cast? Save an image, zoomed in on the southeastern United States. Recalling that PV is conserved for adiabatic, frictionless flow, **what physical processes might be contributing to the development of this lower-tropospheric cyclonic PV anomaly?**

b) **Open the LMT_5.3_PV2 bundle**. Examine this analysis valid at 0000 UTC 25 January. **Compare and contrast this to the corresponding forecast fields from a) above, and speculate as to what physical processes could have led to the differences that you observe between the forecast and analysis**. As before, **save an image, and juxtapose it with your image from the 24-h forecast valid at the same time (from exercise 5.2. a) iv.)**. Given the physical process you identified above, **what meteorological fields or data sources might have been helpful to forecasters during this event?**

5.4. Tendencies Comprising the Thermal Budget of a Midlatitude Cyclone

The exercises above indicated that diabatic heating can be a factor in winter storms, altering the PV fields and thereby the ensuing storm evolution. But in many locations, diabatic effects are weaker in the winter, with little sunshine and limited amounts of water vapor able to condense and release latent heat in the cool-season air masses.* Meanwhile, adiabatic dynamical processes (like advection) are strongest in the winter, because strong gradients are present, and winds are strong.

To gain a quantitative perspective on adiabatic vs. diabatic effects in the evolution of the weather, this exercise examines all the terms in the temperature budget equation for the 10 November 1998 storm that is exhaustively analyzed in chapter 8 of the textbook by Wallace and Hobbs (2006). Our tool will be NASA's Modern-Era Retrospective Analysis (MERRA), with its complete heat budget data, along with some raw satellite data from NOAA to indicate whether the cyclone is accurately analyzed in MERRA.

In a data-assimilating atmosphere model, the heat budget for local tendency of temperature $\partial T/\partial t$ or potential temperature $\partial\theta/\partial t$ can be written schematically as three terms: fluid dynamical tendencies *dyn*, heating and cooling by the model's representations of physical processes *phy*, and "analysis tendencies" *ana* [see exercise 5.4. e) for an explanation of this term].

$$\frac{\partial T}{\partial t} = dyn + phy + ana$$

* Over the oceans, cold air masses flowing over warm water can be subject to strong diabatic heating near the surface.

The dynamical tendency *dyn* is the sum of horizontal and vertical advection by the model's wind field. The physical tendency *phy* = *rad* + *mst* + *trb* + *fri* is the sum of the following:

- Radiative heating *rad* = *swr* + *lwr,* the sum of shortwave or solar heating *swr* and long-wave or infrared heating–cooling *lwr.*
- Moist process heating (such as latent heating) *mst* from the model's convection and cloud schemes.
- Turbulent heating *trb* (another name for this would be *sensible heat flux convergence in the vertical*). For instance, in the case of the boundary layer scheme, this *trb* term is how solar heating of the ground is actually felt by the atmosphere. In the MERRA analysis, this also includes turbulent diffusion that takes place above the boundary layer.
- Frictional heating *fri* is the conversion of the kinetic energy of wind into molecular kinetic energy (that is, heat). It is a small term, but we can see how small.

a) **Open the bundle LMT_5.4**. You will see SLP (`sea level pressure`) contours on a shaded `t2m` temperature map. Can you locate the fronts in this midlatitude cyclone? Toggle the `true IR from satellite` display. **Are the position of the cyclone and its fronts fairly well analyzed in the model fields?** Toggle the display of `MERRA's prectot`, total precipitation produced by the model's convection and cloud schemes. **Does the model's rainfall (and condensation heating) match what you would infer from the satellite imagery? Capture an image indicating a discrepancy between the satellite observations and the model's depiction of the storm. What is your assessment of the general quality of the analysis?**

b) Examine the display of the column-integrated *physical* heating rate `dthdt_phy`. (Here the **th** in d**th**dt means potential temperature θ). Toggle the display of `MERRA's prectot` display on and off. **Do some features in these displays correspond to each other? Which category of physical heating corresponds to `MERRA's prectot`?** Loop between the 1500 and 1800 UTC time steps. **What main differences do you see in non-precipitating regions?** Hints: What is the local time of 1800 UTC in this area? Is the sun shining? Can you interpret some features in the 1800 UTC time step, perhaps with the background map as a guide?

c) Examine the display of the column-integrated *dynamical* (advective) tendency, `dthdt_dyn`. **Does it also have features that correspond to the pattern of `MERRA's prectot`? Explain.** Hint: what are the two big terms that mostly cancel in the temperature budget of a saturated updraft, in a precipitating column of the atmosphere?

d) Examine the `Column Integrated Tendencies` display called `phy+dyn`, the sum of the two fields examined above. **Does this field have much correspondence with `MERRA's prectot`? Why or why not, in light of c) above?** To interpret this field, activate the `Z500` contours display. We can think of the ridge–trough–ridge pattern in `Z500` as a *thickness* pattern (proportional to column temperature), with a cool column of air under the `Z500` trough and its cutoff low. Logically, if the total tendency `phy+dyn` is negative east of the trough, the trough will move eastward. If the tendency is negative within the trough, it will deepen. The same applies to the flanking ridges. **Loop between the two time steps. Using this logic, do the features in the net tendency `phy+dyn` explain the time evolution (motion and/or deepening) of the `Z500` trough/cutoff? Explain, with annotated image captures as needed for clarity.**

e) Examine the display of the column-integrated analysis tendency `dthdt_ana`. This "analysis tendency" is the difference between the *observed* (or more precisely, model-analyzed) *time rate of change* at each grid point $\partial\theta/\partial t$, minus the sum (`phy+dyn`) of the *model's physical and advective* processes that you examined in d) above. It is the *change that must be put in at analysis time to keep the model's time evolution in line with observations*. If the model's dynamics and physics schemes and its data assimilation system were perfect, this field would be exactly 0 everywhere. If the model or its analysis were completely wrong, this field would have magnitudes as large as $\partial\theta/\partial t$, or even larger. **Is this field "large" in magnitude? Compared to what, and why is that the right comparison in light of these considerations? Does it have features that correspond to `MERRA's prectot`? What is your assessment of the general quality of the model's analysis and physics in depicting this storm?**

In the following steps, you will examine cross sections to show vertical structure.

f) Next let's look at *vertical profiles* of the temperature budget terms. Uncheck the box next to `Atm. Column Integrated Tendencies` in the `Legend` to deactivate all those displays. Click the symbol next to that, in order to hide those displays and clean up the `Legend`. Click the corresponding symbol next to `Vertical Cross Sections` to expose the displays hidden there. Set the time step to 1500 UTC, since the cross sections only have data at that time. **Activate the first two cross section displays: `Temperature and Cloudiness`**. Revisit the `MERRA's prectot` display to notice the position of the sections: they cut through the clouds and precipitation near the heart of the cyclone. Click to view the scene from the south. **Where in the cyclone do you see low, middle, and high cloudiness?** Does this agree with your general knowledge of midlatitude cyclones? That is, **is the analysis generally trustworthy in its vertical structure?**

In the following steps, you will examine each of the heating rate displays, one by one.

g) Toggle the display for `dtdtlwr` (the longwave radiative heating rate). **Can you see the expected pattern of 1) heating at cloud bases,** because the upwelling IR absorbed from the warm Earth below exceeds the downward emission from the relatively cooler cloud base**, and 2) cooling to space at cloud tops? Express the approximate magnitude of the heating in K per day, given that the displayed value is in K s^{-1}.** Now do the same examination of `dtdtswr` (the shortwave radiative heating rate due to absorption of sunlight) and the sum of the two tendencies (`dtdtrad`). **Which is more similar to the *net* radiative heating** (toggle `dtdtrad` to see it)**, the shortwave or the longwave?**

h) Examine the turbulent (`dtdttrb`) and frictional (`dtdtfri`) heating terms. **Where are they active? Why? About how big are their largest magnitudes in K day^{-1}?**

i) Examine the moist heating (`dtdtmst`). (Notice that its positive values saturate the color scale, which is the same for all plots, so you can't tell quite how large it gets in the heavy rain region.) **How closely does `dtdtmst` correspond to the `Cloudiness` field?** You should realize that the convection scheme in the model can create precipitation and latent heating without making saturated air and 100% cloudiness on the grid scale. **Where does `dtdtmst` have negative values? How can you understand those negative values in terms of moist processes (related to latent heat)?**

j) Examine the total of all physical processes (`dtdttot`). **Capture an image, and annotate features on it which are contributed by 1) moist, 2) radiative, and 3) turbulent processes, synthesizing your findings above.**

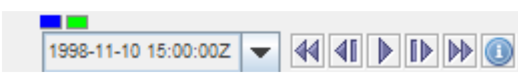
k) Examine the dynamical tendency (`dtdtdyn`). Notice that it saturates the color scale everywhere. **Is the heat budget in this midlatitude cyclone primarily adiabatic?** Next, reactivate the `dthdt_dyn` display under `Column Integrated Tendencies,` to **show that the vertical integral over column mass is mainly contributed by the lower troposphere**, below and including the 500-hPa altitude of the `Z500` display, which can serve as a reference line on your image.

Examine the analysis tendency (`dtdtana`). **Is it safe to say that it is much smaller than the dominant term (`dtdtdyn`)? What would you say about its magnitude relative to some physical tendencies? What does this imply in terms of the quality of the model's physics and dynamics processes?**

Optional: To learn more about these terms in the same storm, consider moving the cross sections. All the dtdt cross sections are bound together, while Temperature and Cloudiness are separately located.

Optional: To study the same set of displays for other cases anywhere other than the dateline, use the bundle **LMT_5.4_MERRA_1979-2015**. This large and complex bundle will access data on NASA and NOAA servers, making very many displays, so that the loading will be slow and may be incomplete—but it still may have value even if some parts fail (click OK to any errors). *If you get impatient with the loading, take a stroll while it loads and think of how long it would take to write code to extract these scientific lessons from these datasets!* Eliminating unwanted displays with the trash can icon before relocating your space and time regions will speed up the process. Save the bundle for yourself if you add any value to it.

To relocate the bundle, the `Time Driver` can be adjusted with the `Animation properties` dialog, found under the animation controller's  button. The displayed area can be adjusted by zooming out to see your desired region, then using a shift + click-and-drag mouse action to select your area (see screenshot below). The bigger your area, the longer it will take, so think carefully and don't zoom out while it is loading. The cross sections will have to be moved manually into the region of your case's data hypercube, either by mouse actions, or by entering new coordinates into their endpoint `Locations` in one of their `Display Controls`, accessed by clicking its hyperlink in the `Legend`. Happy hunting!



Reference

Wallace, J. M., and P. V. Hobbs, 2006: *Atmospheric Science: An Introductory Survey*. 2nd ed. Elsevier Press, 504 pp. (ISBN: 978-0-12-732951-2. Chapter 8 describes this storm in great detail.)