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Description Predicts the occurrence times (in day of year) of spring phenological events. Three methods, including the accumulated degree days (ADD) method, the accumulated days transferred to a standardized temperature (ADTS) method, and the accumulated developmental progress (ADP) method, were used. See Shi et al. (2017a) <doi:10.1016/j.agrformet.2017.04.001> and Shi et al. (2017b) <
tails.

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NeedsCompilation no

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Contents

`ADD` *Function for Implementing the Accumulated Degree Days Method*

Description

Estimates the starting date (S in day of year) and base tempeature (T_0 in °C) in the accumulated degree days method using mean daily air temperatures (Aono, 1993; Shi et al., 2017a, 2017b).

Usage

```
ADD(S.pd = NULL, T0.arr, Year1, Time, Year2, DOY, Temp, DOY.ul = 120,
    fig.opt = TRUE, S.def = 54, verbose = TRUE)
```

Arguments

`S.pd`	the pre-determined starting date for thermal accumulation (in day of year)
`T0.arr`	the candidate base temperatures (in °C)
`Year1`	the vector of the years recording a particular phenological event
`Time`	the vector of the occurence times (in day of year) of a particular phenological event across many years
`Year2`	the vector of the years recording the climate data corresponding to the occurrence times
`DOY`	the vector of the dates (in day of year) when the climate data exist
`Temp`	the mean daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time
`fig.opt`	an optional argument of drawing the figures assoicated with the determinations of the starting date and base temperature, and a comparision between the predicted and observed occurrence times
`S.def`	a mandatory defintion of the starting date when (i) `S.pd` is NULL and (ii) the minimum correlation coefficient method fails to find a suitable starting date
`verbose`	an optional argument of allowing users to suppress printing of computation progress

Details

The default of `S.pd` is NULL. In this case, the date associated with the minimum correlation coefficient [between the mean of the mean daily temperatures (from a candidate starting date to the observed occurrence time) and the observed occurrence time] will be determined to be the starting date on the condition that it is smaller than the mininum phenological occurence time. If the determined date associated with the minimum correlation coefficient is greater than the mininum phenological occurence time, `S.def` will be used as the starting date. If `S.pd` is not NULL, the starting date will be directly assigned as `S.pd` irrespective of the minimum correlation coefficient method and the value of `S.def`. This means, `S.pd` is superior to `S.def` in determining the starting date.

The function does not require that `Year1` is the same as the unique of `Year2`, and the intersection of two years will be finally kept. The unused years that have phenological records but lack the climate data will be showed in `unused.years` in the returned list.

The numerical value of `DOY.ul` should be larger than or equal to the maximum `Time`.

Value

`S.arr`	the candidate starting dates (in day of year), whose default ranges from the minimum `DOY` to min(`DOY.ul`, the maximum `DOY`)
`cor.coef.arr`	the candidate correlation coefficients between the mean of the mean daily tempertures (from a candidate starting date to the observed occurrence time) and the observed occurrence time
`cor.coef`	the minimum correlation coefficient, i.e., min(`cor.coef.arr`)
`search.failure`	a value of 0 or 1 of showing whether the starting date is successfully determined by the minimum correlation coefficient method when `S.pd` = `NULL`, where 0 represents success and 1 represents failure
`mAADD.arr`	an vector saving the interannual mean of the annual acccumulated degree days (AADD) values for each of the candidate base temperatures
`RMSE.arr`	a vector saving the candidate root-mean-square errors (in days) between the observed and predicted occurrence times for each of the candidate base temperatures
`AADD.arr`	the annual accumulated degree days (AADD) values in different years
`Year`	The intersected years between `Year1` and `Year2`
`Time`	The observed occurence times (day of year) in the intersected years between `Year1` and `Year2`
`Time.pred`	the predicted occurence times in different years
`S`	the determined starting date (day of year)
`T0`	the determined base temperature (in °C)
`AADD`	the expected annual accumulated degree days
`RMSE`	the smallest RMSE (in days) from the different candidate base temperatures
`unused.years`	the years that have phenological records but lack the climate data

Note

The entire mean daily temperature data in the spring of each year should be provided. `AADD` is represented by the mean of `AADD.arr` in the output. When the argument of `S.pd` is not `NULL`, the returned value of `search.failure` will be `NA`. When the argument of `S.pd` is `NULL`, and the minimum correlation coefficient method fails to find a suitable starting date, the argument of `S.def` is then defined as the determined starting date, i.e., the returned value of `S`. At the same time, the returned value of `cor.coef` is defined as `NA`.

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References

Aono, Y. (1993) Climatological studies on blooming of cherry tree (Prunus yedoensis) by means of DTS method. *Bulletin of the University of Osaka Prefecture. Ser. B, Agriculture and life sciences* 45, 155−192 (in Japanese with English abstract).

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

See Also

`predADD`

Examples

```
data(apricotFFD)
data(BJMDT)
X1 <- apricotFFD
X2 <- BJMDT

Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
T0.arr0    <- seq(-5, 5, by = 0.1)
S.pd0      <- NULL


  res1 <- ADD( S.pd = S.pd0, T0.arr = T0.arr0, Year1 = Year1.val, Time = Time.val,
               Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val,
               DOY.ul = DOY.ul.val, fig.opt = TRUE, S.def=54, verbose = TRUE )
  res1

  S0 <- res1$S.arr
  r0 <- res1$cor.coef.arr

  dev.new()
  par1 <- par(family="serif")
  par2 <- par(mar=c(5, 5, 2, 2))
  par3 <- par(mgp=c(3, 1, 0))
 plot( S0, r0, cex.lab = 1.5, cex.axis = 1.5, xlab = "Candidate starting date (day of year)",
       ylab="Correlation coefficient between the mean temperature and FFD", type="l" )
  ind <- which.min(r0)
  points(S0[ind], r0[ind], cex = 1.5, pch = 16)
 text(S0[ind], r0[ind] + 0.1, bquote(paste(italic(S), " = ", .(S0[ind]), sep = "")), cex = 1.5)
  par(par1)
  par(par2)
```

```
par(par3)

resu1 <- ADD( S.pd = 47, T0.arr = seq(-10, 0, by = 0.1), Year1 = Year1.val, Time = Time.val,
              Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val,
              DOY.ul = DOY.ul.val, fig.opt = TRUE, S.def = 54, verbose = TRUE )
resu1

# graphics.off()
```

`ADP` *Function for Implementing the Accumulated Developmental Progress Method*

Description

Estimates the starting date (S in day of year) and the parameters in a developmental rate model in the accumulated developmental progress (ADP) method using mean daily air temperatures (Wagner et al., 1984; Shi et al., 2017a, 2017b).

Usage

```
ADP( S.arr, expr, ini.val, Year1, Time, Year2, DOY, Temp, DOY.ul = 120,
     fig.opt = TRUE, control = list(), verbose = TRUE )
```

Arguments

`S.arr`	the candidate starting dates for thermal accumulation (in day of year)
`expr`	a user-defined model that is used in the accumulated developmental progress (ADP) method
`ini.val`	a vector or a list that saves the initial values of the parameters in `expr`
`Year1`	the vector of the years recording a particular phenological event
`Time`	the vector of the occurence times (in day of year) of a particular phenological event across many years
`Year2`	the vector of the years recording the climate data corresponding to the occurrence times
`DOY`	the vector of the dates (in day of year) when the climate data exist
`Temp`	the mean daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time
`fig.opt`	an optional argument of drawing the figures assoicated with the temperature-dependent developmental rate curve, the mean daily temperatures versus years, and a comparision between the predicted and observed occurrence times
`control`	the list of control parameters for using the `optim` function in package **stats**
`verbose`	an optional argument of allowing users to suppress printing of computation progress

Details

It is better not to set too much candiate starting dates, which will be time-consuming. If `expr` is selected as Arrhenius' equation, `S.arr` can be selected as `S` obtained from the output of carrying out the `ADTS` function. Here, `expr` can be other nonlinear temperature-dependent developmental rate functions (see Shi et al. [2017b] for details). Here, `expr` can be any an arbitrary user-defined temperature-dependent developmental rate function, e.g., a function named `myfun`, but it needs to take the following form of `myfun <- function(P, x){...}`, where `P` is the vector of the model parameter(s), and `x` is the vector of the predictor variable, i.e., the temperature variable.

The function does not require that `Year1` is the same as the unique of `Year2`, and the intersection of two years will be finally kept. The unused years that have phenological records but lack the climate data will be showed in `unused.years` in the returned list.

The numerical value of `DOY.ul` should be larger than or equal to the maximum `Time`.

Let r represent the temperature-dependent developmental rate, i.e., the reciprocal of the developmental duration at a constant temperature required for completing a particular phenological event. In the accumulated developmental progress (ADP) method, when the annual accumulated developmental progress (AADP) reaches 100%, the phenological event is predicted to occurr for each year. Let AADP_i denote the AADP of the ith year, which equals

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i} r_{ij}\left(\mathbf{P}; T_{ij}\right),$$

where S represents the starting date (in day of year), E_i represents the ending date (in day of year), i.e., the occurrence time of a pariticular phenological event in the ith year, $\mathbf{P}$ is the vector of the model parameters in `expr`, and T_{ij} represents the mean daily temperature of the jth day of the ith year (in °C or K). In theory, $\mathrm{AADP}_i = 100\%$, i.e., the AADP values of different years are a constant of 100%. However, in practice, there is a certain deviation of AADP_i from 100%. The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F} r_{ij} = 100\%$ (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F} r_{ij} < 100\%$ and $\sum_{j=S}^{F+1} r_{ij} > 100\%$, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time. Assume that there are n-year phenological records. When the starting date S and the temperature-dependent developmental rate model are known, the model parameters can be estimated using the Nelder-Mead optiminization method (Nelder and Mead, 1965) to minimize the root-mean-square error (RMSE) between the observed and predicted occurrence times, i.e.,

$$\hat{\mathbf{P}} = \arg\min_{\mathbf{P}}\left\{\mathrm{RMSE}\right\} = \arg\min_{\mathbf{P}}\sqrt{\frac{\sum_{i=1}^{n}\left(E_i - \hat{E}_i\right)^2}{n}}.$$

Because S is not determined, a group of candidate S values (in day of year) need to be provided. Assume that there are m candidate S values, i.e., $S_1, S_2, S_3, \cdots, S_m$. For each S_q (where q ranges between 1 and m), we can obtain a vector of the estimated model parameters, $\hat{\mathbf{P}}_q$, by minimizing RMSE_q using the Nelder-Mead optiminization method. Then we finally selected $\hat{\mathbf{P}}$ associated with $\min\left\{\mathrm{RMSE}_1, \mathrm{RMSE}_2, \mathrm{RMSE}_3, \cdots, \mathrm{RMSE}_m\right\}$ as the target parameter vector.

Value

`TDDR`	the temperature-dependent developmental rate matrix consisting of the year, day of year, mean daily temperature and developmental rate columns
`MAT`	a matrix consisting of the candidate starting dates, the estimates of candidate model parameters with the corresponding RMSEs
`Dev.accum`	the calculated annual accumulated developmental progresses in different years
`Year`	The intersected years between `Year1` and `Year2`
`Time`	The observed occurence times (day of year) in the intersected years between `Year1` and `Year2`
`Time.pred`	the predicted occurence times in different years
`S`	the determined starting date (day of year)
`par`	the estiamtes of model parameters
`RMSE`	the RMSE (in days) between the observed and predicted occurrence times
`unused.years`	the years that have phenological records but lack the climate data

Note

The entire mean daily temperature data in the spring of each year should be provided. In `TDDR`, the first column of `Year` saves the years, the second column of `DOY` saves the day of year values, the third column of `Temperature` saves the mean daily air temperatures between the starting date to the occurrence times, and the fourth column of `Rate` saves the calculated developmental rates corresponding to the mean daily temperatures.

Author(s)

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References

Nelder, J.A., Mead, R. (1965) A simplex method for function minimization. *Computer Journal* 7, 308–313. doi:10.1093/comjnl/7.4.308

Ring, D.R., Harris, M.K. (1983) Predicting pecan nut casebearer (Lepidoptera: Pyralidae) activity at College Station, Texas. *Environmental Entomology* 12, 482–486. doi:10.1093/ee/12.2.482

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240–241, 78–89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558–564. doi:10.1093/aesa/sax063

Wagner, T.L., Wu, H.-I., Sharpe, P.J.H., Shcoolfield, R.M., Coulson, R.N. (1984) Modelling insect development rates: a literature review and application of a biophysical model. *Annals of the Entomological Society of America* 77, 208–225. doi:10.1093/aesa/77.2.208

See Also

`predADP`

Examples

```
data(apricotFFD)
data(BJMDT)
X1 <- apricotFFD
X2 <- BJMDT

Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
S.arr0     <- 47

#### Defines a re-parameterized Arrhenius' equation ###########################
Arrhenius.eqn <- function(P, x){
  B  <- P[1]
  Ea <- P[2]
  R  <- 1.987 * 10^(-3)
  x  <- x + 273.15
  10^12*exp(B-Ea/(R*x))
}
###############################################################################

#### Provides the initial values of the parameter of Arrhenius' equation #####
ini.val0 <- list( B = 20, Ea = 14 )
###############################################################################


 res5 <- ADP( S.arr = S.arr0, expr = Arrhenius.eqn, ini.val = ini.val0, Year1 = Year1.val,
              Time = Time.val, Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val,
              DOY.ul = DOY.ul.val, fig.opt = TRUE, control = list(trace = FALSE,
              reltol = 1e-12, maxit = 5000), verbose = TRUE )
  res5

  TDDR <- res5$TDDR
  T    <- TDDR$Temperature
  r    <- TDDR$Rate
  Y    <- res5$Year
  DP   <- res5$Dev.accum

  dev.new()
  par1 <- par(family="serif")
  par2 <- par(mar=c(5, 5, 2, 2))
  par3 <- par(mgp=c(3, 1, 0))
  Ind <- sort(T, index.return=TRUE)$ix
  T1  <- T[Ind]
  r1  <- r[Ind]
  plot( T1, r1, cex.lab = 1.5, cex.axis = 1.5, pch = 1, cex = 1.5, col = 2, type = "l",
        xlab = expression(paste("Mean daily temperature (", degree, "C)", sep = "")),
     ylab = expression(paste("Calculated developmental rate (", {day}^{"-1"}, ")", sep = "")) )
  par(par1)
```

```
par(par2)
par(par3)

dev.new()
par1 <- par(family="serif")
par2 <- par(mar=c(5, 5, 2, 2))
par3 <- par(mgp=c(3, 1, 0))
plot( Y, DP * 100, xlab = "Year",
      ylab = "Accumulated developmental progress (%)",
      ylim = c(50, 150), cex.lab=1.5, cex.axis = 1.5, cex = 1.5 )
abline( h = 1 * 100, lwd = 1, col = 4, lty = 2 )
par(par1)
par(par2)
par(par3)

# graphics.off()
```

`ADTS` *Function for Implementing the Accumulated Days Transferred to a Standardized Temperature Method*

Description

Estimates the starting date (S in day of year) and activation free energy (E_a in $\text{kcal} \cdot \text{mol}^{-1}$) in the accumulated days transferred to a standardized temperature (ADTS) method using mean daily air temperatures (Konno and Sugihara, 1986; Aono, 1993; Shi et al., 2017a, 2017b).

Usage

```
ADTS( S.arr, Ea.arr, Year1, Time, Year2, DOY, Temp, DOY.ul = 120,
      fig.opt = TRUE, verbose = TRUE )
```

Arguments

`S.arr`	the candidate starting dates for thermal accumulation (in day of year)
`Ea.arr`	the candidate activation free energy values (in $\text{kcal} \cdot \text{mol}^{-1}$)
`Year1`	the vector of the years recording a particular phenological event
`Time`	the vector of the occurence times (in day of year) of a particular phenological event across many years
`Year2`	the vector of the years recording the climate data corresponding to the occurrence times
`DOY`	the vector of the dates (in day of year) when the climate data exist
`Temp`	the mean daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time

`fig.opt`	an optional argument of drawing the figures assoicated with the determination of the combination the starting date and activation free energy, and a comparision between the predicted and observed occurrence times
`verbose`	an optional argument of allowing users to suppress printing of computation progress

Details

When `fig.opt` is equal to `TRUE`, it will show the contours of the root-mean-square errors (RMSEs) based on different combinations of S and E_a.

The function does not require that `Year1` is the same as the unique of `Year2`, and the intersection of two years will be finally kept. The unused years that have phenological records but lack the climate data will be showed in `unused.years` in the returned list.

The numerical value of `DOY.ul` should be larger than or equal to the maximum `Time`.

Value

`mAADTS.mat`	a matrix consisiting of the means of the annual accumulated days transferred to a standardized temperature (AADTS) values from the combinations of S and E_a
`RMSE.mat`	the matrix consisting of the RMSEs (in days) from different combinations of S and E_a
`AADTS.arr`	the AADTS values in different years associated with the smallest value in `RMSE.mat`
`Year`	The intersected years between `Year1` and `Year2`
`Time`	The observed occurence times (day of year) in the intersected years between `Year1` and `Year2`
`Time.pred`	the predicted occurence times in different years
`S`	the determined starting date (day of year)
`Ea`	the determined activation free energy values (in kcal·mol^{-1})
`AADD`	the expected AADTS
`RMSE`	the smallest RMSE (in days) in `RMSE.mat` from different combinations of S and E_a
`unused.years`	the years that have phenological records but lack the climate data

Note

The entire mean daily temperature data in the spring of each year should be provided. `AADTS` is represented by the mean of `AADTS.arr` in the output.

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References

Aono, Y. (1993) Climatological studies on blooming of cherry tree (Prunus yedoensis) by means of DTS method. *Bulletin of the University of Osaka Prefecture. Ser. B, Agriculture and life sciences* 45, 155−192 (in Japanese with English abstract).

Konno, T., Sugihara, S. (1986) Temperature index for characterizing biological activity in soil and its application to decomposition of soil organic matter. *Bulletin of National Institute for Agro-Environmental Sciences* 1, 51−68 (in Japanese with English abstract).

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

See Also

`predADTS`

Examples

```
data(apricotFFD)
data(BJMDT)
X1 <- apricotFFD
X2 <- BJMDT

Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
S.arr0     <- seq(40, 60, by = 1)
Ea.arr0    <- seq(10, 20, by = 1)


  res3 <- ADTS( S.arr = S.arr0, Ea.arr = Ea.arr0, Year1 = Year1.val, Time = Time.val,
                Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val, DOY.ul = DOY.ul.val,
                fig.opt = TRUE, verbose = TRUE)
  res3

  RMSE.mat0  <- res3$RMSE.mat
  RMSE.range <- range(RMSE.mat0)

  dev.new()
  par1 <- par(family="serif")
  par2 <- par(mar=c(5, 5, 2, 2))
  par3 <- par(mgp=c(3, 1, 0))
  image( S.arr0, Ea.arr0, RMSE.mat0, col = terrain.colors(200), axes = TRUE,
         cex.axis = 1.5, cex.lab = 1.5, xlab = "Starting date (day of year)",
       ylab = expression(paste(italic(E["a"]), " (kcal" %.% "mol"^{"-1"}, ")", sep = "")))
```

```
 points( res3$S, res3$Ea, cex = 1.5, pch = 16, col = 2 )
 contour( S.arr0, Ea.arr0, RMSE.mat0, levels = round(seq(RMSE.range[1],
       RMSE.range[2], len = 20), 4), add = TRUE, cex = 1.5, col = "#696969", labcex = 1.5)
 par(par1)
 par(par2)
 par(par3)

resu3 <- ADTS( S.arr = 47, Ea.arr = seq(10, 20, by = 0.5), Year1 = Year1.val, Time = Time.val,
                Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val, DOY.ul = DOY.ul.val,
                fig.opt = TRUE, verbose = TRUE)
 resu3

 # graphics.off()
```

`apricotFFD` *First flowering date records of* Prunus armeniaca

Description

The data consist of the first flowering date records of *Prunus armeniaca* at the Summer Palace (39°54′38″ N, 116°8′28″ E, 50 m a.s.l.) in Beijing of China between 1963 and 2010. **Data source**: Chinese Phenological Observation Network (Guo et al., 2015).

Usage

```
data(apricotFFD)
```

Details

In the data set, there are two columns of vectors: `Year`, and `Time`. `Code` saves the recording years; and `Time` saves 1963−2010 first flowering dates of *Prunus armeniaca* in day of year.

References

Guo, L., Xu, J., Dai, J., Cheng, J., Wu, H., Luedeling, E. (2015) Statistical identification of chilling and heat requirements for apricotflower buds in Beijing, China. *Scientia Horticulturae* 195, 138−144. doi:10.1016/j.scienta.2015.09.006

Examples

```
data(apricotFFD)
attach(apricotFFD)

dev.new()
par1 <- par(family="serif")
par2 <- par(mar=c(5, 5, 2, 2))
par3 <- par(mgp=c(3, 1, 0))
```

```
plot( Year, Time, asp = 1, cex.lab = 1.5, cex.axis = 1.5,
      xlab = "Year", ylab = "First flowering date (day of year)" )
par(par1)
par(par2)
par(par3)

# graphics.off()
```

BJMDT *Mean Daily Temperature Data of Beijing from 1951 to 2012 with the exception of 1968.*

Description

The data include the mean daily temperatures (in °C) of Beijing between 1951 and 2012 with the exception of 1968. **Data source**: China Meteorological Data Service Centre (`https://data.cma.cn/en`).

Usage

```
data(BJMDT)
```

Details

In the data set, there are five columns of vectors: `Year`, `Month`, `Day`, `DOY`, and `MDT`. `Year` saves the recording years; `Month` saves the recording months; `Day` saves the recording days; `DOY` saves the dates in day of year; and `MDT` saves the mean daily temperatures (in °C) corresponding to `DOY`.

References

Guo, L., Xu, J., Dai, J., Cheng, J., Wu, H., Luedeling, E. (2015) Statistical identification of chilling and heat requirements for apricotflower buds in Beijing, China. *Scientia Horticulturae* 195, 138−144. doi:10.1016/j.scienta.2015.09.006

Examples

```
data(BJMDT)
attach(BJMDT)

x    <- as.numeric( tapply(DOY, DOY, mean) )
y    <- as.numeric( tapply(MDT, DOY, mean) )
y.sd <- as.numeric( tapply(MDT, DOY, sd) )

dev.new()
par1 <- par(family="serif")
par2 <- par(mar=c(5, 5, 2, 2))
par3 <- par(mgp=c(3, 1, 0))
plot( x, y, cex = 1.5, xlim = c(0, 367), ylim = c(-10, 30),
      cex.lab = 1.5, cex.axis = 1.5, type = "n", xlab = "Day of Year",
```

```
     ylab = expression(paste("Mean daily temperature (", degree, "C)", sep="")) )
for(i in 1:length(x)){
  lines(c(x[i], x[i]), c(y[i]-y.sd[i], y[i]+y.sd[i]), col=4)
}
points(x, y, cex = 1.5)
par(par1)
par(par2)
par(par3)

# graphics.off()
```

`predADD` *Prediction Function of the Accumulated Degree Days Method*

Description

Predicts the occurrence times using the accumulated degree days method based on observed or predicted mean daily air temperatures (Aono, 1993; Shi et al., 2017a, 2017b).

Usage

```
predADD(S, T0, AADD, Year2, DOY, Temp, DOY.ul = 120)
```

Arguments

`S`	the starting date for thermal accumulation (in day of year)
`T0`	the base temperature (in °C)
`AADD`	the expected annual accumulated degree days
`Year2`	the vector of the years recording the climate data for predicting the occurrence times
`DOY`	the vector of the dates (in day of year) when the climate data exist
`Temp`	the mean daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time

Details

In the accumulated degree days (ADD) method (Shi et al., 2017a, 2017b), the starting date (S) and the base temperature (T_0), and the annual accumulated degree days (AADD which is denoted by k) are assumed to be constants across different years. Let k_i denote the AADD of the ith year, which equals

$$k_i = \sum_{j=S}^{E_i} \left(T_{ij} - T_0\right),$$

where E_i represents the ending date (in day of year), i.e., the occurrence time of a pariticular phenological event in the ith year, and T_{ij} represents the mean daily temperature of the jth day of the ith year (in °C). In theory, $k_i = k$, i.e., the AADD values of different years are a constant. However, in practice, there is a certain deviation of k_i from k. The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F}\left(T_{ij} - T_0\right) = k$ (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F}\left(T_{ij} - T_0\right) < k$ and $\sum_{j=S}^{F+1}\left(T_{ij} - T_0\right) > k$, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time.

Value

`Year`	the years with climate data
`Time.pred`	the predicted occurence times (day of year) in different years

Note

The entire mean daily temperature data in the spring of each year should be provided.

Author(s)

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References

Aono, Y. (1993) Climatological studies on blooming of cherry tree (Prunus yedoensis) by means of DTS method. *Bulletin of the University of Osaka Prefecture. Ser. B, Agriculture and life sciences* 45, 155−192 (in Japanese with English abstract).

Ring, D.R., Harris, M.K. (1983) Predicting pecan nut casebearer (Lepidoptera: Pyralidae) activity at College Station, Texas. *Environmental Entomology* 12, 482−486. doi:10.1093/ee/12.2.482

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

See Also

`ADD`

Examples

```
data(apricotFFD)
data(BJMDT)
X1 <- apricotFFD
X2 <- BJMDT
Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
```

```
S.val      <- 65
T0.val     <- -0.5
AADD.val   <- 235.6447

res2 <- predADD( S = S.val, T0 = T0.val, AADD = AADD.val,
                 Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val,
                 DOY.ul = DOY.ul.val )
res2


ind1  <- res2$Year %in% intersect(res2$Year, Year1.val)
ind2  <- Year1.val %in% intersect(res2$Year, Year1.val)
RMSE1 <- sqrt( sum((Time.val[ind2]-res2$Time.pred[ind1])^2) / length(Time.val[ind2]) )
RMSE1
```

`predADP` *Prediction Function of the Accumulated Developmental Progress Method*

Description

Predicts the occurrence times using the accumulated developmental progress (ADP) method based on observed or predicted mean daily air temperatures (Wagner et al., 1984; Shi et al., 2017a, 2017b).

Usage

```
predADP(S, expr, theta, Year2, DOY, Temp, DOY.ul = 120)
```

Arguments

`S`	the starting date for thermal accumulation (in day of year)
`expr`	a user-defined model that is used in the accumulated developmental progress (ADP) method
`theta`	a vector saves the numerical values of the parameters in `expr`
`Year2`	the vector of the years recording the climate data for predicting the occurrence times
`DOY`	the vector of the dates (in day of year) when the climate data exist
`Temp`	the mean daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time

Details

Organisms showing phenological events in early spring often experience several cold days during the development. In this case, Arrhenius' equation (Shi et al., 2017a, 2017b, and references therein) has been recommended to describe the effect of the absolute temperature (T in Kelvin [K]) on the developmental rate (r):

$$r = \exp\left(B - \frac{E_a}{RT}\right),$$

where E_a represents the activation free energy (in kcal $\cdot$ mol^{-1}); R is the universal gas constant (= 1.987 cal $\cdot$ mol^{-1} $\cdot$ K^{-1}); B is a constant. To keep the consistence of the unit used in E_a and R, we need to re-assign R to be 1.987$\times$10^{-3} to make its unit 1.987$\times$10^{-3} kcal $\cdot$ mol^{-1} $\cdot$ K^{-1} in the above formula.

In the accumulated developmental progress (ADP) method, when the annual accumulated developmental progress (AADP) reaches 100%, the phenological event is predicted to occurr for each year. Let AADP_i denote the AADP of the ith year, which equals

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i} r_{ij},$$

where E_i represents the ending date (in day of year), i.e., the occurrence time of a pariticular phenological event in the ith year. If the temperature-dependent developmental rate follows Arrhenius' equation, the AADP of the ith year is equal to

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i} \exp\left(B - \frac{E_a}{RT_{ij}}\right),$$

where T_{ij} represents the mean daily temperature of the jth day of the ith year (in K). In theory, $\mathrm{AADP}_i = 100\%$, i.e., the AADP values of different years are a constant of 100%. However, in practice, there is a certain deviation of AADP_i from 100%. The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F} r_{ij} = 100\%$ (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F} r_{ij} < 100\%$ and $\sum_{j=S}^{F+1} r_{ij} > 100\%$, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time.

The argument of `expr` can be any an arbitrary user-defined temperature-dependent developmental rate function, e.g., a function named `myfun`, but it needs to take the following form of `myfun <- function(P, x){...}`, where `P` is the vector of the model parameter(s), and `x` is the vector of the predictor variable, i.e., the temperature variable.

Value

`Year`	the years with climate data
`Time.pred`	the predicted occurence times (day of year) in different years

Note

The entire mean daily temperature data in the spring of each year should be provided. There is a need to note that the unit of `Temp` in **Arguments** is °C, not K. In addition, when using Arrhenius' equation to describe r, to reduce the size of B in this equation, Arrhenius' equation is multiplied by 10^{12} in calculating the AADP value for each year, i.e.,

$$\mathrm{AADP}_i = \sum_{j=S}^{E_i} \left[10^{12} \cdot \exp\left(B - \frac{E_a}{R\,T_{ij}} \right) \right].$$

Author(s)

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References

Ring, D.R., Harris, M.K. (1983) Predicting pecan nut casebearer (Lepidoptera: Pyralidae) activity at College Station, Texas. *Environmental Entomology* 12, 482−486. doi:10.1093/ee/12.2.482

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

Wagner, T.L., Wu, H.-I., Sharpe, P.J.H., Shcoolfield, R.M., Coulson, R.N. (1984) Modelling insect development rates: a literature review and application of a biophysical model. *Annals of the Entomological Society of America* 77, 208−225. doi:10.1093/aesa/77.2.208

See Also

`ADP`

Examples

```
data(apricotFFD)
data(BJMDT)
X1 <- apricotFFD
X2 <- BJMDT
Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
S.val      <- 47

# Defines a re-parameterized Arrhenius' equation
Arrhenius.eqn <- function(P, x){
  B  <- P[1]
  Ea <- P[2]
  R  <- 1.987 * 10^(-3)
  x  <- x + 273.15
  10^12*exp(B-Ea/(R*x))
```

```
}

P0 <- c(-4.7823, 14.8198)
T2 <- seq(-10, 20, len = 2000)
r2 <- Arrhenius.eqn(P = P0, x = T2)

dev.new()
par1 <- par(family="serif")
par2 <- par(mar=c(5, 5, 2, 2))
par3 <- par(mgp=c(3, 1, 0))
plot( T2, r2, cex.lab = 1.5, cex.axis = 1.5, pch = 1, cex = 1.5, col = 2, type = "l",
      xlab = expression(paste("Temperature (", degree, "C)", sep = "")),
      ylab = expression(paste("Developmental rate (", {day}^{"-1"}, ")", sep="")) )
par(par1)
par(par2)
par(par3)

res6 <- predADP( S = S.val, expr = Arrhenius.eqn, theta = P0, Year2 = Year2.val,
                 DOY = DOY.val, Temp = Temp.val, DOY.ul = DOY.ul.val )
res6

ind5 <- res6$Year %in% intersect(res6$Year, Year1.val)
ind6  <- Year1.val %in% intersect(res6$Year, Year1.val)
RMSE3 <- sqrt( sum((Time.val[ind6]-res6$Time.pred[ind5])^2) / length(Time.val[ind6]) )
RMSE3
```

`predADTS` *Prediction Function of the Accumulated Days Transferred to a Standardized Temperature Method*

Description

Predicts the occurrence times using the accumulated days transferred to a standardized temperature (ADTS) method based on observed or predicted mean daily air temperatures (Konno and Sugihara, 1986; Aono, 1993; Shi et al., 2017a, 2017b).

Usage

```
predADTS(S, Ea, AADTS, Year2, DOY, Temp, DOY.ul = 120)
```

Arguments

`S`	the starting date for thermal accumulation (in day of year)
`Ea`	the activation free energy (in kcal $\cdot$ mol^{-1})
`AADTS`	the expected annual accumulated days transferred to a standardized temperature
`Year2`	the vector of the years recording the climate data for predicting the occurrence times

`DOY`	the vector of the dates (in day of year) when the climate data exist
`Temp`	the mean daily air temperature data (in °C) corresponding to `DOY`
`DOY.ul`	the upper limit of `DOY` used to predict the occurrence time

Details

Organisms showing phenological events in early spring often experience several cold days during the development. In this case, Arrhenius' equation (Shi et al., 2017a, 2017b, and references therein) has been recommended to describe the effect of the absolute temperature (T in Kelvin [K]) on the developmental rate (r):

$$r = \exp\left(B - \frac{E_a}{R\,T}\right),$$

where E_a represents the activation free energy (in kcal $\cdot$ mol^{-1}); R is the universal gas constant (= 1.987 cal $\cdot$ mol^{-1} $\cdot$ K^{-1}); B is a constant. To keep the consistence of the unit used in E_a and R, we need to re-assign R to be 1.987$\times$10^{-3} to make its unit 1.987$\times$10^{-3} kcal $\cdot$ mol^{-1} $\cdot$ K^{-1} in the above formula.

According to the definition of the developmental rate (r), it is the developmental progress per unit time (e.g., per day, per hour), which equals the reciprocal of the developmental duration D, i.e., $r = 1/D$. Let T_s represent the standard temperature (in K), and r_s represent the developmental rate at T_s. let r_j represent the developmental rate at T_j, an arbitrary temperature (in K). It is apparent that $D_s r_s = D_j r_j = 1$. It follows that

$$\frac{D_s}{D_j} = \frac{r_j}{r_s} = \exp\left[\frac{E_a\,(T_j - T_s)}{R\,T_j\,T_s}\right],$$

where D_s/D_j is referred to as the number of days transferred to a standardized temperature (DTS) (Konno and Sugihara, 1986; Aono, 1993).

In the accumulated days transferred to a standardized temperature (ADTS) method, the annual accumulated days transferred to a standardized temperature (AADTS) is assumed to be a constant. Let AADTS_i denote the AADTS of the ith year, which equals

$$\mathrm{AADTS}_i = \sum_{j=S}^{E_i}\left\{\exp\left[\frac{E_a\,(T_{ij} - T_s)}{R\,T_{ij}\,T_s}\right]\right\},$$

where E_i represents the ending date (in day of year), i.e., the occurrence time of a pariticular phenological event in the ith year, and T_{ij} represents the mean daily temperature of the jth day of the ith year (in K). In theory, AADTS_i = AADTS, i.e., the AADTS values of different years are a constant. However, in practice, there is a certain deviation of AADTS_i from AADTS. The following approach is used to determine the predicted occurrence time. When $\sum_{j=S}^{F}\left\{\exp\left[\frac{E_a(T_{ij}-T_s)}{R\,T_{ij}\,T_s}\right]\right\} =$ AADTS (where $F \geq S$), it follows that F is the predicted occurrence time; when $\sum_{j=S}^{F}\left\{\exp\left[\frac{E_a(T_{ij}-T_s)}{R\,T_{ij}\,T_s}\right]\right\} <$ AADTS and $\sum_{j=S}^{F+1}\left\{\exp\left[\frac{E_a(T_{ij}-T_s)}{R\,T_{ij}\,T_s}\right]\right\} >$ AADTS, the trapezoid method (Ring and Harris, 1983) is used to determine the predicted occurrence time.

Value

`Year`	the years with climate data
`Time.pred`	the predicted occurence times (day of year) in different years

Note

The entire mean daily temperature data in the spring of each year should be provided. There is a need to note that the unit of `Temp` in **Arguments** is °C, not K.

Author(s)

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References

Aono, Y. (1993) Climatological studies on blooming of cherry tree (Prunus yedoensis) by means of DTS method. *Bulletin of the University of Osaka Prefecture. Ser. B, Agriculture and life sciences* 45, 155−192 (in Japanese with English abstract).

Konno, T., Sugihara, S. (1986) Temperature index for characterizing biological activity in soil and its application to decomposition of soil organic matter. *Bulletin of National Institute for Agro-Environmental Sciences* 1, 51−68 (in Japanese with English abstract).

Ring, D.R., Harris, M.K. (1983) Predicting pecan nut casebearer (Lepidoptera: Pyralidae) activity at College Station, Texas. *Environmental Entomology* 12, 482−486. doi:10.1093/ee/12.2.482

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

See Also

`ADTS`

Examples

```
data(apricotFFD)
data(BJMDT)
X1 <- apricotFFD
X2 <- BJMDT
Year1.val  <- X1$Year
Time.val   <- X1$Time
Year2.val  <- X2$Year
DOY.val    <- X2$DOY
Temp.val   <- X2$MDT
DOY.ul.val <- 120
S.val      <- 47
Ea.val     <- 14
AADTS.val  <-  9.607107
```

```
res4 <- predADTS( S = S.val, Ea = Ea.val, AADTS = AADTS.val,
                  Year2 = Year2.val, DOY = DOY.val, Temp = Temp.val,
                  DOY.ul = DOY.ul.val )
res4

ind3  <- res4$Year %in% intersect(res4$Year, Year1.val)
ind4  <- Year1.val %in% intersect(res4$Year, Year1.val)
RMSE2 <- sqrt( sum((Time.val[ind4]-res4$Time.pred[ind3])^2) / length(Time.val[ind4]) )
RMSE2
```

`spphpr` *Spring Phenological Prediction*

Description

Predicts the occurrence times (in day of year) of spring phenological events. Three methods, including the accumulated degree days (ADD) method, the accumulated days transferred to a standardized temperature (ADTS) method, and the accumulated developmental progress (ADP) method, were used. See Shi et al. (2017a, 2017b) for details.

Details

The DESCRIPTION file:

Package:	spphpr
Type:	Package
Title:	Spring Phenological Prediction
Version:	0.1.4
Date:	2024-12-12
Authors@R:	c(person(given="Peijian", family="Shi", email="pjshi@njfu.edu.cn", role=c("aut", "cre")), person(given=c("Z
Author:	Peijian Shi [aut, cre], Zhenghong Chen [aut], Brady K. Quinn [aut]
Maintainer:	Peijian Shi <pjshi@njfu.edu.cn>
Description:	Predicts the occurrence times (in day of year) of spring phenological events. Three methods, including the accu
Depends:	R (>= 4.2.0)
License:	GPL (>= 2)

Index of help topics:

```
ADD                     Function for Implementing the Accumulated
                        Degree Days Method
ADP                     Function for Implementing the Accumulated
                        Developmental Progress Method
ADTS                    Function for Implementing the Accumulated Days
                        Transferred to a Standardized Temperature
                        Method
```

`BJMDT`	Mean Daily Temperature Data of Beijing from 1951 to 2012 with the exception of 1968.
`apricotFFD`	First flowering date records of _Prunus armeniaca_
`predADD`	Prediction Function of the Accumulated Degree Days Method
`predADP`	Prediction Function of the Accumulated Developmental Progress Method
`predADTS`	Prediction Function of the Accumulated Days Transferred to a Standardized Temperature Method
`spphpr`	Spring Phenological Prediction
`toDOY`	Function for Transferring a Date to the Value of Day of Year

Note

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Author(s)

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Maintainer: Peijian Shi <pjshi@njfu.edu.cn>

References

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

`toDOY` *Function for Transferring a Date to the Value of Day of Year*

Description

Transfers the date (from year, month and day) to the value of day of year.

Usage

```
toDOY(Year, Month, Day)
```

Arguments

`Year`	the vector of years
`Month`	the vector of months
`Day`	the vector of days

Details

The user needs to provide the three separate vectors of `Year`, `Month` and `Day`, rather than providing a single date vector. The arguments can be numerical vectors or character vectors.

Value

The returned value is a vector of transferred dates in day of year.

Note

The returned vector, `DOY`, usually mathes with the year vector and the mean daily temperature vector as arguments in other functions, e.g., the `ADD` function.

Author(s)

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References

Shi, P., Chen, Z., Reddy, G.V.P., Hui, C., Huang, J., Xiao, M. (2017a) Timing of cherry tree blooming: Contrasting effects of rising winter low temperatures and early spring temperatures. *Agricultural and Forest Meteorology* 240−241, 78−89. doi:10.1016/j.agrformet.2017.04.001

Shi, P., Fan, M., Reddy, G.V.P. (2017b) Comparison of thermal performance equations in describing temperature-dependent developmental rates of insects: (III) Phenological applications. *Annals of the Entomological Society of America* 110, 558−564. doi:10.1093/aesa/sax063

See Also

`BJMDT`

Examples

```
data(BJMDT)
X2   <- BJMDT
DOY2 <- toDOY(X2$Year, X2$Month, X2$Day)
# cbind(X2$DOY, DOY2)
```

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