;
        arm_PW:long_name = "ARM observed column precipitable water" ;
        arm_PW:units = "cm" ;
        arm_PW:variable_source = "pwv from mosarmbecldradM1" ;
        arm_PW:missing_value = -9999. ;
        arm_PW:_FillValue = -9999. ;
    double arm_lw_dn_srf(time) ;
        arm_lw_dn_srf:long_name = "ARM observed surface downwelling
longwave flux" ;
        arm_lw_dn_srf:units = "W/m2" ;
        arm_lw_dn_srf:variable_source = "lwdn from mosarmbecldradM1" ;
        arm_lw_dn_srf:missing_value = -9999. ;
        arm_lw_dn_srf:_FillValue = -9999. ;
    double arm_sw_dn_srf(time) ;
        arm_sw_dn_srf:long_name = "ARM observed surface downwelling
shortwave flux" ;
        arm_sw_dn_srf:units = "W/m2" ;
        arm_sw_dn_srf:variable_source = "swdn from mosarmbecldradM1" ;
        arm_sw_dn_srf:missing_value = -9999. ;
        arm_sw_dn_srf:_FillValue = -9999. ;
    double arm_lw_up_srf(time) ;
        arm_lw_up_srf:long_name = "ARM observed surface upwelling
longwave flux" ;
```

```
        arm_lw_up_srf:units = "W/m2" ;
        arm_lw_up_srf:variable_source = "lwup from mosarmbecldradM1" ;
        arm_lw_up_srf:missing_value = -9999. ;
        arm_lw_up_srf:_FillValue = -9999. ;
    double arm_sw_up_srf(time) ;
        arm_sw_up_srf:long_name = "ARM observed surface upwelling
shortwave flux" ;
        arm_sw_up_srf:units = "W/m2" ;
        arm_sw_up_srf:variable_source = "swup from mosarmbecldradM1" ;
        arm_sw_up_srf:missing_value = -9999. ;
        arm_sw_up_srf:_FillValue = -9999. ;
    double arm_LWP(time) ;
        arm_LWP:long_name = "ARM observed liquid water path" ;
        arm_LWP:units = "g/m2" ;
        arm_LWP:variable_source = "lwp from mosarmbecldradM1" ;
        arm_LWP:missing_value = -9999. ;
        arm_LWP:_FillValue = -9999. ;
    double arm_tdry(time, lev) ;
        arm_tdry:long_name = "ARM observed dry bulb temperature" ;
        arm_tdry:units = "degC" ;
        arm_tdry:variable_source = "tdry from mossondewnpnM1.b1" ;
        arm_tdry:missing_value = -9999. ;
        arm_tdry:_FillValue = -9999. ;
    double arm_rh(time, lev) ;
        arm_rh:long_name = "ARM observed relative humidity" ;
        arm_rh:units = "%" ;
        arm_rh:variable_source = "rh from mossondewnpnM1.b1" ;
        arm_rh:missing_value = -9999. ;
        arm_rh:_FillValue = -9999. ;
    double arm_u_wind(time, lev) ;
        arm_u_wind:long_name = "ARM observed eastward wind component"
;
        arm_u_wind:units = "m/s" ;
        arm_u_wind:variable_source = "u_wind from mossondewnpnM1.b1" ;
        arm_u_wind:missing_value = -9999. ;
        arm_u_wind:_FillValue = -9999. ;
    double arm_v_wind(time, lev) ;
        arm_v_wind:long_name = "ARM observed northward wind component"
;
        arm_v_wind:units = "m/s" ;
        arm_v_wind:variable_source = "v_wind from mossondewnpnM1.b1" ;
        arm_v_wind:missing_value = -9999. ;
        arm_v_wind:_FillValue = -9999. ;
    double lat(time) ;
        lat:long_name = "North latitude" ;
            lat:units = "degree_N" ;
        lat:valid_min = "-90" ;
        lat:valid_max = "90" ;
        lat:standard_name = "latitude" ;
        lat:missing_value = -9999. ;
        lat:_FillValue = -9999. ;
    double lon(time) ;
```

```
        lon:long_name = "East longitude" ;
        lon:units = "degree_E" ;
        lon:valid_min = "-180" ;
        lon:valid_max = "180" ;
        lon:standard_name = "longitude" ;
        lon:missing_value = -9999. ;
        lon:_FillValue = -9999. ;
    double alt(time) ;
        alt:long_name = "Altitude above mean sea level" ;
        alt:units = "m" ;
        alt:standard_name = "altitude" ;
        alt:missing_value = -9999. ;
       alt:_FillValue = -9999. ;

// global attributes:
           :_NCProperties = "version=2,netcdf=4.9.2,hdf5=1.14.2" ;
           :Conventions = "ARM-1.3" ;
           :title = "Hourly Lagrangian large-scale forcing data based
on ECMWF data" ;
           :description = "This Lagrangian large-scale forcing data is
developed following the ship-based moving observational platform. The
domain size is about 111x111 km²." ;
           :process_version = "" ;
           :dod_version = "60armlagtrajecmwf-c1-1.0" ;
           :datastream = "mos60armlagtrajecmwfM1.c1" ;
           :platform_id = "" ;
           :data_level = "" ;
           :site_id = "" ;
           :facility_id = "" ;
           :location_description = "" ;
           :command_line = "save_selected_outputs.ipynb" ;
           :doi = "10.5439/2376902" ;
           :averaging_interval = "60 minutes" ;
           :references =
"https://www.arm.gov/capabilities/vaps/armlagtraj" ;
           :history = "run on jade.dmf.arm.gov" ;
}
```

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