U.S. NAVAL RESEARCH LABORATORY

NAVGEM Reanalysis Along NGV Flight Tracks During DEEPWAVE: Version 1.1

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Contents

Summary

This document provides summary information and guidance on netCDF files that contain high-altitude NAVGEM reanalysis winds, temperatures and densities on constant geometric height levels from 0-110 km, registered at 1 s intervals along the flight tracks of all 26 research flights conducted by the NSF/NCAR Gulfstream V (NGV) research aircraft during the Deep Propagating Gravity Wave Experiment (DEEPWAVE). These netCDF files will be archived on the DEEPWAVE data catalog at https://data.eol.ucar.edu/master_list/?project=DEEPWAVE.

Background

DEEPWAVE took place from May-July 2014 from an operating base in Christchurch, New Zealand (Fritts et al. 2016). While DEEPWAVE was supported by a suite of global and regional numerical weather prediction (NWP) modeling and analysis capabilities (Fritts et al. 2016; Gisinger et al. 2017), both the operational analysis and scientific reanalysis fields issued by these and other systems extended only to ~60-80 km altitude. Yet many of the most spectacular gravity wave outbreaks observed from the NGV during DEEPWAVE were provided by the onboard Advanced Mesospheric Temperature Mapper (AMTM) and Na lidar, which observed the mesosphere and lower thermosphere (MLT) from ~80-100 km altitude (Bossert et al. 2015; Pautet et al. 2016; Eckermann et al. 2016; Broutman et al. 2017; Bossert et al. 2018; Fritts et al. 2018). Modeling the MLT gravity waves observed by these sensors requires knowledge of background winds, temperatures, stability and densities from the ground to the MLT. Thus the analysis gap above ~60-80 km altitude limits the available information on background winds, temperatures and densities for modeling waves in this critical MLT region. Deep gravity-wave dynamics as observed from the NGV need to be accurately modeled for the improved scientific understanding that was the prime driver of DEEPWAVE.

High-Altitude NAVGEM Reanalysis

To address this reanalysis gap for DEEPWAVE science, the U.S. Naval Research Laboratory (NRL) has created a high-altitude (HA) configuration of the Navy Global Environmental Model (NAVGEM) that extends to ~116 km in pressure altitude. This HA NAVGEM system was operated in a series of different configurations to provide high-altitude global atmospheric meteorological reanalysis fields for DEEPWAVE. A particular emphasis was to provide reanalysis fields from the ground through the MLT to ~100 km altitude, having sufficient accuracy and quality to be used as reliable atmospheric backgrounds for scientific research studies, particularly as backgrounds for high-resolution modeling of MLT gravity waves observed from the NGV and ground-based sites during DEEPWAVE.

Eckermann et al. (2018) provide a detailed description of this HA NAVGEM configuration, the reanalysis experiments that were performed using this system, the amount and types of observational data that were assimilated (including satellite MLT observations), comparisons of the MLT reanalysis fields to independent MLT wind and temperature observations, and preliminary use of these HA reanalyses to study aspects of the deep planetary-wave dynamics that occurred in the greater New Zealand region during DEEPWAVE.

NAVGEM Reanalysis Along NGV Flight Tracks

Choice of and Rationale for File Content

HA NAVGEM reanalyses have been used in a series of published studies to define the background winds, temperatures and densities within the MLT, through which the MLT gravity waves observed from the NGV propagated and evolved (Eckermann et al. 2016; Broutman et al. 2017; Bossert et al. 2018; Fritts et al. 2018). In most of these studies, it has proven most useful to issue these fields on a regular geometric height grid, to facilitate use of these fields and backgrounds for high-resolution regional models of gravity-wave dynamics.

Eckermann et al. (2018) performed 4 different HA reanalysis experiments using NAVGEM, including a purely four-dimensional variational (4DVAR) data assimilation (DA) run using static background error covariances, and a so-called hybrid-4DVAR run in which static error covariances were linearly blended with a flow covariance derived from correlations among an 80-member ensemble of forecasts at the inner-loop resolution. Eckermann et al. (2018) reported significant improvements in hybrid-4DVAR reanalysis skill in the MLT relative to 4DVAR. Note that Kuhl et al. (2013) also reported improvements in tropospheric and stratospheric analysis skill of hybrid 4DVAR analyses relative to 4DVAR.

Based on the findings summarized above, the following choices were made for our base distribution of reanalysis data along NGV flight tracks for the DEEPWAVE data catalog in this version 1.1 data release:

1. we provide results from the hybrid-4DVAR reanalysis only, with reanalysis results from the high-resolution (T425L74) and low-resolution (T119L74) runs provided in separate files
2. we provide the reanalysis on a regular geometric height grid of 111 equispaced levels, extending from the ground (mean sea-level pressure) to ~110 km altitude, at a constant 1 km vertical resolution
3. we issue reanalyzed zonal winds, meridional winds, temperatures and densities on the height grid in (2) from the reanalyses in (1), at 1s time intervals along NGV flight tracks

Next we discuss and justify our choices (1)-(3) above in more detail.

Our decision in (1) to provide only the hybrid-4DVAR reanalysis is based on: (a) the superior quality of this reanalysis relative to 4DVAR noted above, as documented in greater detail by Kuhl et al. (2013) and Eckermann et al. (2018), and; (b) an effort to keep the volume and range of different reanalysis data to manageable amounts for scientists wanting a straightforward reliable source of MLT backgrounds for their work. If subsequently needed, however, results from the 4DVAR reanalysis can be provided in future data versions or on request to the NRL PoC.

We decided to issue both low- and high-resolution versions of the hybrid-4DVAR reanalysis, since one or the other may be preferable depending on the research application. For example, the low-resolution hybrid-4DVAR reanalysis performed best in terms of validation with synoptic large-scale MLT backgrounds (see Figs. 10, 11 and 15 of Eckermann et al. 2018) and thus is a good choice as backgrounds for use in high-resolution gravity-wave modeling studies. The high-resolution reanalysis contains explicitly resolved large-scale gravity waves that may augment DEEPWAVE gravity-wave science in other research studies. If subsequently needed, additional types of data at different resolutions can be provided: for example, we have a capability to issue along-track reanalysis after the global reanalysis fields at every grid point have been spatially averaged within an area centered on the model gird point with a specifiable great circle radius. In this way, along-track gravity-wave perturbations can be easily isolated by subtracting the raw along track fields from the averaged along track fields.

Our decision in (2) to provide reanalysis fields on a regular geometric height grid is based on: (a) most NGV remote-sensing observations of gravity waves are registered on geometric height levels, and; (b) most high-resolution gravity-wave-resolving regional models used to understand the dynamics of these gravity waves use a geometric height coordinate (e.g., Eckermann et al. 2016; Heale et al. 2017; Broutman et al. 2017). Geometric height regridding was performed by computing prognostic geometric height fields from the geopotential height fields on the model grid (see Eckermann et al. 2018) and then using those to linearly interpolate winds, temperatures and densities from hybrid sigma-pressure model levels onto a regular geometric height grid. The chosen range for this regular geometric-height grid (0-110 km) often leads to missing data (as flagged using missing data codes in the netCDF files) at the very bottom and top of the range. Missing data at the bottom correspond to subterranean values over high mountainous terrain, while missing data at the top correspond to an underlying thermal structure that leads to the top full model layer at a pressure height of ~110 km being at a geometric height that is <110 km.

The choice of a constant vertical resolution of 1 km for the geometric grid was again based on a convenient choice for modeling studies: for example, an equispaced vertical grid is common in many models and simplifies the calculation of vertical derivatives needed, for example, for key terms in the gravity-wave equations, such as background buoyancy frequencies N, density scale heights H_ρ, and various wind-shear terms in the Scorer parameter. Equispaced vertical grids also simplify interpolation to any other vertical geometric-height grid of choice. Note that this 1 km resolution for the geometric-height grid undersamples the intrinsic vertical resolution of the reanalysis in the troposphere, but oversamples the intrinsic vertical resolution of the reanalysis in the stratosphere and MLT: see Fig. 3b of Eckermann et al. (2018).

It should be noted for future releases that it is straightforward to output these data onto a range of other model levels as well: for example, onto the intrinsic hybrid sigma-pressure L74 model levels, onto constant pressure levels, onto constant geopotential-height levels, or onto constant potential-temperature levels, with arbitrarily specifiable grid ranges and resolutions in each case.

Our decision in (3) to output only zonal winds, meridional winds, temperatures and densities on the height grid in (2) is based on our experience to date that most DEEPWAVE gravity-wave researchers use these HA NAVGEM reanalyses as atmospheric backgrounds for their gravity-wave modeling or theoretical studies. Winds, temperatures, densities and their respective vertical derivatives are the fundamental background parameters controlling gravity-wave dynamics, propagation and breakdown. Other parameters of interest can also be calculated from these base-level fields. For example, pressure can be calculated directly from the density and temperature at each height level using the ideal gas equation and the NAVGEM ideal gas constant of R=287.04 J kg^{-1} K^{-1}. Buoyancy frequency can be calculated using a vertical temperature gradient derived by finite differencing of the temperature profile on the equispaced geometric-height grid. That said, any number of other reanalysis variables can be provided in any future version of these data files, given sufficient demand from the DEEPWAVE science community, or via special request to the NRL PoC. Examples of variables of potential DEEPWAVE relevance that are currently supported by our postanalysis software include (but are not restricted to) vertical velocity, divergence, and Ertel's potential vorticity (EPV).

Interpolation Along Flight Tracks

Latitude and longitude information associated with navigation data files for each NGV flight track are stored on the DEEPWAVE data catalog in a number of different files and variables (UCAR/NCAR EOL 2015). To simplify comparisons with existing analysis data sets, since the ECMWF operational analysis along NGV flight tracks that is currently stored on the data catalog used the so-called "GGLAT" and "GGLON" navigation variables (Dörnbrack 2014), we use the same navigation variables to define the NGV flight tracks for our NAVGEM along-track interpolation. The GGLON and GGLAT navigation data come from an onboard Global Positioning System (GPS) sensor on the NGV, which was updated in real time using OmniStar satellite data (Smith et al. 2016). We use the low-resolution 1 s navigation data as our time series for latitude and longitude during each NGV flight for interpolating the NAVGEM reanalysis.

As discussed by Eckermann et al. (2018), the NAVGEM reanalysis is issued at a 1 hr time cadence due to the need to resolve semidiurnal tidal winds in the MLT. This is achieved by splicing in the +1-5 hr outer-loop forecasts between the 6 hr analysis fields. Again, however, additional forms of the analyses along NGV flights can be generated on special request using different time cadences, such as the conventional 6 hr analysis update cycle, or an intermediate 3 hr cadence in which +3 hr forecasts are spliced between the 6 hr analyses (see Eckermann et al. 2018 for examples of each).

When interpolating the HA NAVGEM reanalysis to each DEEPWAVE flight trajectory, we first interpolated the global reanalysis fields from model levels onto the regular grid of 111 geometric height levels from 0-110 km. Next we identified the start and end times of the flight in question, then located all 1 hr global reanalysis fields that were located within this flight-time window, as well as the two end times that were located just outside of the start and end of the flight window, all of which are required for time interpolation of the reanalysis data to the flight track times. Finally, for every point along the flight track, the 1 hr reanalysis data were linearly interpolated at all 111 geometric heights to the precise time, longitude and latitude of that point along the flight track, as defined by the navigation variables *Time*, *GGLON* and *GGLAT*, respectively (see below).

Data Files

Format and Naming Convention

The resulting data files are written using the network common data format (netCDF) version 4. The file naming convention of our base release for the data catalog is as follows:

navgemZL111_gsarHHHkm_T**xxxx**L074-hybrid4dvar_rf**nn_YYYYMMDD**.nc

The values shown in blue are the parts of the file name that never change in this version 1.1 release: for example, "navgem" is the NWP system, "ZL111" refers to output on a constant geometric-height grid of 111 levels extending from 0-110 km, "L074" refers to the model levels used for the NAVGEM runs (see Fig. 3 of Eckermann et al. 2018), "hybrid4dvar" refers to the hybrid 4DVAR DA algorithm used to generate these fields, and the file appellation ".nc" signifies that these are files saved using the netCDF format.

The value shown in green is an optional filename parameter that does not appear in the default versions of these files. At present there is only one such optional filename parameter: "gsar" stands for "great circle averaging radius," and indicates that the analysis value at this location is the mean value of all analysis values at this location averaged within a circle, centered on the longitude-latitude point with a radius as indicated by the value in kilometers supplied immediately after it. When no great-circle averaging is applied, as is the default, then this part of the filename is absent.

The values shown in red change from file to file. They are:

- Txxxx: this identifies the triangular spectral wavenumber truncation of the outer loop of the analysis run in question. There are only two options: T0119, corresponding to around 1^ox1^o resolution on the quadratic Gaussian grid, and T0425, which, given the use of a reduced Gaussian grid in this case, varies in longitude resolution from location to location but corresponds to around 0.38^ox0.28^o in longitude-latitude resolution at ~45^oS.
- rfnn_YYYYMMDD: this identifies the DEEPWAVE NGV research flight, along whose trajectory the NAVGEM reanalysis fields are interpolated: nn is the research flight number and ranges from 01 to 26; YYYYMMDD is the corresponding date of this research flight, where YYYY is the year, MM is the month, and DD is the day – thus rf23_20140714 corresponds to DEEPWAVE research flight No. 23, which occurred on 14 July 2014.
- gsarHHHkm: this identifies a great circle averaging radius of HHH kilometers, which is applied to all the the analysis fields at each height at every longitude-latitude point in the file. This further "smooths" the profile by removing any small-scale resolved gravity waves in the reanalysis.

Data File Contents

Global Attributes

- *Creation_Date*: date the file was created by the PoC at NRL
- *Version_Number*: version number of this data release, currently at v1.1
- *OuterLoopResolution*: the outer-loop resolution of this reanalysis, one of either T0119L074 or T0425L074 (see Eckermann et al. 2018)
- *InnerLoopResolution*: the inner-loop resolution of this reanalysis, one of either T0047L074 or T0119L074 (see Eckermann et al. 2018)
- *DataAssimilationMethod*: the data assimilation method, one of either hybrid 4DVAR or 4DVAR
- *PointOfContact*: the NRL PoC for questions or issues (Steve Eckermann: stephen.eckermann@nrl.navy.mil)

Dimensions

0. *t*: the time dimension for each flight. The number of time points varies from flight to flight, depending on the duration of the flight, given a constant 1 s time cadence of the time series
1. *z*: the geometric height dimension. The number of points is always 111, and the vertical resolution is a constant of 1000 m (1 km).

Variables

- *Time*: [1D *t* series]: UTC seconds along the flight track
- *GGLON*: [1D *t* series]:GPS longitude along the flight track
- *GGLAT*: [1D *t* series]: GPS latitude along the flight track
- *GeometricHeight*: [1D *z* series]: geometric heights in meters[1]
- *ZonalWind*: [2D *t,z* series]: reanalyzed zonal winds ($m\ s^{-1}$) along the flight track
- *MeridionalWind*: [2D *t,z* series]: reanalyzed meridional winds ($m\ s^{-1}$) along the flight track
- *Temperature*: [2D *t,z* series]: reanalyzed temperatures (K) along the flight track
- *Density*: [2D *t,z* series]: reanalyzed atmospheric densities ($kg\ m^{-3}$) along the flight track

Missing Data Codes

Each variable above has its own missing data field that can be accessed from the netCDF file by interrogating the "*_FillValue*" attribute of the variable in question. The fill values for the NGV navigation data are unchanged from those in the original files provided by NCAR EOL on the DEEPWAVE catalog, which are typically set to -32767. For the two-dimensional NAVGEM reanalysis variables cited above, the value used to flag missing data is -99999.0. As explained earlier, missing data can occur in the reanalysis near the bottom and top of the geometric height range.

Sample Results

The plots at the end of this document show temperature results for all 26 DEEPWAVE NGV research flights. For each flight, four panels, labeled (a)-(d), plot temperatures as a function of geometric height (20-100 km) and time (in UTC hours) along the flight track. Considering each panel in turn, these panels plot:

(a) stratospheric temperatures from ~30-60 km altitude as measured onboard the NGV by the Rayleigh lidar (Williams 2015);
(b) HA NAVGEM reanalysis temperatures from the T119L74 hybrid-4DVAR reanalysis experiment (Eckermann et al. 2018) using the data in these version 1.1 files without any great-circle averaging applied;
(c) HA NAVGEM reanalysis temperatures from the T425L74 hybrid-4DVAR reanalysis experiment (Eckermann et al. 2018) using the data in these version 1.1 files without any great-circle averaging applied;
(d) operational ECMWF analysis temperatures from the T1279L137 Integrated Forecast System (IFS) configuration that was operational at the time of the DEEPWAVE deployment (Dörnbrack 2014). These analyses, provided on model levels along each flight track by Dörnbrack (2014), were reinterpolated to geometric heights using the prognostic geopotential height and model terrain height fields contained within the files on the DEEPWAVE data catalog.

[1] Note that the lowest (surface) level is set to 20 m rather than 0 m to avoid an ocean-atmosphere discontinuity in the interpolation method from model levels to geometric height levels: this value can be reset to 0 m in practice.

Usage Conditions

Any use of these data in scientific publications will, at a minimum, cite Eckermann et al. (2018) as the fundamental scientific and technical source document for the HA NAVGEM reanalysis. Users are encouraged where/if appropriate to reach out to the NRL PoC for assistance and collaboration in using these data to further their scientific research.

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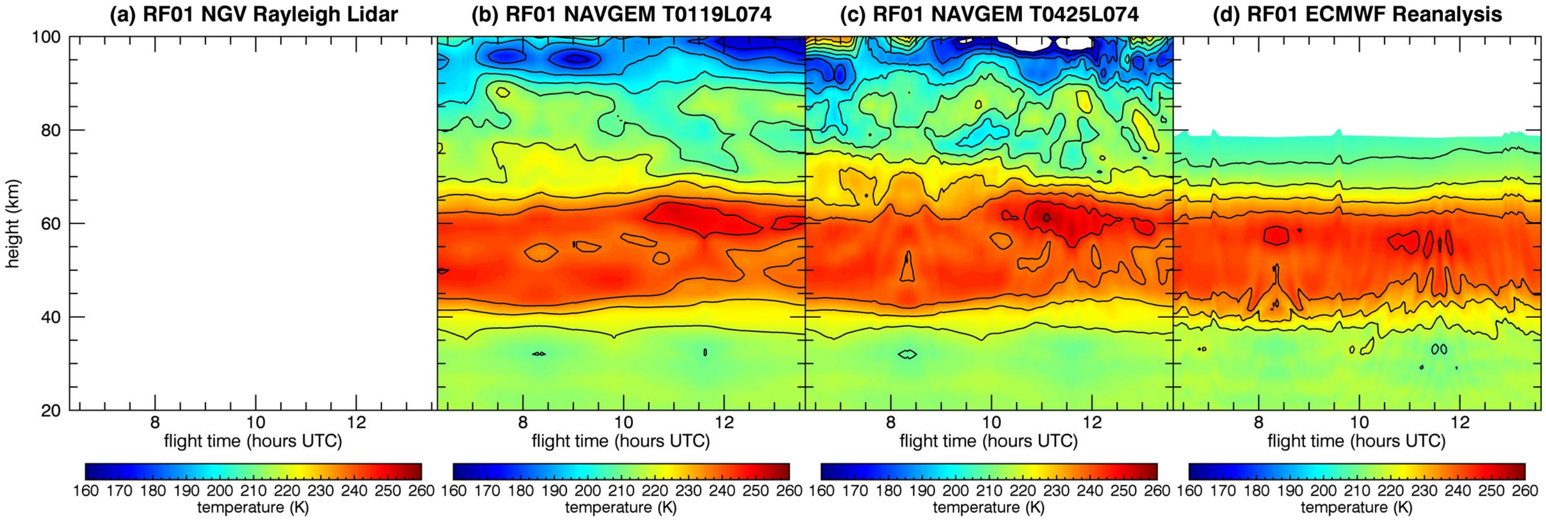
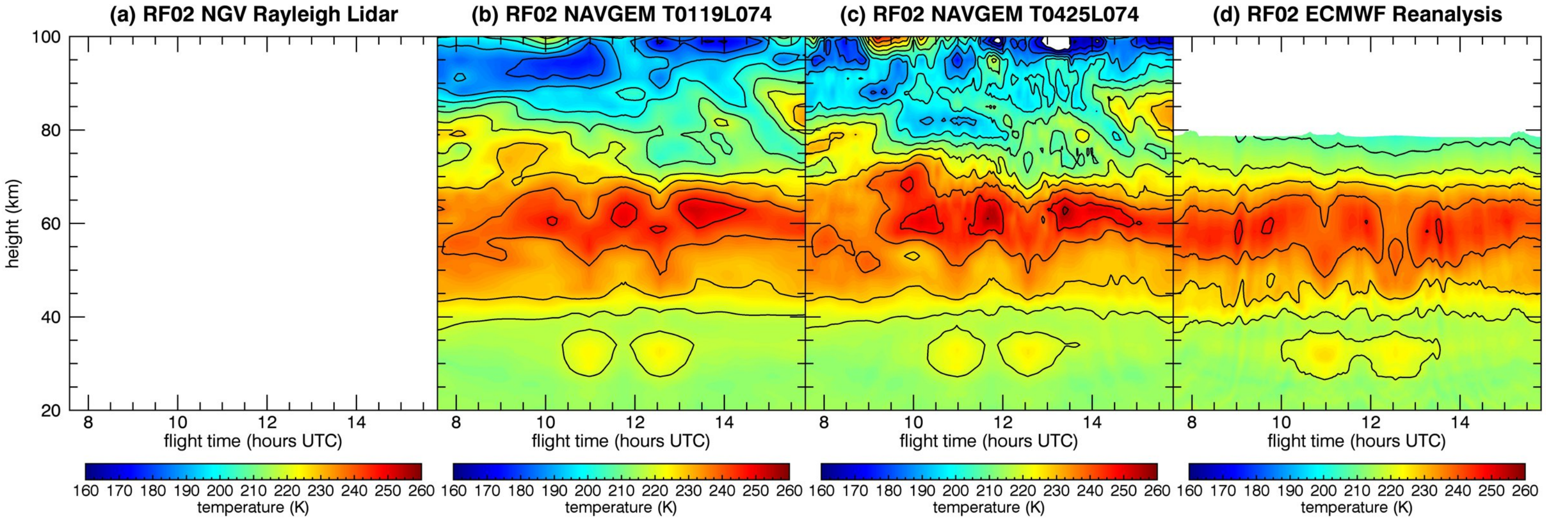


(a) RF01 NGV Rayleigh Lidar
(b) RF01 NAVGEM T0119L074
(c) RF01 NAVGEM T0425L074
(d) RF01 ECMWF Reanalysis
height (km)
100
80
60
40
20
8
10
12
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260
temperature (K)



(a) RF02 NGV Rayleigh Lidar
(b) RF02 NAVGEM T0119L074
(c) RF02 NAVGEM T0425L074
(d) RF02 ECMWF Reanalysis
height (km)
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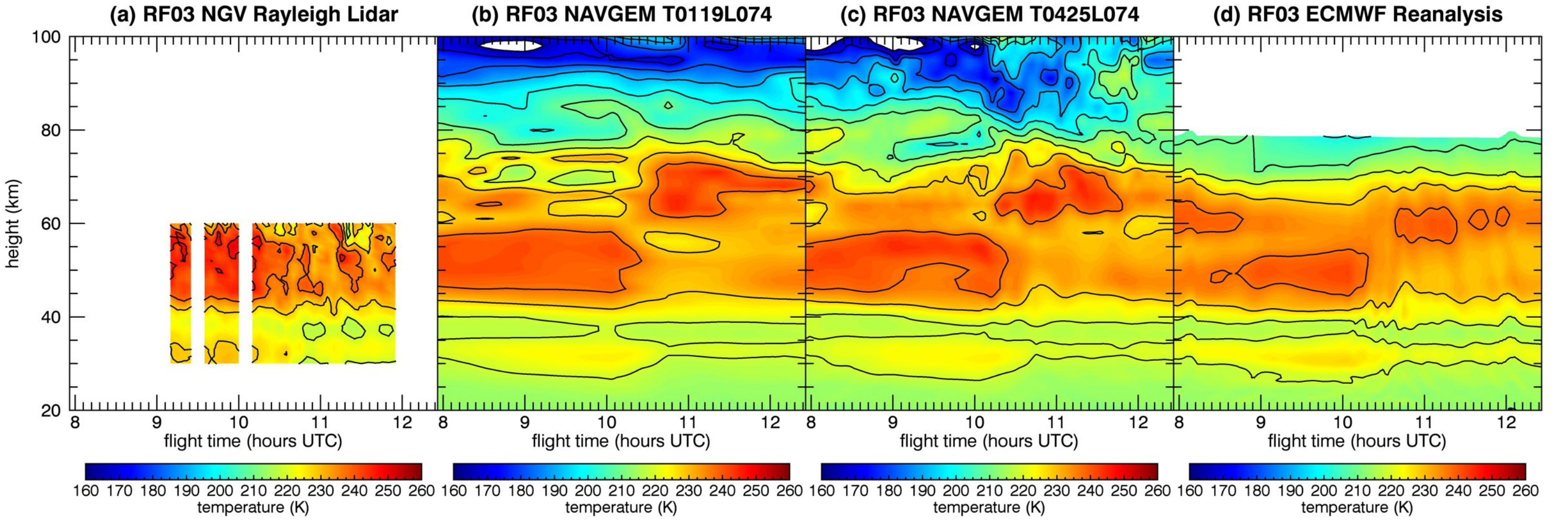
80
60
40
20
8
10
12
14
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260
temperature (K)



(a) RF03 NGV Rayleigh Lidar
(b) RF03 NAVGEM T0119L074
(c) RF03 NAVGEM T0425L074
(d) RF03 ECMWF Reanalysis
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80
100
8
9
10
11
12
flight time (hours UTC)
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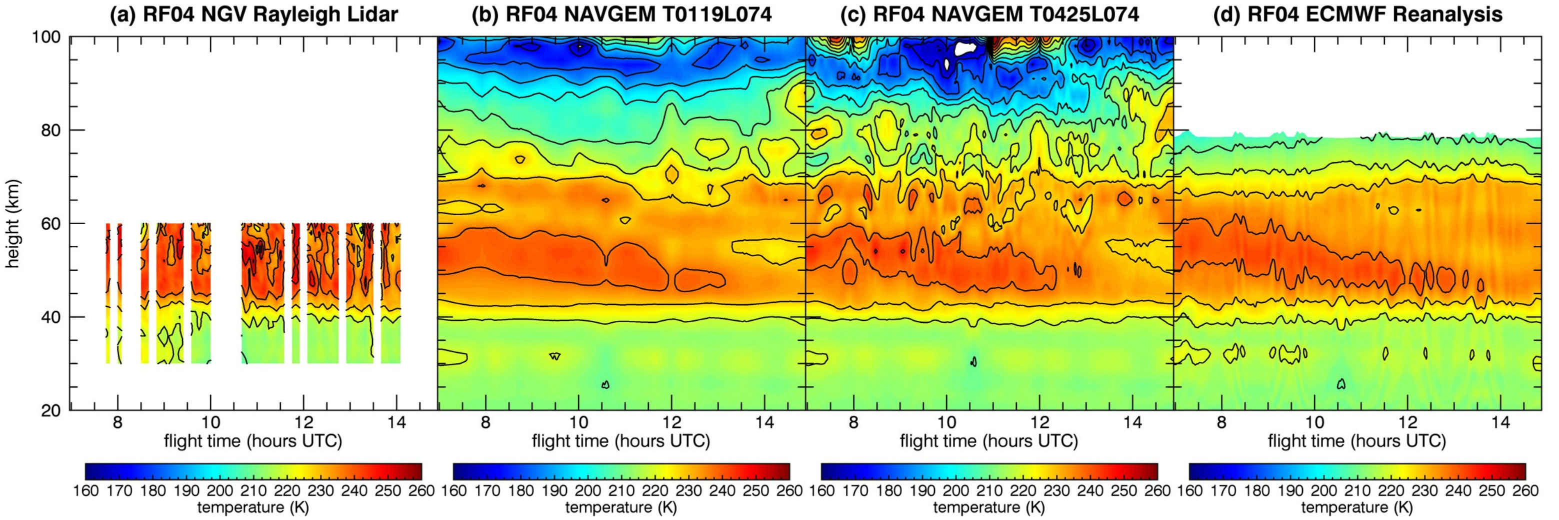
temperature (K)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(b) RF04 NAVGEM T0119L074
(c) RF04 NAVGEM T0425L074
(d) RF04 ECMWF Reanalysis
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flight time (hours UTC)
8
10
12
14
temperature (K)
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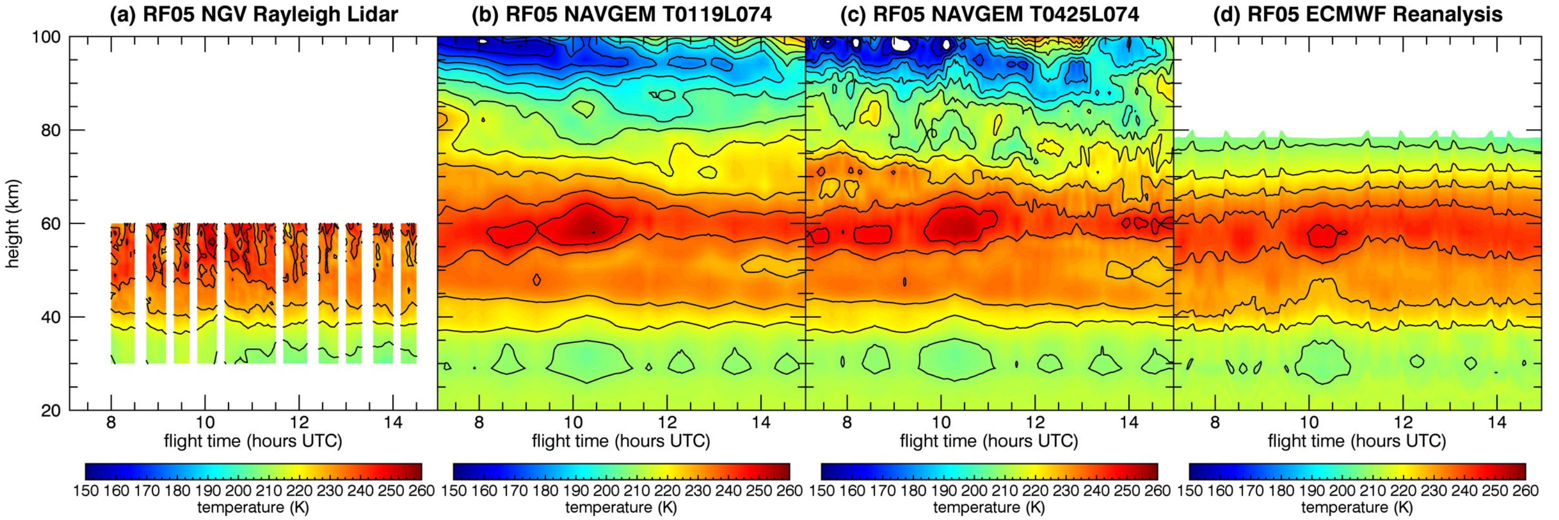

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(b) RF05 NAVGEM T0119L074
(c) RF05 NAVGEM T0425L074
(d) RF05 ECMWF Reanalysis
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flight time (hours UTC)
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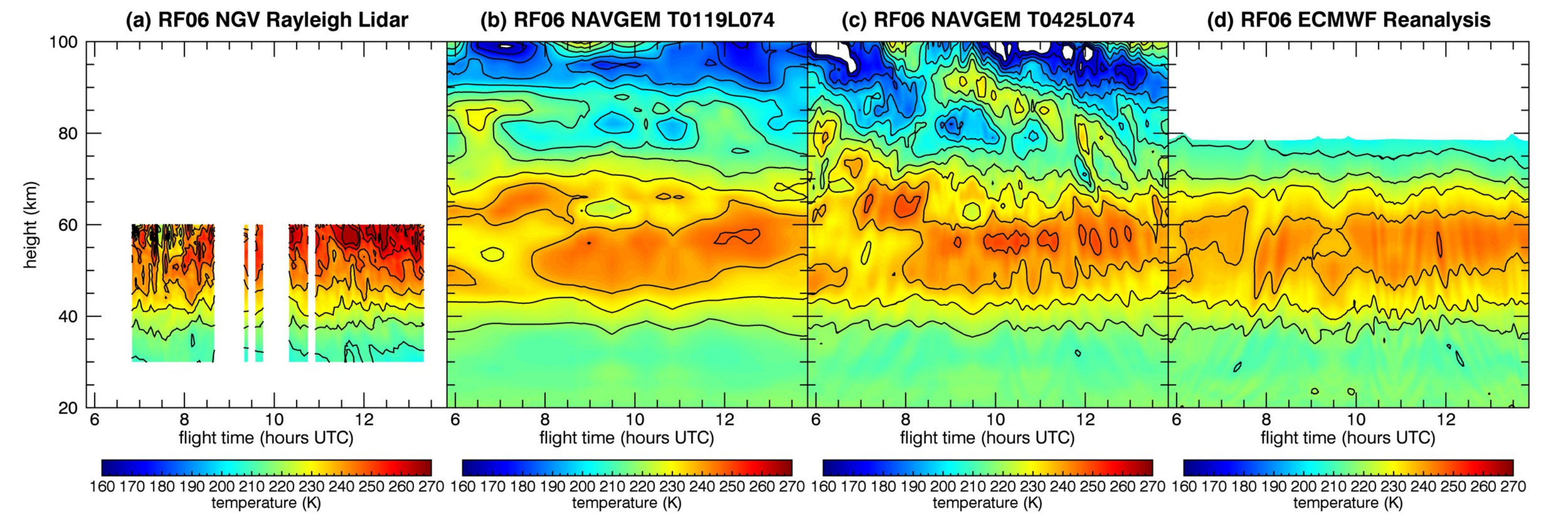
temperature (K)



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(b) RF06 NAVGEM T0119L074
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(d) RF06 ECMWF Reanalysis
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flight time (hours UTC)
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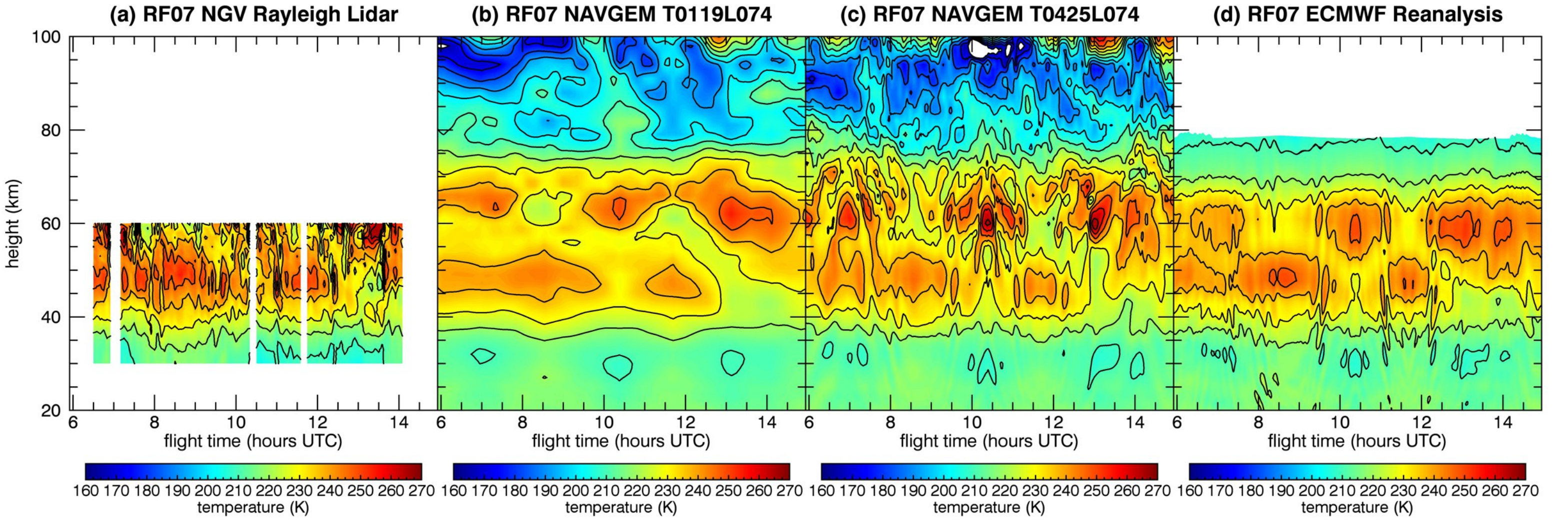
temperature (K)


(a) RF07 NGV Rayleigh Lidar
(b) RF07 NAVGEM T0119L074
(c) RF07 NAVGEM T0425L074
(d) RF07 ECMWF Reanalysis
height (km)
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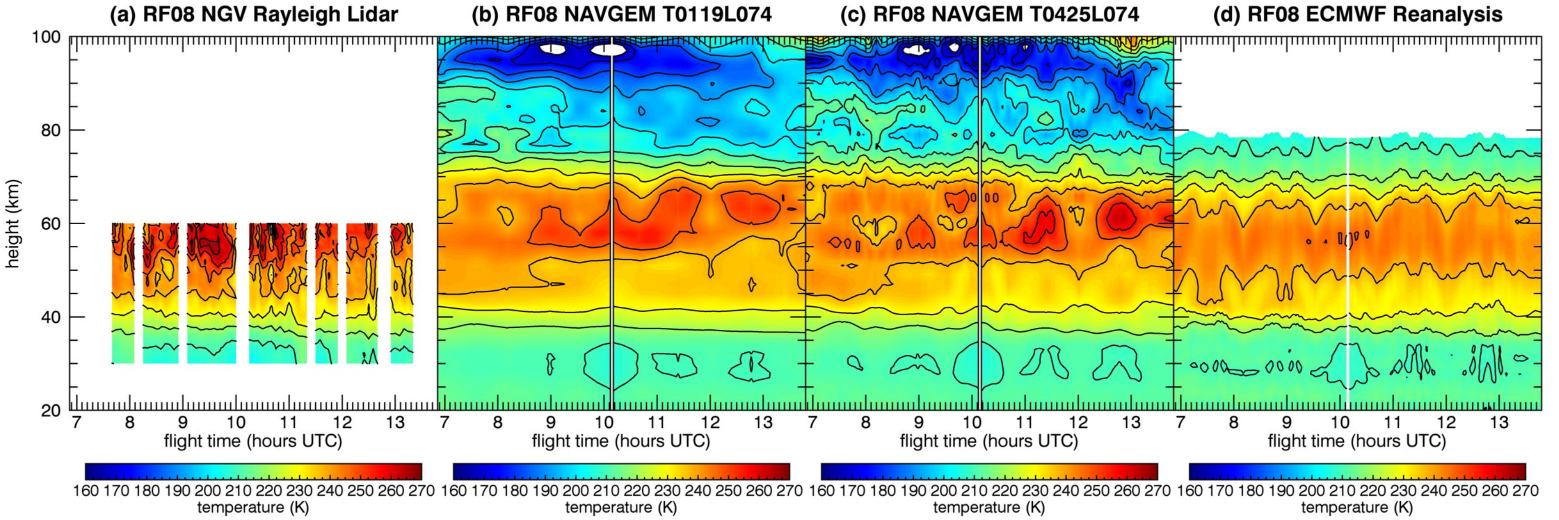
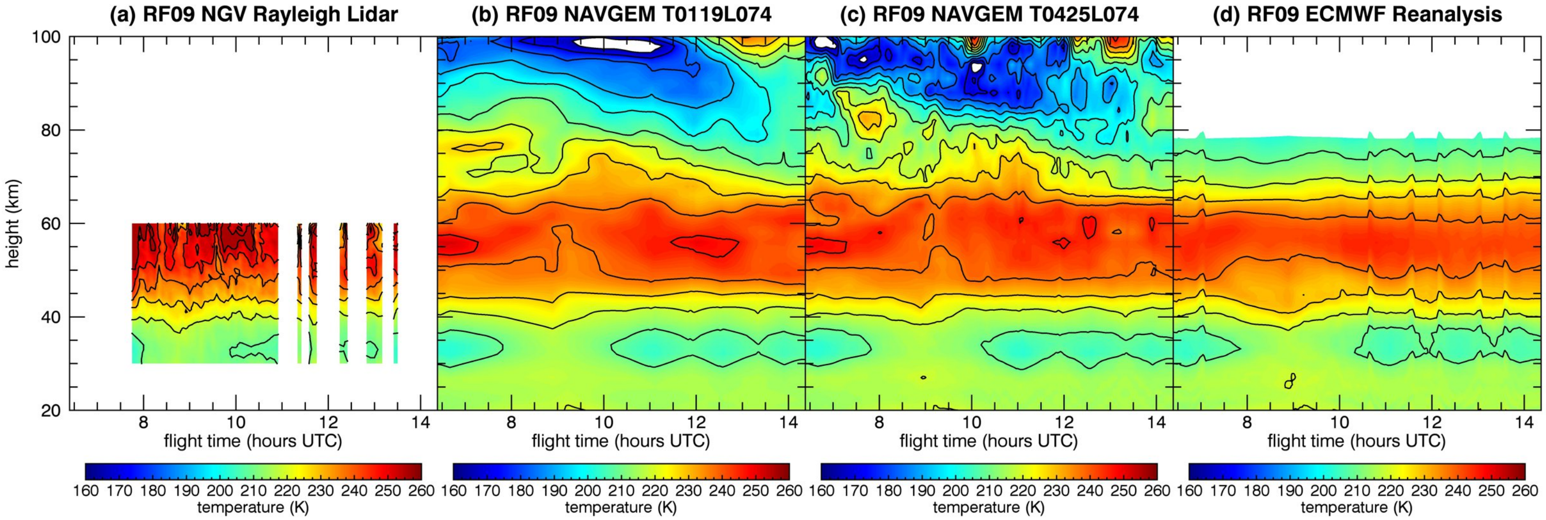
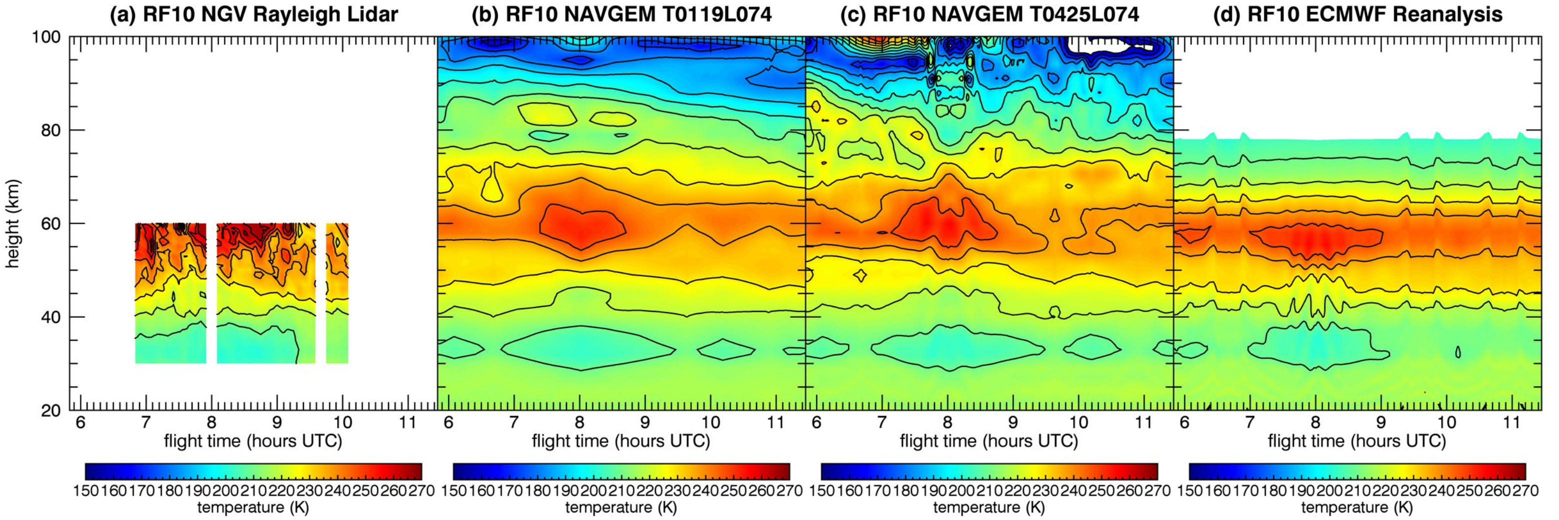
80
60
40
20
6 8 10 12 14
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260 270
temperature (K)



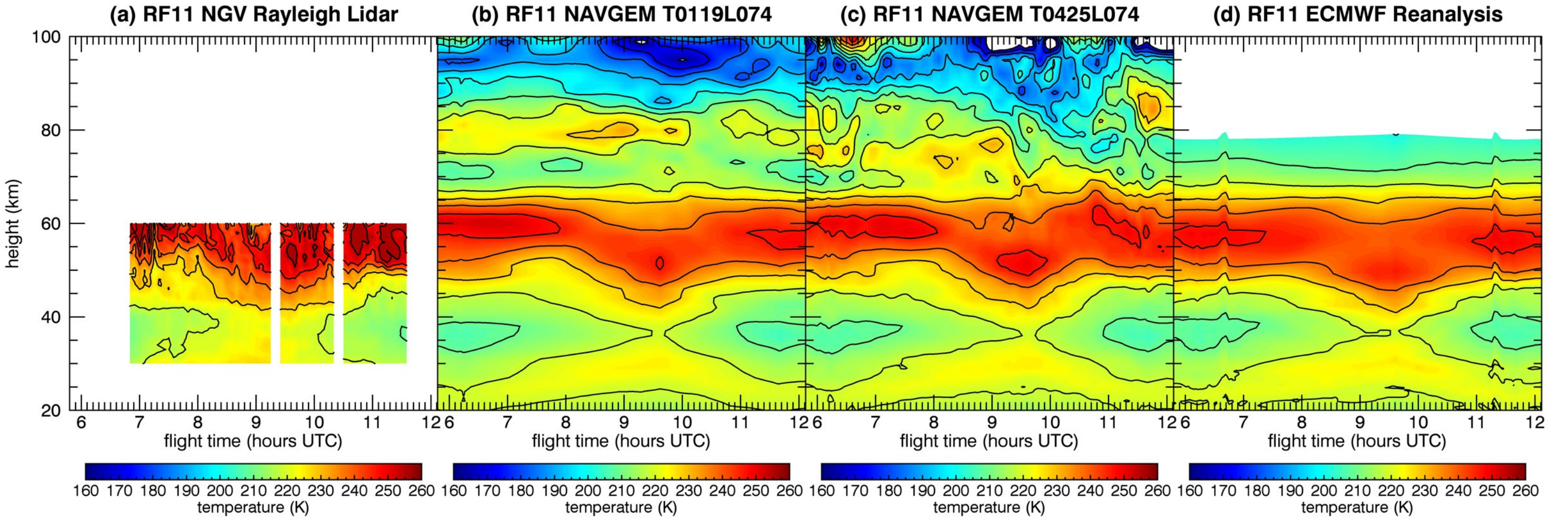
(a) RF08 NGV Rayleigh Lidar
(b) RF08 NAVGEM T0119L074
(c) RF08 NAVGEM T0425L074
(d) RF08 ECMWF Reanalysis
height (km)
20
40
60
80
100
7 8 9 10 11 12 13
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260 270
temperature (K)

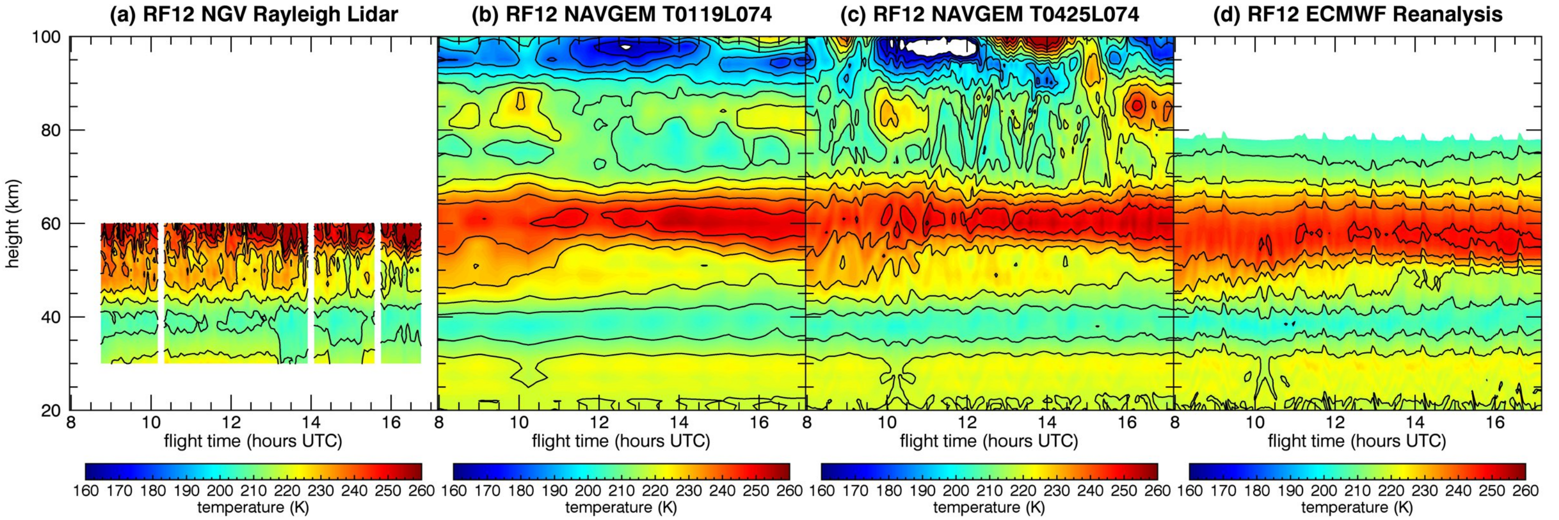


(a) RF09 NGV Rayleigh Lidar
(b) RF09 NAVGEM T0119L074
(c) RF09 NAVGEM T0425L074
(d) RF09 ECMWF Reanalysis
height (km)
100
80
60
40
20
8
10
12
14
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260
temperature (K)

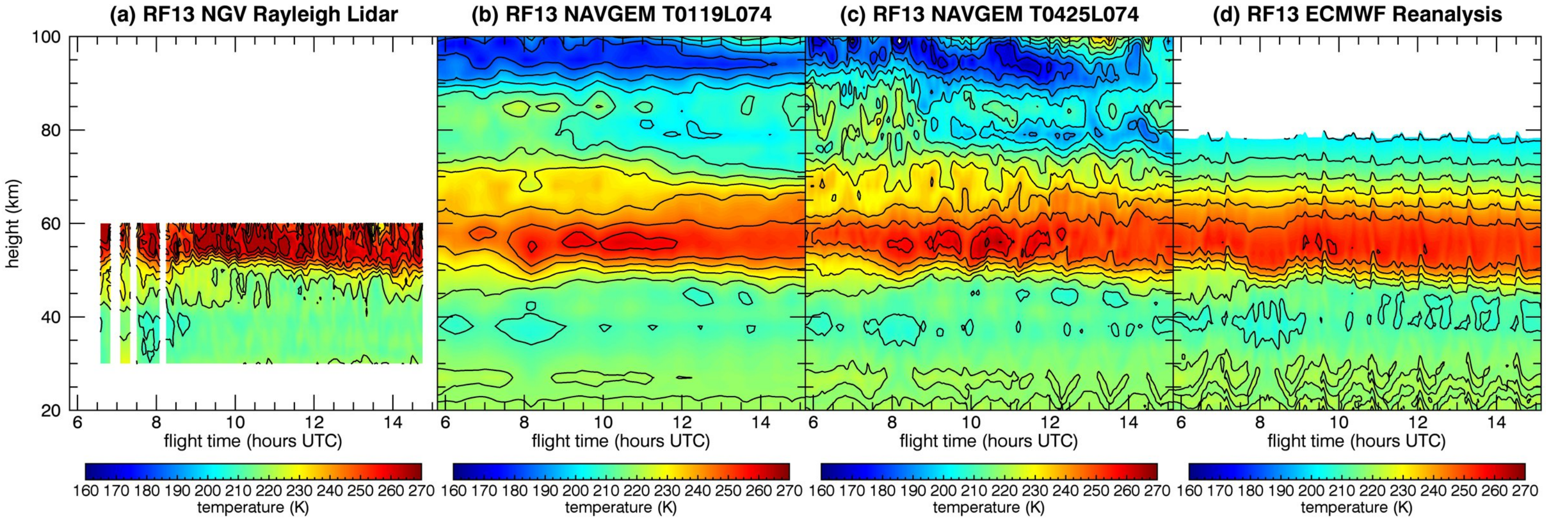


(a) RF10 NGV Rayleigh Lidar
(b) RF10 NAVGEM T0119L074
(c) RF10 NAVGEM T0425L074
(d) RF10 ECMWF Reanalysis
height (km)
20
40
60
80
100
6
7
8
9
10
11
flight time (hours UTC)
150 160 170 180 190 200 210 220 230 240 250 260 270
temperature (K)

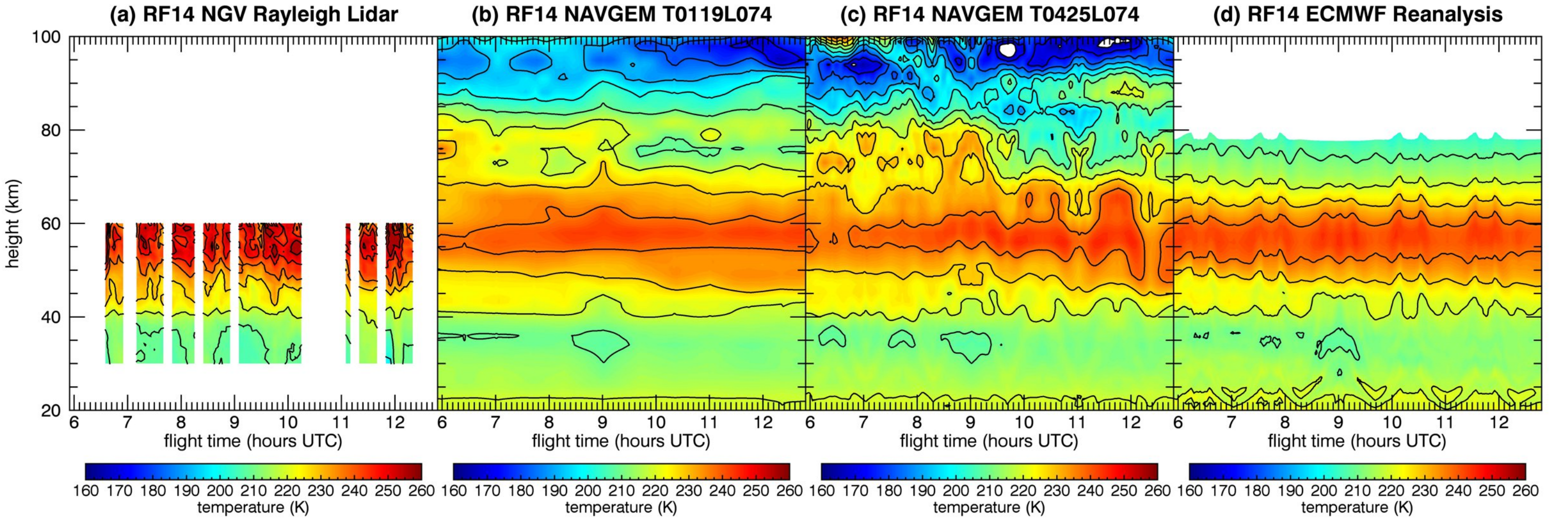

(a) RF11 NGV Rayleigh Lidar
(b) RF11 NAVGEM T0119L074
(c) RF11 NAVGEM T0425L074
(d) RF11 ECMWF Reanalysis
height (km)
100
80
60
40
20
6 7 8 9 10 11 12
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260
temperature (K)

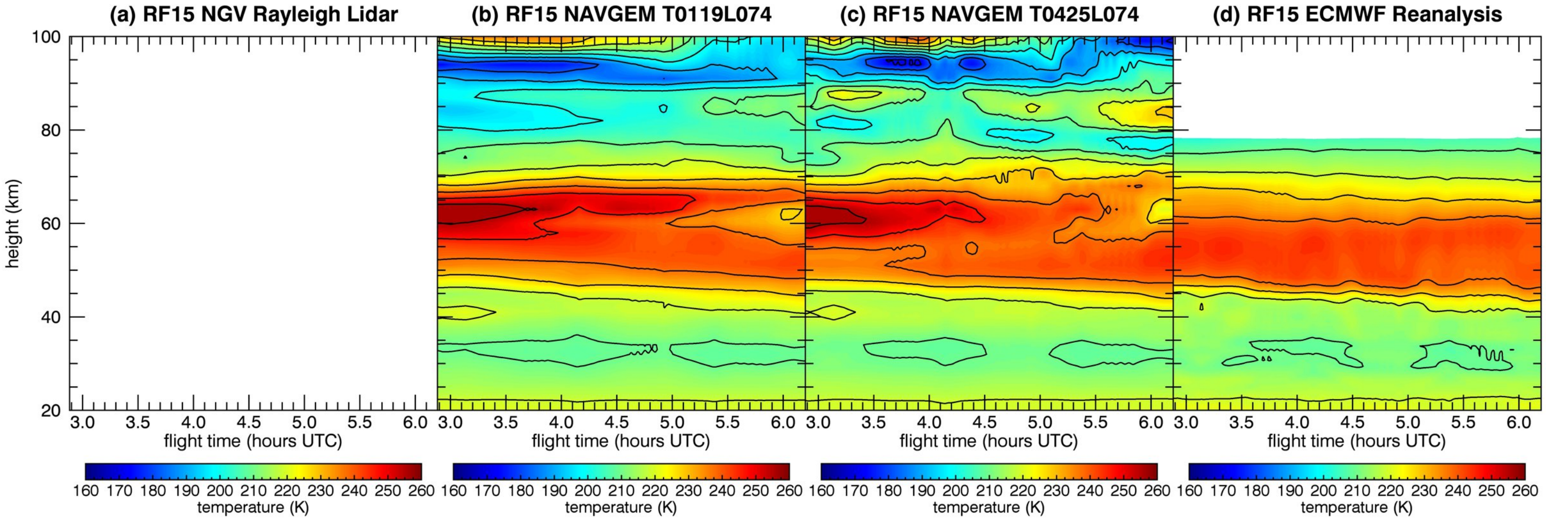


(a) RF12 NGV Rayleigh Lidar
(b) RF12 NAVGEM T0119L074
(c) RF12 NAVGEM T0425L074
(d) RF12 ECMWF Reanalysis
height (km)
20
40
60
80
100
8
10
12
14
16
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260
temperature (K)

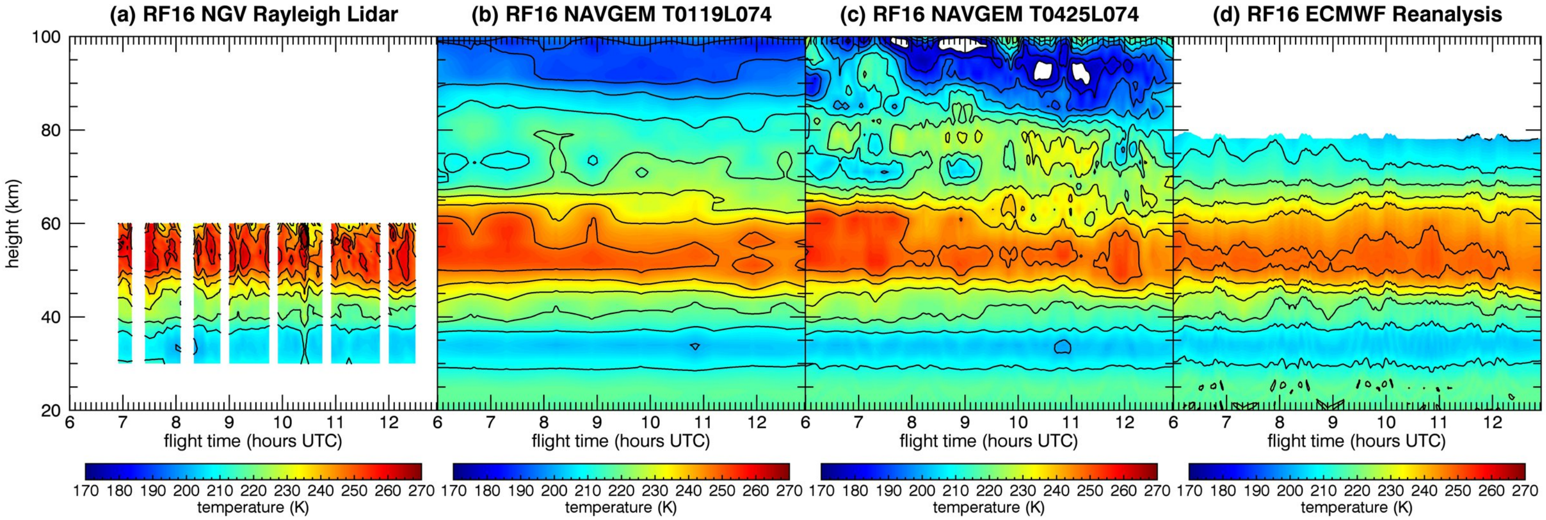


(a) RF13 NGV Rayleigh Lidar
(b) RF13 NAVGEM T0119L074
(c) RF13 NAVGEM T0425L074
(d) RF13 ECMWF Reanalysis
height (km)
100
80
60
40
20
6
8
10
12
14
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260 270
temperature (K)

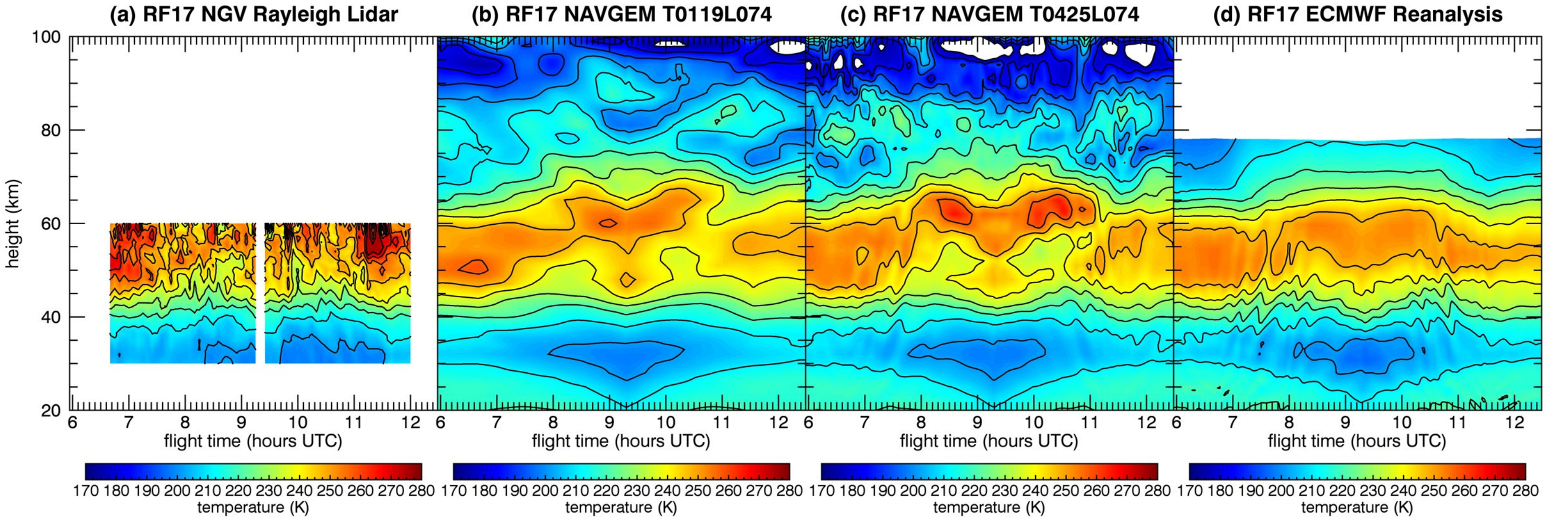

(a) RF14 NGV Rayleigh Lidar
(b) RF14 NAVGEM T0119L074
(c) RF14 NAVGEM T0425L074
(d) RF14 ECMWF Reanalysis
height (km)
100
80
60
40
20
6 7 8 9 10 11 12
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260
temperature (K)

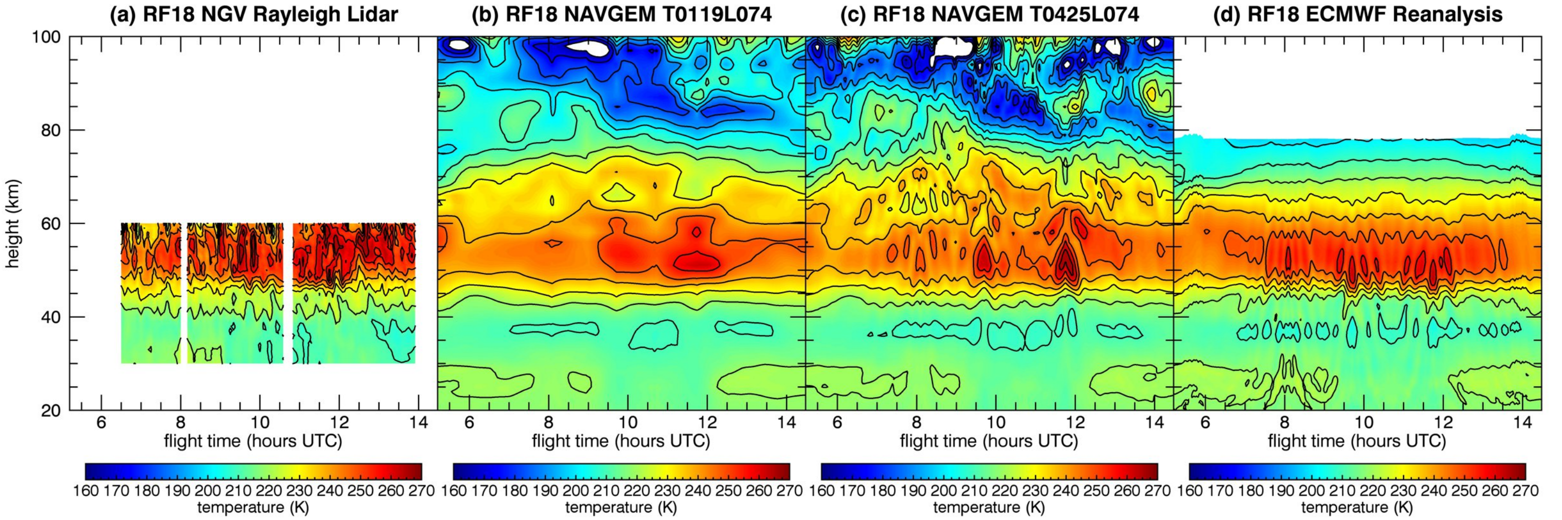


(a) RF15 NGV Rayleigh Lidar
(b) RF15 NAVGEM T0119L074
(c) RF15 NAVGEM T0425L074
(d) RF15 ECMWF Reanalysis
height (km)
20
40
60
80
100
3.0 3.5 4.0 4.5 5.0 5.5 6.0
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260
temperature (K)

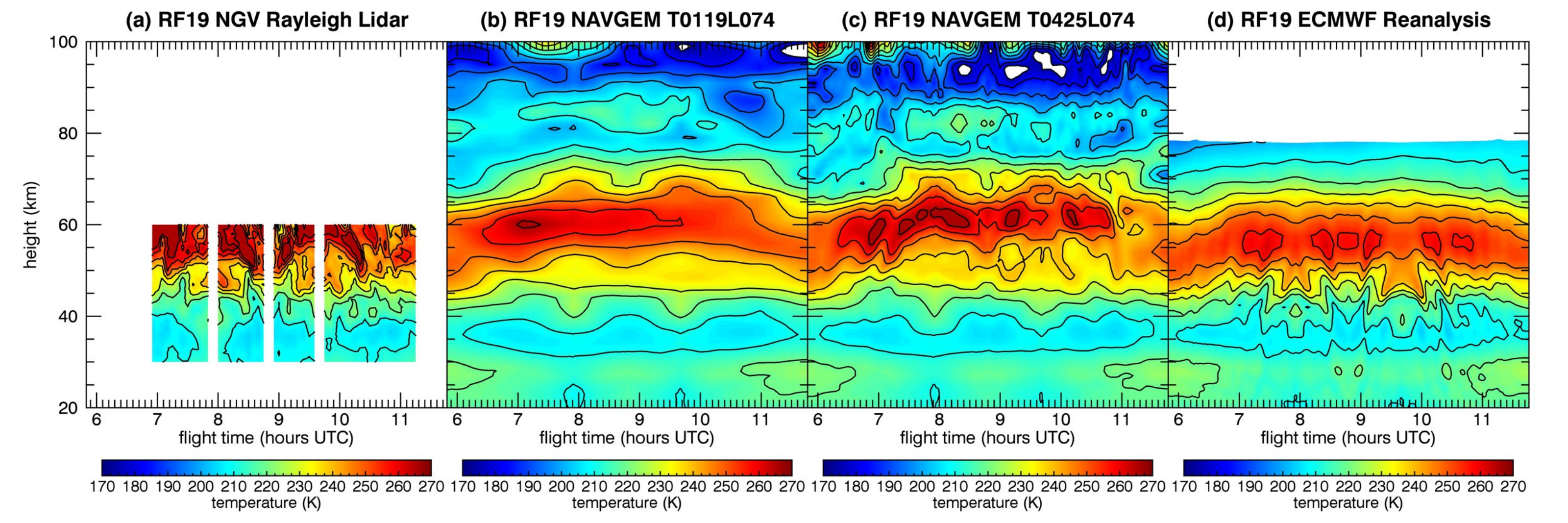


(a) RF16 NGV Rayleigh Lidar
(b) RF16 NAVGEM T0119L074
(c) RF16 NAVGEM T0425L074
(d) RF16 ECMWF Reanalysis
height (km)
20
40
60
80
100
flight time (hours UTC)
6 7 8 9 10 11 12
temperature (K)
170 180 190 200 210 220 230 240 250 260 270

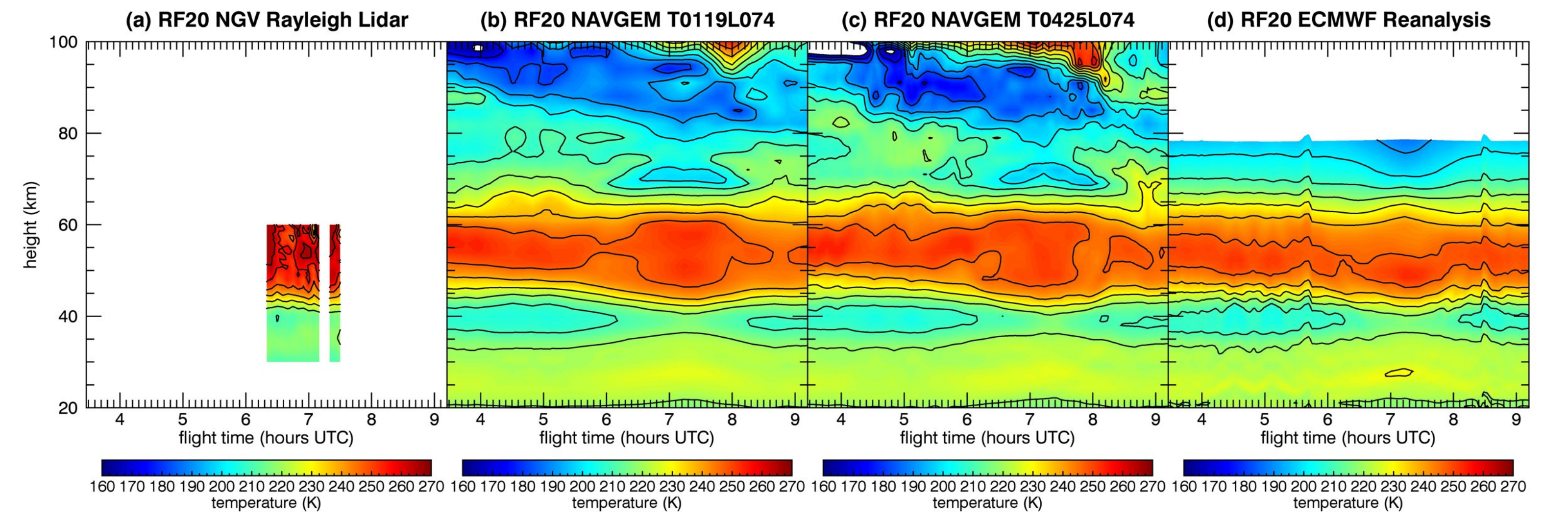

(a) RF17 NGV Rayleigh Lidar
(b) RF17 NAVGEM T0119L074
(c) RF17 NAVGEM T0425L074
(d) RF17 ECMWF Reanalysis
height (km)
20
40
60
80
100
6 7 8 9 10 11 12
flight time (hours UTC)
170 180 190 200 210 220 230 240 250 260 270 280
temperature (K)



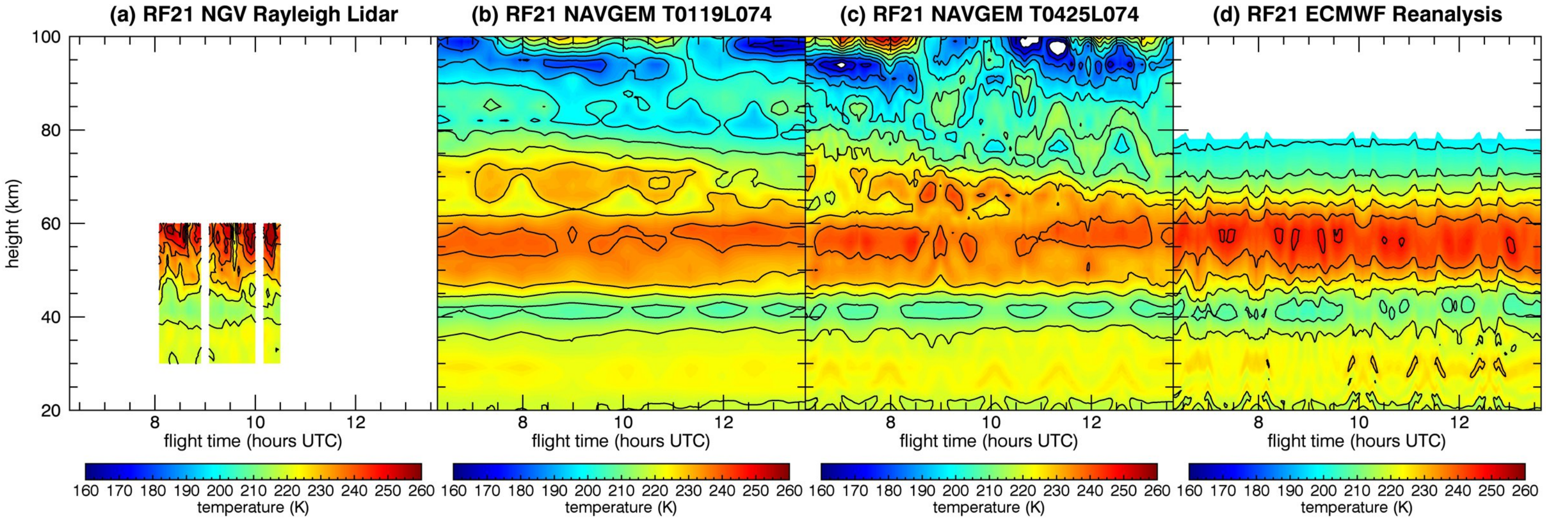
(a) RF18 NGV Rayleigh Lidar
(b) RF18 NAVGEM T0119L074
(c) RF18 NAVGEM T0425L074
(d) RF18 ECMWF Reanalysis
height (km)
20
40
60
80
100
6 8 10 12 14
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260 270
temperature (K)

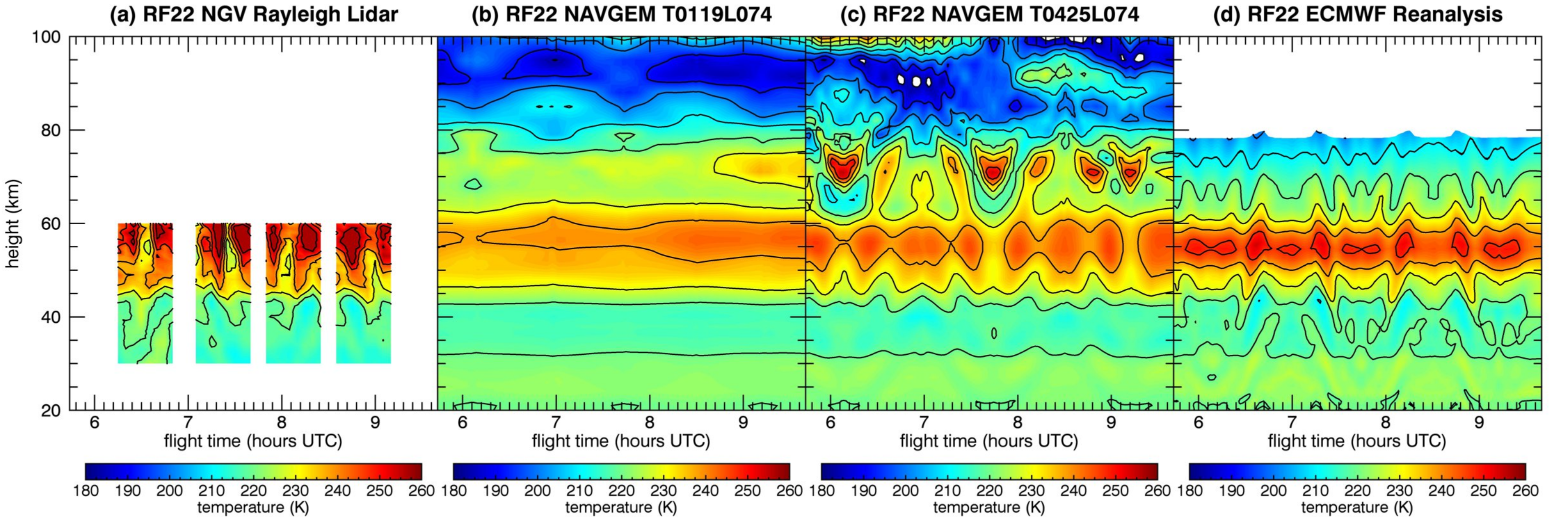


(a) RF19 NGV Rayleigh Lidar
(b) RF19 NAVGEM T0119L074
(c) RF19 NAVGEM T0425L074
(d) RF19 ECMWF Reanalysis
height (km)
20
40
60
80
100
6 7 8 9 10 11
flight time (hours UTC)
170 180 190 200 210 220 230 240 250 260 270
temperature (K)

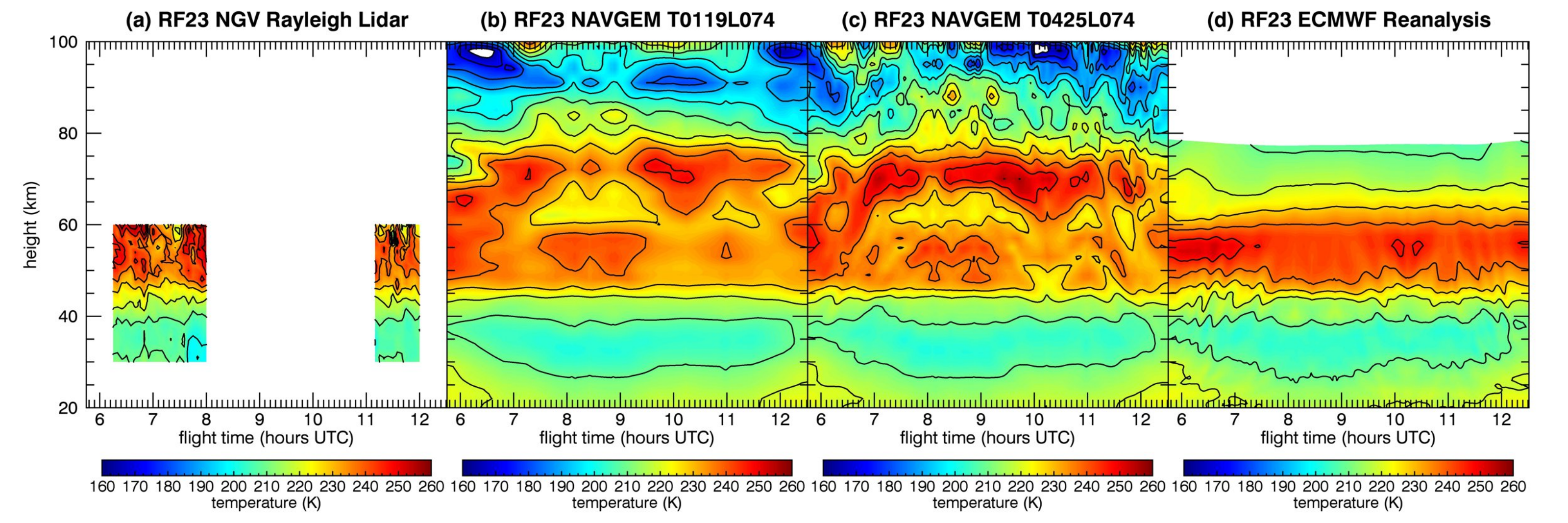


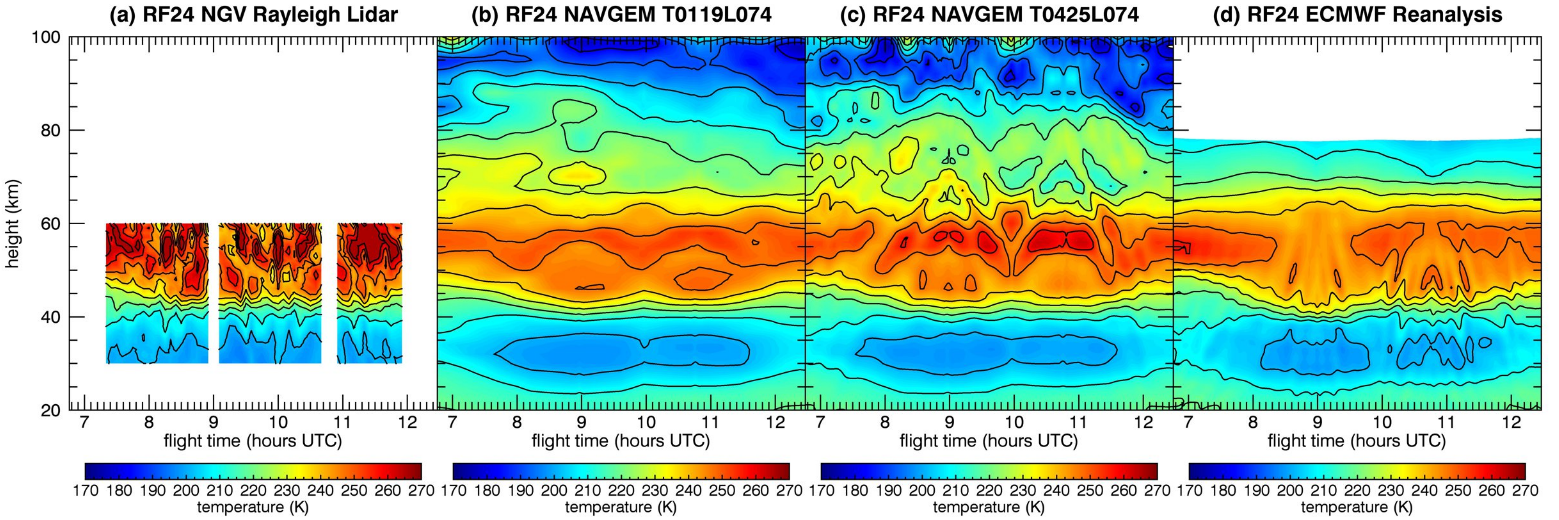
(a) RF20 NGV Rayleigh Lidar
(b) RF20 NAVGEM T0119L074
(c) RF20 NAVGEM T0425L074
(d) RF20 ECMWF Reanalysis
height (km)
20
40
60
80
100
4 5 6 7 8 9
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260 270
temperature (K)


(a) RF21 NGV Rayleigh Lidar
(b) RF21 NAVGEM T0119L074
(c) RF21 NAVGEM T0425L074
(d) RF21 ECMWF Reanalysis
height (km)
20
40
60
80
100
flight time (hours UTC)
8
10
12
160 170 180 190 200 210 220 230 240 250 260
temperature (K)

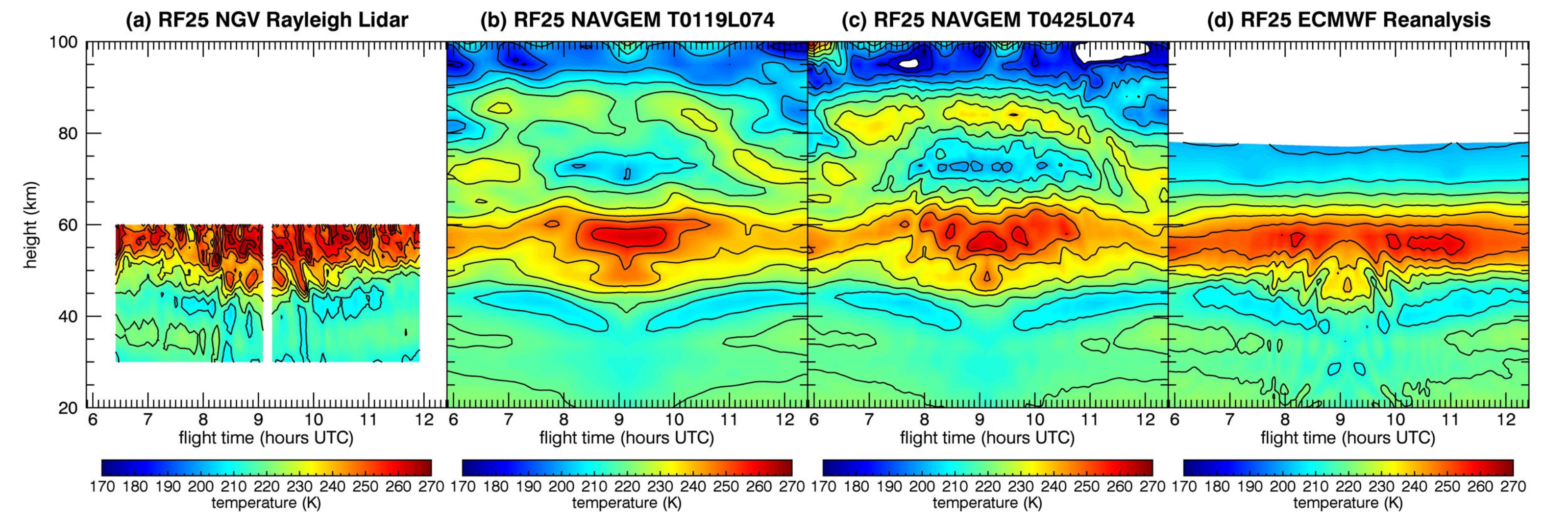


(a) RF22 NGV Rayleigh Lidar
(b) RF22 NAVGEM T0119L074
(c) RF22 NAVGEM T0425L074
(d) RF22 ECMWF Reanalysis
height (km)
20
40
60
80
100
6
7
8
9
flight time (hours UTC)
180
190
200
210
220
230
240
250
260
temperature (K)

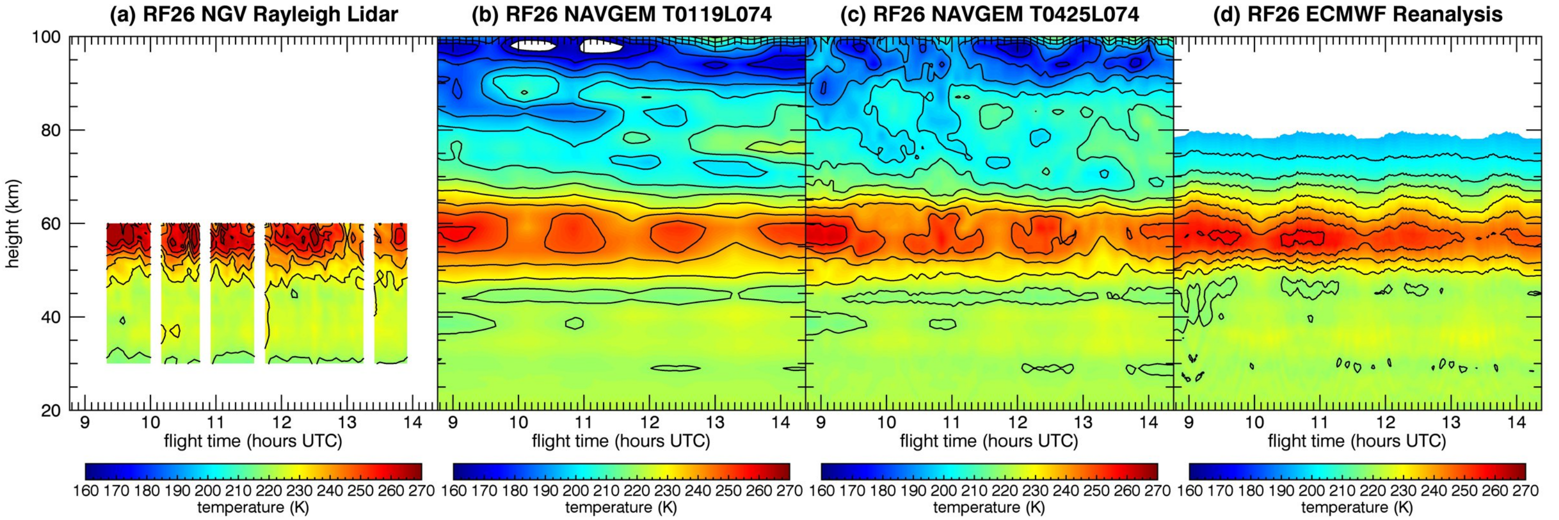

(a) RF23 NGV Rayleigh Lidar
(b) RF23 NAVGEM T0119L074
(c) RF23 NAVGEM T0425L074
(d) RF23 ECMWF Reanalysis
height (km)
20
40
60
80
100
6 7 8 9 10 11 12
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260
temperature (K)



(a) RF24 NGV Rayleigh Lidar
(b) RF24 NAVGEM T0119L074
(c) RF24 NAVGEM T0425L074
(d) RF24 ECMWF Reanalysis
height (km)
20
40
60
80
100
7
8
9
10
11
12
flight time (hours UTC)
170 180 190 200 210 220 230 240 250 260 270
temperature (K)



(a) RF25 NGV Rayleigh Lidar
(b) RF25 NAVGEM T0119L074
(c) RF25 NAVGEM T0425L074
(d) RF25 ECMWF Reanalysis
height (km)
20
40
60
80
100
flight time (hours UTC)
6 7 8 9 10 11 12
temperature (K)
170 180 190 200 210 220 230 240 250 260 270



(a) RF26 NGV Rayleigh Lidar
(b) RF26 NAVGEM T0119L074
(c) RF26 NAVGEM T0425L074
(d) RF26 ECMWF Reanalysis
height (km)
100
80
60
40
20
9 10 11 12 13 14
flight time (hours UTC)
160 170 180 190 200 210 220 230 240 250 260 270
temperature (K)